Regular Features of the Solar System

- All of the planets orbit the Sun in the same plane
- All planetary orbits are nearly circular
- All planets orbit the Sun in the same “direction”
- Most planets rotate in the same sense as the orbit.
Regular Features of the Solar System

- The Jovian and Terrestrial planets are well sorted in terms of distance from the Sun.
  - rocky worlds close – gaseous/icy worlds far away
Regular Features of the Solar System

- All of the planets orbit the Sun in the same plane
- All planetary orbits are nearly circular
- All planets orbit the Sun in the same “direction”
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Obliquity of the Nine Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Obliquity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.1°</td>
</tr>
<tr>
<td>Venus</td>
<td>177°</td>
</tr>
<tr>
<td>Earth</td>
<td>23°</td>
</tr>
<tr>
<td>Mars</td>
<td>25°</td>
</tr>
<tr>
<td>Jupiter</td>
<td>3°</td>
</tr>
<tr>
<td>Saturn</td>
<td>27°</td>
</tr>
<tr>
<td>Uranus</td>
<td>98°</td>
</tr>
<tr>
<td>Neptune</td>
<td>30°</td>
</tr>
<tr>
<td>Pluto</td>
<td>120°</td>
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</table>
Regular Features of the Solar System

- The Giant Planet satellite systems resemble the Solar System.
Regular Features of the Solar System

- Exposed solid surfaces are heavily cratered throughout the Solar System.
  - The process was messy and produced lots of leftovers.
Exposed solid surfaces are heavily cratered throughout the Solar System.

- The process was messy and produced lots of leftovers.
The Galaxy is rich in dense interstellar clouds, ripe for the formation of new generations of stars.
Gravity Makes Stars

- In some places gravity has begun to compress the gas (and dust) to make new generations of stars.
Why Should We Expect to Find Other Planets?

We see stars forming elsewhere
Gravity Makes Stars

- Star forming regions are common throughout the Galaxy
Formation of a “Circumstellar Disk”

• Focus now on the formation of a single star.
  - If a cloud undergoing gravitational collapse has even the slightest bit of rotation the “conservation of angular momentum” will cause some of the material to form a thin flat disk.
Formation of a “Circumstellar Disk”

- Most of the material works its way down to the center to form a star.
- A small amount of material remains in the disk.
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- A small amount of material remains in the disk.
Building Planets: The Story of Accretion

- Recall that, on average, the universe is 99% hydrogen and helium and 1% other stuff.
- Interestingly, initial planetary growth involves the rare 1%

<table>
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<tr>
<th>Materials in the Solar Nebula</th>
<th>Metals</th>
<th>Rocks</th>
<th>Hydrogen Compounds</th>
<th>Light Gases</th>
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<tr>
<td>Examples</td>
<td>iron, nickel, aluminum</td>
<td>silicates</td>
<td>water (H₂O) methane (CH₄) ammonia (NH₃)</td>
<td>hydrogen, helium</td>
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<tr>
<td>Typical Condensation Temperature</td>
<td>1,000–1,600 K</td>
<td>500–1,300 K</td>
<td>&lt; 500 K</td>
<td>(do not condense in nebula)</td>
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<tr>
<td>Relative Abundance (by mass)</td>
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<td>(0.4%)</td>
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<td>(98%)</td>
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Why only the Rare 1%???

- Planets grow by “accretion” - the sticking together of solid particles.
  - The solid particles are things like metal, rock, and ices – primarily made of the 1%.
  - Hydrogen and helium remain gaseous and do not form solid particles.

Artists concept

Real microscopic interplanetary grains
How to Build a Planet

Initially the disk contains only tiny dust grains, but through collisions and sticking they grow to become successively larger until most of the solid material is in a few big lumps – the planets.
Planet Building is a Messy Process

- The cleanup from this accretion process still goes on today.
  - Every day tons of interplanetary material is accreted by the Earth. You see some of these events as meteors.
    - “Tons” is still an insignificant fraction of the Earth's current mass, however.
  - Every few million years a larger leftover lump strikes the Earth
A Messy Process

- Old surfaces have been battered by this process
A Messy Process

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A Messy Process

- Old surfaces have been battered by this process
A Violent Universe

- The final stages of accretion likely involve titanic collisions between worlds.
  - We're pretty sure the Moon is a byproduct of such a collision.
The Jovian/Terrestrial Distinction

- Rocky worlds lie close to the Sun. Gas Giants with icy moons lie further away.
The Jovian/Terrestrial Distinction

- Planets accrete from the solid particles in the disk.
- The local temperature of the disk determines what types of particles can survive in solid form.

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The Jovian/Terrestrial Distinction

- Planets accrete from the solid particles in the disk.
- The local temperature of the disk determines what types of particles can survive in solid form.
The Jovian/Terrestrial Distinction

- Close to the Sun, rock and metal are the primary building materials.
- Ice dominates at greater distance.
The Jovian/Terrestrial Distinction

- This picture is consistent with finding rocky worlds close to the Sun and icy ones (moons in particular) farther away.

Earth's Moon (mostly rock)

Saturn's Moon Dione (mostly ice)
Why the Gasballs?

- Gas does not participate in the accretion process, however
  - if a growing planet grows large enough it's gravity can become strong enough to collect gas (which is far more abundant than the dust) directly.
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  - if a growing planet grows large enough it's gravity can become strong enough to collect gas (which is far more abundant than the dust) directly.
  - Jupiter, Saturn, Uranus and Neptune drew in thick mantles of gas.
Why the Gasballs?

- Gas does not participate in the accretion process, however
  - if a growing planet grows large enough it's gravity can become strong enough to collect gas (which is far more abundant than the dust) directly.
  - Ice is much more abundant than rock and metal. In the outer solar system it was possible to grow the large “cores” needed to accumulate gas.
How Many Other Solar Systems?

- This process of disk formation and accretion is common to any forming star anywhere.
  - Many, if not most, stars are likely to have planets around them.
Where's the Evidence??

- Other forming stars should show evidence for disks and planetary systems.
Infrared Observations Reveal Disks

- Warm dust glows at infrared wavelengths.
- Infrared observations of forming stars reveal excess infrared light coming from these stars.
  - The distribution of infrared light is consistent with the material being spread out in a disk.
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Disks are Seen Directly

Disks around Young Stars
PRC99-05b • STScI OPO
C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA

Protoplanetary Disks
Orion Nebula
PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O’Dell (Rice University), NASA
Disks Should Fade As Planets Grow

- As planets grow the disk should begin to clear.
- Simulations/calculations say that within 10 million years most of the small dust should be gone.
  - This age corresponds well with observations of young stars showing the infrared excesses go away after 10 million years.
Faint Disks Should Linger

- Leftover comets and asteroids should continue to collide and generate faint dust signatures.

- We see it in our solar system and elsewhere!