Formation of the Sun and the Planets

Notes compiled by

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1. Patterns of Motion

a) All planets orbit the sun in the same direction, counterclockwise when viewed from far above the earth’s north pole.

b) All the planets orbit the sun in nearly the same plane.

c) Orbits of planets are nearly circular, and they increase in spacing with distance from the sun in a fairly regular trend. (An exception is the wide gap from Mars to Jupiter that is populated with asteroids.)

d) Most planets rotate in the same direction that they orbit, and with fairly small axis tilts.

e) Almost all moons orbit their planet in the same direction that the planet rotates, and in the planet’s equatorial plane.

f) The Sun rotates in the same direction that the planets orbit.
2. **Categorizing Planets**

   a) Rocky terrestrial planets in the inner solar system.
      Solid rocky surfaces with an abundance of metals in their interiors.
      Few or no moons.
      No rings.

   b) Giant gaseous planets (Jovian planets) in the outer solar system, made mostly of hydrogen, helium, and hydrogen compounds, such as water, ammonia, and methane.
      Rings.
      Extensive system of moons, made mostly of low-density ices and rocks.
<table>
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<tr>
<th>Photo</th>
<th>Planet</th>
<th>Average Distance from Sun (AU)</th>
<th>Temperature $\dagger$</th>
<th>Relative Size</th>
<th>Average Radius (km)</th>
<th>Average Density (g/cm$^3$)</th>
<th>Composition</th>
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<td>a few km?</td>
<td>&lt;1?</td>
<td>Ices, dust</td>
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</table>

$\dagger$Appendix C gives a more complete list of planetary properties. $\dagger$Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-fog temperatures are listed. $\ddagger$Includes water (H$_2$O), methane (CH$_4$), and ammonia (NH$_3$). $\ddagger$Comets passing close to the Sun warm considerably, especially their outer layers.
• Categorizing Planets

a) Rocky terrestrial planets in the inner solar system. Solid rocky surfaces with an abundance of metals in their interiors. Few or no moons. No rings.

b) Giant gaseous planets (Jovian planets) in the outer solar system, made mostly of hydrogen, helium, & hydrogen compounds, such as water, ammonia, and methane. Rings. Extensive system of moons, made mostly of low-density ices and rocks.
• **Exceptions to the Rules**

- Mercury and Pluto have larger orbital eccentricities and inclinations than the other planets.
- The rotational axes of Uranus and Pluto are substantially tilted.
  - Venus rotates backwards.
  - Earth has an unusually large moon.
  - Pluto has a moon almost as big as itself.
- A few moons of the Jovian planets orbit in the “wrong” direction.
• Debris: Asteroids and Comets and Meteoroids

a) These are the most numerous objects in the solar system.

b) Asteroids are small, rocky bodies and are located mainly in the asteroid belt between the orbits of Mars and Jupiter.

c) The largest asteroids are only a few hundred km in radius.

d) Asteroids orbit the sun in the same direction as the planets.

e) Asteroid orbits lie close to the plane of the planets’ orbits, although they are usually a bit tilted.

f) Some asteroids have quite eccentric orbits compared to the nearly circular orbits of the planets.

g) Kuiper Belt Objects: The Kuiper Belt is similar to Asteroid Belt but 20 times as wide. Extends from Orbit of Neptune (30 AU) to 100 AU. Dwarf planets: Pluto, Haumea, and Makemake.
Kuiper Belt and Oort Cloud
We will discuss the most popular theory of solar system formation at the moment, the nebular theory.

In this theory, the solar system formed out of a huge cloud of interstellar gas and dust.

This theory is motivated by a great many observations.

The most compelling of these have been quite recent.

The origin of the gas cloud from which the solar system formed may have been primordial. It may have been part of the gas cloud that originally collapsed to form the galaxy.

The gas may also have come from gas outflows from stars in stellar winds or in stellar explosions.

Most likely, both origins are involved, and the gas that formed the solar system was a mixture of “original” gas with gas processed in stars.
A good example is the Orion Nebula, a huge cloud of gas in our neighborhood of the galaxy from which a large number of stars have recently formed.

The Orion nebula is lit up by the brilliant light of massive young stars. Their radiation is energetic enough to ionize the surrounding gas and heat it up, so that the gas that did not collapse into these young stars is pushed away.

Behind the visible nebula is a dense cloud of molecular hydrogen gas, from which infrared observations show that many more stars have recently formed.

In time, these newest stars will also expel the bulk of the gas in the cloud which now obscures them from view in visible light.

Thus the process of star formation appears to be quite inefficient. As soon as some of the gas in a cloud collapses to form a few massive stars, their radiation effectively shuts off the process.
A mosaic of the central region of the Orion Nebula, from the Hubble Space Telescope

(from *Hubble Revisited*, p. 98)
The inner part of the Orion Nebula, with the trapezium stars and other young stars.

Hubble Space Telescope image.

(from *Hubble Revisited*, p. 99)
The close-up views of the region immediately surrounding the 4 brightest young stars in the Orion Nebula, the so-called trapezium stars (because they form a trapezoid on the sky), show that their radiation is not only expelling the local gas, but it is also compressing regions of that surrounding gas that were initially a bit denser.

Could these compressed regions become sites of secondary star formation?

Possibly.

It is also possible that these denser regions had already begun the process of star formation before the trapezium stars “turned on” and began to expel the gas around them.
Hubble Space Telescope close-up of the trapezium stars at the center of the Orion Nebula.
Hubble Space Telescope image of a section of the Orion Nebula near the trapezium.

The area of the infrared image on the next slide is indicated.

This marked region contains a massive young star, the Becklin-Neugebauer object, which is obscured in visible light by a dense surrounding cloud of dust.

(from Hubble Revisited, p. 101)
This region of the Orion Nebula, near the trapezium and marked on the previous slide, contains a dense cloud of dust and gas which obscures this massive young star, the so-called Becklin-Neugebauer object, from view in visible light. Here it is revealed in infrared light by the Hubble Space Telescope.

(from Hubble Revisited, p. 101)
On the next slide is a gallery of possible circumstellar disks from the Orion Nebula.

Some of these may merely be globs of gas compressed by the action of the intense, energetic ionizing radiation from the massive young stars of the nebula.

Others, particularly those in which the circumstellar disks are clearly seen in absorption against the bright nebula, may be protoplanetary systems in formation or soon to form.
Circumstellar Disks in Orion
This slice of the Orion Nebula, only 0.14 light-years wide, shows young stars enshrouded in disks of dust and gas. (Hubble S. T.)
The Hubble Space Telescope pictures on the next 2 slides show “elephant trunks” in the Eagle Nebula (M16).

These images caused a sensation when they first appeared, since they illustrate so beautifully the process of compression of gas and dust driven by the rocket effect that results when energetic, ionizing radiation from a massive, young star heats and ablates gas from a denser region of a nebula surrounding the star.

This is much the same physical process used in laser fusion to compress tiny pellets of hydrogen (or deuterium) gas to generate micro-explosions, except that in the laser fusion case, the intense radiation is brought to bear on the pellet from all sides.

Could this be a major mechanism for the formation of new stars?
The “elephant trunks” of the Eagle Nebula (M16) and the EGGs (Evaporating Gaseous Globules) at their ends provide dramatic evidence of the gradual destruction of a molecular cloud under the bombardment of the radiation from stars that developed there. It has not been shown that the EGGs contain new stars.

(Hubble Revisited, p. 104)
A close-up view of the EGGs (Evaporating Gaseous Globules) at the ends of the elephant trunks of the Eagle Nebula (M16)

Hubble Space Telescope.
The star formation process is inefficient not only at the start but also at the finish.

A massive star, upon exhausting its nuclear fuel in its core can lose the bulk of its mass in a strong stellar wind near the end of its life, forming what is called a planetary nebula, or it can explode as a supernova, expelling the bulk of its mass back into the interstellar medium as a supernova remnant.

A small collection of Hubble Space Telescope images of planetary nebulae is shown on the next slide. The mass of gas ejected from a star in this manner can be up to 75% of the total.
Hubble Space Telescope images.
The Crab Nebula, shown on the next slide, is the remnant of a recent supernova, a star that exploded in 1054.

The shock wave from such an explosion can strongly compress a cloud of interstellar gas, pushing it over the brink of gravitational collapse, so that a star is formed.

There is evidence from the Allende meteorite that such an event may indeed have initiated the formation of the solar system.

Globs of gas driven to high densities by the energetic, ionizing radiation of nearby massive young stars are accelerated strictly from one side by this process, and are therefore not so likely to be set into gravitational collapse.

Even though a supernova shock comes from one side only, it refracts around a denser region of interstellar gas, so that the gas is accelerated inward from all sides (although not equally from all sides). Gravitational collapse is thus more likely.
The Crab Nebula, the remnant of a star (a supernova) that exploded in 1054, is seen here with the Hubble space telescope.
An early computation of an interstellar gas cloud being imploded by a shock wave. (Woodward 1976)
FIGURE 9  (a) A reflected light photograph of a piece of the Allende meteorite, cut to expose its interior structure. The meteorite has retained a high abundance of volatile elements, and yet also contains many light, irregular-shaped "pebbles" made of refractory material, the calcium- and aluminum-rich inclusions, referred to by the abbreviation CAIs. These inclusions are igneous (melted and recrystallized) stones, apparently made in the solar nebula and are the oldest objects to have had their formation ages accurately determined. The field of view is approximately 2 cm square. (Courtesy of Robert Gibb, California State University, Fullerton student.) (b) A fragment of an unusually large and rounded CAI in Allende. It is viewed in transmitted light in an optical microscope with crossed polarizers to reveal the interference colors, which allow the different minerals composing the inclusions to be distinguished. The original inclusion was about 1.6 cm in diameter. (Courtesy of Glenn J. MacPherson, Smithsonian Institution.)

(from Encyclopedia of the Solar System, p.56)
Evidence of the initial composition of the proto-solar nebula comes from the carbonaceous chondrite meteorites.

Radioactive isotope dating indicates that these meteorites are truly ancient.

The chemical composition of these meteorites (classified CI) is essentially the same as that of the solar photosphere. There are exceptions, of course, for the very most volatile elements and for light elements like lithium, which are depleted in the sun by thermonuclear reactions.

The isotopic abundances in these meteorites are what we expect from neutron capture inside stars and in exploding stars. They do not seem to have been altered by any further chemical processing, and are thus believed to be representative of the original mix in the primitive solar nebula.
FIGURE 7 Elemental abundances in the solar photosphere are shown on a log–log plot versus those abundances measured in the CI carbonaceous chondrites. The abundances are normalized to \(10^{10}\) hydrogen atoms: \(\log N_H = 12.00\). The remarkable 1:1 correspondence displayed for all but the most volatile elements is strong evidence for the creation of the CI meteorites out of unfractionated solar material, as well as for the essential homogeneity of the solar nebula. (Even some of the deviations are well understood. For instance, lithium in the Sun is low relative to CI abundances because lithium has been destroyed by nuclear reactions in the Sun.)

(from Encyclopedia of the Solar System, p. 54)
Note that each step from one horizontal level indicated here to the next represents a factor of 100.
Analysis of the Uranium isotope decay products in the calcium-aluminum-rich inclusions (CAIs) in the carbonaceous chondrite of the Allende meteorite yields an average crystallization age of 4.566 ± 0.002 billion years.

This is the oldest solar system material found so far.

The chemical composition of the Allende CAIs is as predicted for objects in equilibrium with a high temperature gas of solar composition.

These CAIs are likely to have formed in the initial episode of solidification in the proto-solar nebula.
The next slide shows a plot of the decays over time of potassium-40 into argon-40.

For the CAIs of the Allende meteorite, the conversion of the Uranium isotopes over time into other elements is similar to this potassium-argon process and can be used to give very reliable age estimates.
Figure 8.17: Radioactive decay of Potassium-40 to Argon-40.
These CAIs contain the products of short-lived radionuclides that are long since extinct. They thus may have formed close to the time of nucleosynthesis, which presumably occurred before the formation of the solar nebula.

The CAIs from the Allende meteorite contain magnesium-26, the decay product of radioactive aluminum-26, which has a half-life of only 1.07 million years.

It has been suggested that the event that formed the aluminum-26, perhaps the explosion of a supernova, was the same event that caused the solar nebula to form only about one million years later.

The oldest moon rocks, taken from the moon’s crust, are 4.45 and 4.48 billion years old, only about 100 million years younger than the Allende CAIs. This indicates that the Moon’s crust crystallized only about 100 million years after the formation of the solar nebula.
A fragment of an unusually large and rounded CAI (calcium-aluminum rich inclusion) in the Allende meteorite. It is viewed in transmitted light in an optical microscope with crossed polarizers to reveal the interference colors, which allow the different minerals composing the inclusions to be distinguished. The original inclusion was about 1.6 cm in diameter.
A part of the Allende meteorite.
It is clear from the observed abundances of elements heavier than hydrogen and helium in the sun’s photosphere, namely about 2%, and of course from the existence of the heavy elements that condensed from the protosolar nebula to form planets like the earth, that the gas cloud from which the solar system formed had been enriched by gas processed in earlier generations of stars.

This enrichment could have come from mechanisms like planetary nebula ejection and supernova explosions over several generations of stars before our particular bit of gas collapsed to form the solar system.

We will refer to the particular piece of any larger interstellar gas cloud that collapsed to form the solar system under its own gravity as the solar nebular, or as the protosolar nebula.
We imagine that the protosolar nebula began as a three-dimensional cloud of roughly similar proportions in all directions.

As it collapsed under gravity, the gravitational potential energy released by the collapse took the form both of the inward motion and also as heat.

Globs of gas falling inward that collide do so inelastically. That is, they do not bounce off each other but instead tend to result in merged globs of gas going more or less in the average direction at the average velocity of the original colliders.

This process of inelastic collisions, which leads to the dissipation of kinetic energy of organized gas motion into heat, is essential in forming a flattened disk from the original cloud.

The random motions of the infalling globs of gas are dissipated, producing heat some of which is radiated away in the form of light.
Because of the physical law that says that angular momentum is conserved, motions in the cloud that on average represent rotation about an axis cannot be dissipated by collisions.

Instead, these rotational motions emerge as highly ordered, nearly circular motions that only rarely lead to collisions.

As the nebula contracts under its gravity, the rotation of the nebula must increase in order to conserve angular momentum (remember the angular momentum is \( mvr \); as \( r \) decreases, \( v \) must increase proportionally).

The rotation of the solar nebula produces a centrifugal force that can balance the gravitational attraction, halting the nebula’s collapse in radius within the rotational plane. (Once the nebula has flattened, as the disk shrinks, the centrifugal acceleration, \( v^2/r \), increases in proportion to \( (1/r)^3 \), while the gravitational acceleration, \( \sim GM/r^2 \), increases less rapidly, in proportion to \( (1/r)^2 \).)
Star Formation

Star formation must occur in dark (dusty) cold ($T < 10 \, K$) regions – Gas cloud can collapse only if self-gravity exceeds internal pressure
Fig. 8.6: The collapse of an interstellar cloud.

(a) The original cloud is large and diffuse, and its rotation is almost imperceptibly slow.
(b) The cloud heats up and spins faster as it contracts.
(c) The result is a spinning, flattened disk, with mass concentrated near the center, where the central star will form.
FIGURE 8.7 As shown in this painting, collisions between particles in the solar nebula average out their random motions and flatten the cloud into a disk. The green arrow represents the path of a particle that originally had a tilted orbit. After the collision, its orbit lies closer to the plane of the other particles. If the particles had started an eccentric orbit, collisions would have made its orbit more circular. (Particle sizes are highly exaggerated.)
The conservation of angular momentum might have prevented the protosolar disk from condensing sufficiently in the center to form the sun, were it not for a number of processes that transport angular momentum outward (while conserving it).

Inelastic collisions and turbulent viscosity (like friction) transport angular momentum outward, allowing the inner parts of the disk to continue their gravitational collapse.

Magnetic fields embedded in the gas can also transport angular momentum outward from the central to the outer portions of the collapsing disk.

Finally waves called spiral density waves can transport angular momentum outward. We will say more about these waves in rotating, self-gravitating disk systems when we discuss galaxies in the later part of this course.
Conservation of angular momentum caused most of the material that collapsed to form the solar system to first form a nebular disk. The disk, known as the primitive solar nebula, was maintained by a near-balance of centrifugal force and gravity. Within the disk, processes that transfer angular momentum, such as turbulent friction or wave propagation, allowed material in the inner parts of the disk to transfer its angular momentum to material in the outer parts, so that the former moved inward to form the Sun, while the latter moved outward, absorbing the angular momentum now carried in the planets. Energetic processes operating near the region in which material was being accreted from the nebula onto the young Sun conspired to drive a flow of gas, called a stellar wind, to accelerate outward along the rotation axis. [Adapted from F. A. Podosek and P. Cassen (1994). Theoretical, observational, and isotopic estimates of the lifetime of the solar nebula. *Meteoritics* 29, 6–25.]

(from Encyclopedia of the Solar System, p. 39)
An artist’s conception of the proto-solar nebula
These points help us to explain some of the patterns of motion in the present solar system (our first challenge to theory):

1. The flattening of the protoplanetary disk explains why all planets orbit in nearly the same plane.

2. The regular rotation of the disk explains why all planets orbit the sun in the same direction as the sun’s rotation. It also plays a role in making most planets rotate in this same direction.

3. The inelastic collisions, which dissipate random particle velocities in the protoplanetary nebula, explain why most planets have nearly circular orbits.
2. Categorizing Planets

a) Rocky terrestrial planets in the inner solar system.  
Solid rocky surfaces with an abundance of metals in their interiors.  
Few or no moons.  
No rings.

b) Giant gaseous planets (Jovian planets) in the outer solar system, made mostly of hydrogen, helium, and hydrogen compounds, such as water, ammonia, and methane.  
Rings.  
Extensive system of moons, made mostly of low-density ices and rocks.
We believe that the chemical composition of the protosolar nebula was originally uniform.

However, the chemical compositions of the inner and outer planets are completely different.
We can easily understand how gravity caused the sun to condense in the center of the protosolar nebula by accumulating gas as angular momentum was transported outward in the rotating protoplanetary disk.

However, we believe that for the planets to condense out of the rotating disk it was necessary for solid chunks of matter to act as seeds for their gravitational accumulation.

Even though the hydrogen and helium comprising 98% of the solar nebula remains gaseous even at very low temperatures, the other 2% of heavier elements could condense out as solid particles where the temperature in the nebula was low enough.

The nebula was hot near the protosun, both due to the gravitational potential energy released in the collapse and due to heating by the protosun.
Condensation

As disk cools, solids condense (snowflakes) – inner disk is richer in less-volatile elements.

- We need to understand relative abundances and volatility of elements.
The temperature in the nebula decreased with distance from the hot protosun and also because, at these greater distances from the central condensation, the material had fallen less far under gravity, so that less gravitational potential energy was released.

In the inner region of the protoplanetary disk, only solid particles made of certain materials able to exist as solids at high temperatures could be found to act as seeds for planetary accumulation.

If we were to take a section of the protoplanetary nebular material and to gradually lower its temperature from a very high value, our knowledge of material properties indicates that heavy constituent elements would condense out in the following sequence:
1. **Metals** such as iron, nickel, aluminum, etc. Some of these materials can remain solid at 1600 K. These materials made up less than 0.2% of the mass of the nebula.

2. **Rocks**, materials common on the surface of the earth, primarily silicon-based minerals. These materials melt or vaporize between 500 and 1300 K. They made up about 0.4% of the mass of the nebula.

3. **Hydrogen compounds**, molecules such as methane (CH₄), ammonia (NH₃), and water (H₂O) that solidify into ices below about 150 K. These molecules made up about 1.4% of the mass of the nebula.

4. **Light gases**, hydrogen and helium, never condensed into solids under conditions in the protosolar nebula. These gases made up the other 98% of the mass of the nebula.
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<th>$T(K)$</th>
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<td>1500</td>
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<td>Mercury</td>
</tr>
<tr>
<td>1300</td>
<td>Fe (iron), Ni (nickel)</td>
<td>Venus</td>
</tr>
<tr>
<td>1200</td>
<td>Silicates</td>
<td>Venus</td>
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<tr>
<td>1000</td>
<td>Aluminum oxides</td>
<td>Venus</td>
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<tr>
<td>680</td>
<td>FeS (iron sulfates)</td>
<td>Earth, Mars</td>
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<tr>
<td>175</td>
<td>H2O (water)</td>
<td>Jovian</td>
</tr>
<tr>
<td>150</td>
<td>NH3 (ammonia)</td>
<td>Jovian</td>
</tr>
<tr>
<td>120</td>
<td>CH4 (methane)</td>
<td>Pluto</td>
</tr>
<tr>
<td>65</td>
<td>Ar (argon), Ne (neon)</td>
<td>Pluto</td>
</tr>
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</table>
Rocks and metals condense, hydrogen compounds stay vaporized.

Hydrogen compounds, rocks, and metals condense.
The first condensates in the nebula were microscopic. They orbited in orderly, circular orbits, like the gas, collided very gently, and could stick together by electrostatic forces.

As the particles grew, gravity aided their sticking together.

The growing particles formed by accretion are called planetessimals.

As they grew, both their surface areas and their gravitational attractions grew, accelerating their further growth.

In a few million years, some planetessimals grew to hundreds of km in size.

Collisions of such large objects altered orbits, resulting in higher velocity collisions, which could fragment them.

Only the largest planetessimals could survive the collisions and grow into planets.
Weak gravity is unable to deform small objects.

Stronger gravity makes larger objects spherical.
The planetessimals in the inner part of the nebula were made up of metals and rocks, since only these could exist in the high temperatures there in solid form.

This explains the rocky nature of the inner planets.

Because the nebular material contained only very small amounts of metals and rocky material, the inner planets are relatively small.

Evidence for accretion comes from meteorites, like the one on the next slide, or like the Allende meteorite mentioned earlier. These are clearly jumbles of smaller objects.

Further evidence comes from close-up views of the asteroids and of comets.

Finally, of course, there is the evidence of craters on the moon and other solar system bodies, including the earth.
FIGURE 8.11 Shiny flakes of metal are clearly visible in this meteorite, mixed in among the rocky material. Such metallic flakes are just what we would expect to find if condensation really occurred in the solar nebula as described by the nebular theory.
We believe that the Jovian planets began their accumulation from solid particles sticking together.

At the orbit of Jupiter and beyond, these solid particles contained ices in abundance.

The greater abundance of solid particles in this cooler part of the nebula allowed planetessimals to grow to large sizes, even larger than the earth.

The large sizes of these planetessimals resulted in gravity strong enough to accumulate envelopes of gas, hydrogen and helium.

This process of nebular capture by the Jovian planets explains their great masses, large sizes, low average densities, and the abundance of hydrogen and helium in their composition.

Nebular capture resulted in small, spinning disks of material around the Jovian planets, from which their moons were formed.
Fig. 8.12: Large icy planetessimals in the cold outer regions of the solar nebula captured significant amounts of hydrogen and helium gas. This process of nebular capture created Jovian nebulae, resembling the solar nebula in miniature, in which the Jovian planets and satellites formed. This painting shows a Jovian nebula (enlarged at left) located within the solar nebula.
Nebular capture for the Jovian planets explains why their systems of moons generally orbit in nearly circular orbits lying in the same planes as the equators of the parent planets and in the same direction as the parent planet’s rotation.

The icy and rocky mixtures that compose these moons are also explained by the condensates present in this outer portion of the solar nebula.

We believe that the gas remaining after the accretion of the planets was blown out of the solar system by the solar wind.

The solar wind today is a stream of low density plasma from the sun, but we believe that it was a much stronger stream of plasma when the sun was young.

The initially strong solar wind, which was whipped around by the early sun’s strong magnetic field according to the early sun’s rapid rotation, caused the sun’s rotation rate to decrease to its present low value.
Planet Formation

As central regions contract to form the Sun, the “snowflakes” begin to stick together and grow by accretion.
Planetesimals form by accretion (snowballs).
– gentle collisions, since in similar orbits
– planetesimals have sizes up to about 1 km
Planetesimals coalesce to form *protoplanets*
FIGURE 8.13  The magnetic braking process: Charged particles in the solar nebula tend to move with the Sun's magnetic field (represented by the purple loops). As the magnetic field rotates with the Sun, these charged particles are dragged through the disk. Friction between the charged particles and the rest of the disk slows the Sun's rotation. The Sun's relatively slow rotation probably resulted from this process. (Particle sizes are highly exaggerated.)
When the solar wind cleared the gas from the solar nebula, not only the newly formed planets but also a large number of planetessimals were left in nearly circular orbits, arranged in composition according to their distance from the sun.

We believe that, over time, gravitational encounters between planetessimals and between planetessimals and planets caused the orbits of the planetessimals to become more random.

Many of the planetessimals were certainly ejected from the solar system by encounters with the much more massive planets.

Planetessimals remaining today are the asteroids and the comets.

The asteroids of the asteroid belt were unable to form a planet in the early phase because of the gravitational perturbations of Jupiter.

The Kuiper belt, in the plane of the solar nebula disk, beyond the orbit of Neptune, is believed to contain many leftover icy planetessimals, with Pluto perhaps the largest of them.
The inner planets formed from planetessimals of metals and rock.

The earth’s oceans, the polar caps of the earth and Mars, and the atmospheres of Venus, Earth, and Mars, are believed to have come from planetessimals, a combination of asteroids and comets, that formed beyond the orbit of Mars.

Gravitational perturbations from Jupiter probably played a major role in bringing these planetessimals into the inner solar system.

The few moons that orbit in the wrong direction are likely to be planetessimals that were captured as satellites.

The captures may have occurred while the Jovian planets still had surrounding gaseous disks to provide friction to reduce the orbital energy of an incoming planetesimal.
Miranda, the fifth largest satellite of Uranus, shows evidence of violent collisions late in its formation history.

The Final Stage: Giant Impacts

- Coalescence of large bodies can have dramatic effects – violent geological history of some planetary satellites
Jupiter’s satellite Callisto also shows the result of a large direct impact.
The moon may have formed as the result of the impact with the earth of a Mars-sized object soon after the earth’s formation. The ejected material would have come mainly from the outer rocky layers and would have accreted, in orbit around the earth, to form the Moon (which is metal poor). It’s possible.
Fig. 8.14
An artist’s concept of the young Earth and Moon glowing with the heat of accretion, and with an impact in progress on the Earth.
We can build our confidence in the nebular collapse theory by seeing if we can observe any such nebulae that might correspond to solar systems now in the process of formation.
**December 23, 2009**—Planets take shape in the dusty disk around a young star in an artist's conception. The scene is an example of what things might be like around MWC 419, a blue star about 2,100 light-years from Earth that astronomers recently probed using the W. M. Keck Observatory in Hawaii.

Using a device that reads near-infrared light, the team was able to measure the dust disk's temperature to within about 50 million miles of the star—about half the distance from Earth to the sun.

Temperature differences in the disk might be linked to chemical composition and other properties, which may affect how planets form around the star.
HST sees a dust disk around a young star that shows a gap in the disk that could be being swept out by a planet in the process of formation.
In the fall of 2014, a new, extremely large radio telescope array called ALMA (the Atacama Large Millimeter/submillimeter Array), operated by an international collaboration including the National Radio Astronomy Observatory (NRAO) in Charlottesville, Virginia, began its new mode of extreme high resolution observing. Its press release, via the BBC News, follows:

• **The clearest ever image of planets forming around an infant star has been taken by the Alma radio telescope.**
• In a vast disc of dust and gas, dark rings are clearly visible: gaps in the cloud, swept clear by brand new planets in orbit.
• The sun-like star at the centre, HL Tau, is less than a million years old and is 450 light years from Earth in the constellation Taurus.
• The image was made possible by Alma's new high-resolution capabilities.
• Because the process of planet formation takes place in the midst of such a huge dust cloud, it can't be observed using visible light.
• Alma, the Atacama Large Millimeter/submillimeter Array, has snapped the impressive new image using much longer wavelengths, which it detects by comparing the signal from multiple antennas up to 15km apart.

• To test out its latest high-resolution capability, only in operation since September, 2014, Alma scientists pointed the antennas at HL Tau. They found themselves looking at a "protoplanetary disc" in more detail than ever before.

• "I think it's phenomenal," said Dr Aprajita Verma, an astrophysicist at the University of Oxford.

• "This shows how exciting Alma is going to be - it's going to be an incredible instrument."

• Prof Tim de Zeeuw is director general of the European Southern Observatory, one of several organisations involved in Alma. He said: "Most of what we know about planet formation today is based on theory. Images with this level of detail have up to now been relegated to computer simulations or artist's impressions."
Dr Verma agreed that the image was a significant new piece of evidence - particularly because the star HL Tau is very young.

"I think the big result is that you might have expected just a smooth disc," she told the BBC.

"But you're really seeing multiple rings - and where it's darker, that's where you've cleared the material already in the disc."

The whole process is happening faster than we would have predicted from existing data, Dr Verma explained.

"It means that things are coagulating. It's really a planetary system, that you're seeing at a very early time.

"These rings will form planets, asteroids, comets... And eventually as the star evolves, this will cool and settle and there will be more clearing and more individual objects, just like we see in our solar system."
Radio telescopes of the ALMA array high in Chile’s Atacama desert
A protoplanetary disc has formed around the young star HL Tau; ALMA image, Nov., 2014. This star, perhaps only about 1 million years old, is in the constellation Taurus 450 light years from us.
A protoplanetary disc has formed around the young star HL Tau; ALMA image, Nov., 2014.
This star is much smaller than our sun, but its disk of dust extends to roughly 3 times the radius of the orbit of Neptune.
Here we see the protostar in its larger context, an image of the region taken with the Hubble Space Telescope.
Matching “artist’s impression,” informed by computer simulations.
Evidence for protoplanetary disks around other stars is scarce.

However, the disk around the star Beta Pictoris is one good case.

We see this disk, discovered in 1984, nearly edge on. Hubble Space Telescope observations have shown that this disk is extremely thin.

The thinness of the disk indicates that dust has had time to collect, and perhaps also protoplanets.

The diameter of this disk is 300 billion km, and its inner parts are warped. Perhaps the warp in the disk, which is shown on the next slide, was created by the passage of a star nearby, or, just possibly, it is caused by a planet, from 1/20 to 20 Jupiter masses, orbiting at a slight inclination to the plane of the disk. Another possibility is that it is caused by an unseen brown dwarf companion in a much larger orbit.
Hubble Space Telescope observations of the faint disk, with its considerable warp, next to the bright star Beta Pictoris. This disk of dust, discovered in 1984, is extremely thin. An unseen planet (like Jupiter) or distant brown dwarf companion could have caused the warp.
Hubble Space Telescope observations of the faint disk, with its considerable warp, next to the bright star Beta Pictoris. This disk of dust, discovered in 1984, is extremely thin. An unseen planet (like Jupiter) or distant brown dwarf companion could have caused the warp.
A more recent HST image clearly shows a secondary dust disk rather than a warp. This is probably associated with a large planet.
FIGURE 8.8 Evidence for disks around other stars.

a. Dust disks similar to protoplanetary disks around the stars Beta Pictoris (left) and HR4796 (right). The central star is blocked out in the image of Beta Pictoris.

b. Protoplanetary disks around stars in the Orion Nebula.
The binary star system TMR-1A/B in the Taurus molecular ring, believed to be only a few hundred thousand years old. The 100 billion mile long gaseous tail appears connected to what may be an ejected planet 2 to 3 times more massive than Jupiter, still contracting. If so, it formed very early.
The brown dwarf Gliese 229B.
This object was detected with a 1.5 m telescope on the ground (left) but the Hubble Space Telescope provided a much sharper image (right). The small companion, Gliese 229B, has a mass of only 20 to 50 times that of Jupiter. Gliese 229B is the companion of an ordinary star, but it has a luminosity of only 2 to 4 millionths that of the sun. Its spectrum resembles that of Jupiter. It has a lot of methane and a surface temperature of 600°C to 700°C.
A periodic Doppler shift in the spectrum of 51 Pegasi shows the presence of a large planet with an orbital period of about 5 days. Dots are actual data points; bars through dots represent measurement uncertainty.
• The Keck telescope on Mauna Kea, Hawaii, was recently used to
discover a Neptune-sized planet orbiting very close to a star
about 40% of the size of our sun.

• Hubble observations were combined with those of several other
telescopes to unravel a nearby system with 4 orbiting planets.

• We cannot yet detect planets the size of Earth orbiting solar-type
stars at the radius of the Earth’s orbit, but new detectors are
planned that may be able to do this.
Scientists Discover First of a New Class of Extrasolar Planets

08.31.04

Results from NASA-funded research have put humankind just a little closer to answering the age old question, "Are we alone in the universe?"

Astronomers have announced the first discovery of a new class of planets beyond our solar system. The Neptune-sized planets -- about 10 to 20 times the size of Earth -- are far smaller than any of the previously detected extrasolar "gas giants." It's even possible that the new class of planets is rocky, like Earth and Mars, and scientists are enthusiastic about the discoveries that may come next.

Image above: This artist's concept shows the newly discovered Neptune-sized extrasolar planet circling the star Gliese 436. In this depiction, the planet appears gaseous like Jupiter, with a cloudy atmosphere. In reality, astronomers do not know if this planet is gaseous, or rocky, like Earth and Mars. + Click for larger image. Image courtesy: NASA.
• The new planets are about 20 times the mass of the Earth.
• This means they are probably about 3 times the Earth’s diameter.
• They were detected by the wobbling that they induce on the stars they orbit.
• One of these new Neptune-sized objects is in a system that has 3 other planets.
• The stars with these planets are “nearby,” at distances of 30 to 40 light years.
• Many other, larger planets have been discovered since the Hubble telescope was launched and the large ground-based telescopes, like the Keck telescope, were put in place.
• Before this, one astronomer used over 30 years of observations of a single star to see its wobble clearly enough, on the average, to claim discovery of a planet, but other astronomers were not convinced. The new observations have convinced everyone.
Astronomers announced at the end of August, 2004, the first discovery of a new class of planets beyond our solar system. The Neptune-sized planets -- about 10 to 20 times the size of Earth -- are far smaller than any of the previously detected extrasolar “gas giants.” It’s even possible that the new class of planets is rocky, like Earth and Mars.

Two new planets were discovered by Butler and Marcy of the Carnegie Institute of Washington and University of California, Berkeley, respectively; and Barbara McArthur of the University of Texas, Austin.

Future NASA planet-hunting missions, including Kepler, the Space Interferometry Mission and the Terrestrial Planet Finder, will seek such Earth-like planets. Nearly 140 extrasolar planets have been discovered.
The first planet, discovered by Marcy and Butler, circles a small star called Gliese 436 about every two-and-one-half days at just a small fraction of the distance between Earth and the Sun, or 4.1 million kilometers (2.6 million miles). This planet is only the second known to orbit an M dwarf, a type of low-mass star four-tenths the size of our own sun. Gliese 436 is located in our galactic backyard, 30 light-years away in the constellation Leo.

The second planet, found by McArthur, speeds around 55 Cancri in just under three days, also at a fraction of the distance between Earth and the sun, at approximately 5.6 million kilometers (3.5 million miles). Three larger planets also revolve around the star every 15, 44 and 4,520 days, respectively. Marcy and Butler discovered the outermost of these in 2002. It is still the only known Jupiter-like gas giant to reside as far away from its star as our own Jupiter. 55 Cancri is about 5 billion years old, a bit lighter than the sun, and is located 41 light-years away in the constellation Cancer.
Both discoveries were made using the “radial velocity” technique, in which a planet's gravitational tug is detected by the wobble it produces in the parent star. Butler, Marcy and collaborators, including Dr. Deborah Fischer of San Francisco State University and Dr. Steven Vogt of the University of California, Santa Cruz, discovered their “Neptune” after careful observation of 950 nearby stars with the W.M. Keck Observatory in Mauna Kea, Hawaii. They were able to spot such a relatively small planet, because the star it tugs on is small and more susceptible to wobbling.

McArthur and collaborators Drs. Michael Endl, William Cochran and Fritz Benedict of the University of Texas discovered their “Neptune” after obtaining over 100 observations of 55 Cancri from the Hobby-Eberly Telescope at McDonald Observatory in West Texas. Combining this data with past data from Marcy, Fischer and Butler from the Lick Observatory in California, and archival data from NASA’s Hubble Space Telescope, the team was able to model the orbit of 55 Cancri’s outer planet. This, in turn, allowed them to clearly see the orbits of the other three inner planets, including the new Neptune-sized one.
The discovery of a planet with about three times the Earth’s mass orbiting the nearby red dwarf star Gliese 581 was recently announced. Such a planet is very hard to detect. The planet’s distance from the star puts it in the “Goldilocks Zone,” the region where liquid water could exist on its surface.

The announcement blurb follows:
First, a few things: 1) Gliese 581 is a dinky, cool red dwarf about 20 light years away. That’s pretty close as stars go; only a handful are closer. Bear in mind it’s still 200 trillion kilometers (120 trillion miles) away, and that’s still a bit of a drive.
2) The planet is one of six now known to orbit the star [that link goes to a PDF of the journal paper]. Apparently, all the planets have neat, circular orbits, so the system seems to be stable. This new planet takes 37 days to orbit the star once, and orbits at a distance about 1/6 the distance of the Earth from the Sun. As far as we know, it’s the fourth planet from its star.
3) The planets have all been found by the Doppler method.
HR 8799 Planetary System
(Sept. 2008)