## ASTRONOMY

Chapter 7 OTHER WORLDS: AN INTRODUCTION TO THE SOLAR SYSTEM


## CLEAR PATTERNS IN THE SOLAR SYSTEM

## 1. Patterns of motion

- All planetary orbits are nearly circular and lie nearly in the same plane.
- All planets orbit the Sun in the same direction: counterclockwise as viewed from high above Earth's North Pole.
- Most planets rotate in the same direction in which they orbit (counterclockwise as viewed from above the North Pole), with fairly small axis tilts.
- The Sun also rotates in this same direction.
- Most of the solar system's large moons exhibit similar properties in their orbits around their planets, such as orbiting in their planet's equatorial plane in the same direction that the planet rotates.


## FIGURE 7.3



Orbits of the Planets. All eight major planets orbit the Sun in roughly the same plane. The five currently known dwarf planets are also shown: Eris, Haumea, Pluto, Ceres, and Makemake. Note that Pluto's orbit is not in the plane of the planets.

## CLEAR PATTERNS IN THE SOLAR SYSTEM

## 2. Two types of planets

## Table 4.2 Comparison of Terrestrial and Jovian Planets

## Terrestrial Planets

Smaller size and mass
Higher density
Made mostly of rock and metal
Solid surface
Few (if any) moons and no rings
Closer to the Sun (and closer together), with warmer surfaces

## Jovian Planets

Larger size and mass
Lower density
Made mostly of hydrogen, helium, and hydrogen compounds No solid surface
Rings and many moons
Farther from the Sun (and farther apart), with cool temperatures at cloud tops


From Table 4.1. Page 58.

## FIGURE 7.17



Solar Nebula. This artist's conception of the solar nebula shows the flattened cloud of gas and dust from which our planetary system formed. Icy and rocky planetesimals (precursors of the planets) can be seen in the foreground. The bright center is where the Sun is forming. (credit: William K. Hartmann, Planetary Science Institute)

## FIGURE 7.18



Atlas of Planetary Nurseries. These Hubble Space Telescope photos show sections of the Orion Nebula, a relatively close-by region where stars are currently forming. Each image shows an embedded circumstellar disk orbiting a very young star. Seen from different angles, some are energized to glow by the light of a nearby star while others are dark and seen in silhouette against the bright glowing gas of the Orion Nebula. Each is a contemporary analog of our own solar nebula-a location where planets are probably being formed today. (credit: modification of work by NASA/ESA, L. Ricci (ESO))

## FIGURE 14.14



Protoplanetary Disk in the Orion Nebula. The Hubble Space Telescope imaged this protoplanetary disk in the Orion Nebula, a region of active star formation, using two different filters. The disk, about 17 times the size of our solar system, is in an edge-on orientation to us, and the newly formed star is shining at the center of the flattened dust cloud. The dark areas indicate absorption, not an absence of material. In the left image we see the light of the nebula and the dark cloud; in the right image, a special filter was used to block the light of the background nebula. You can see gas above and below the disk set to glow by the light of the newborn star hidden by the disk. (credit: modification of work by Mark McCaughrean (Max-Planck-Institute for Astronomy), C. Robert O'Dell (Rice University), and NASA)

## FIGURE 14.15


(a)

(b)

## Protoplanetary Disk around HL Tau.

(a) This image of a protoplanetary disk around HL Tau was taken with the Atacama Large Millimeter/submillimeter Array (ALMA), which allows astronomers to construct radio images that rival those taken with visible light.
(b) Newly formed planets that orbit the central star clear out dust lanes in their paths, just as our theoretical models predict. This computer simulation shows the empty lane and spiral density waves that result as a giant planet is forming within the disk. The planet is not shown to scale. (credit a: modification of work by ALMA (ESO/NAOJ/NRAO); credit b: modification of work by NASA/ESA and A. Feild (STScl))

## GRAVITATIONAL COLLAPSE OF A LARGE CLOUD



The planets orbit the Sun in nearly the same plane because they formed in a flat disk.

The direction in which the disk was spinning became the direction of the Sun's rotation and the orbits of the planets.

## CONDENSATION



Figure 4.7 | Temperature differences in the solar nebula led to different kinds of condensed materials at different distances from the Sun.

## FIGURE 14.12

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Chemical Condensation Sequence in the Solar Nebula. The scale along the bottom shows temperature; above are the materials that would condense out at each temperature under the conditions expected to prevail in the nebula.

## THE INNER PLANETS

The four inner planets-Mercury, Venus, Earth, and Mars-are all quite small and close together compared to the outer planets.

These four planets also share similar compositions of metal and rock, which is why we often refer to them as the terrestrial planets.
(Terrestrial means "Earth-like.")

They also have very significant differences

## THE TERRESTRIAL PLANETS



Figure 4.1. Page 59. The Cosmic Perspective Fundamentals. Publisher: Addison-Wesley. © 2010

## CONDENSATION \& ACCRETION: INNER PLANETS

In the inner solar system, where only metal and rock could condense into solid particles, the planetesimals ended up being made of metal and rock.

These planetesimals grew rapidly at first, with some probably reaching hundreds of kilometers in size in only a few million years
Further growth became more difficult once the planetesimals reached these relatively large sizes.
Gravitational encounters between planetesimals tended to alter their orbits, particularly those of the smaller planetesimals.
With different orbits crossing each other, collisions between planetesimals occurred at higher speeds and hence became more destructive.
Such collisions produced fragmentation more often than accretion.
Only the largest planetesimals avoided being shattered and grew into full-fledged planets.

## FIGURE 14.18

Accretion, heating, differentiation

Formation of solid crust, heavy cratering

Widespread mare-like volcanism

Reduced volcanism, possible plate tectonics

Mantle solidification, end of tectonic activity

Cool interior, no activity


Stages in the Geological History of a Terrestrial Planet. In this image, time increases downward along the left side, where the stages are described. Each planet is shown roughly in its present stage. The smaller the planet, the more quickly it passes through these stages.

## THE OUTER PLANETS

Jupiter, Saturn, Uranus, and Neptune are much larger and much farther apart than the terrestrial planets.

They are also very different in composition from the terrestrial planets, because they contain vast amounts of materials that would be gaseous on Earth, including hydrogen, helium, and hydrogen compounds such as water ( H 2 O ), methane $(\mathrm{CH} 4)$, and ammonia ( NH 3 ).

## THE JOVIAN PLANETS

The lower temperatures beyond the frost line meant that ices condensed along with metal and rock.
Because ices were more abundant than rock and metal (see Table 4.3), the icy planetesimals in the outer solar system grew to larger sizes than the rocky planetesimals of the inner solar system.

According to the leading model of jovian planet formation, some of the icy planetesimals grew to masses many times that of Earth.

With these large masses, their gravity became strong enough to capture and hold some of the hydrogen and helium gas that made up the vast majority of the surrounding solar nebula. As the growing planets accumulated gas, their gravity grew stronger still, allowing them to capture even more gas.

## FIGURE 7.5



The Four Giant Planets. This montage shows the four giant planets: Jupiter, Saturn, Uranus, and Neptune. Below them, Earth is shown to scale. (credit: modification of work by NASA, Solar System Exploration)

## DISKS OF GAS FORMED AROUND THE JOVIAN PLANETS

Each Jovian planet became surrounded by its own disk of gas, spinning in the same direction as the planet rotated.
Moons that accreted from icy planetesimals within these disks therefore ended up with nearly circular orbits going in the same direction as their planet's rotation and lying close to their planet's equatorial plane.
This also explains the rings.

## FIGURE 7.14



Jupiter with Huge Dust Clouds. The Hubble Space Telescope took this sequence of images of Jupiter in summer 1994, when fragments of Comet Shoemaker-Levy 9 collided with the giant planet. Here we see the site hit by fragment G, from five minutes to five days after impact. Several of the dust clouds generated by the collisions became larger than Earth. (credit: modification of work by H. Hammel, NASA)

## MOONS AND RINGS

The Terrestrial planets have only a few moons.

The Jovian planets each have a large number of moons.

- Many of these moons are amazing worlds in their own right.
- Jupiter's moon lo is the most volcanically active world in our solar system;
- Jupiter's moon Europa is thought to have a deep subsurface ocean of liquid water;
- Saturn's moon Titan is the only moon in the solar system with a thick atmosphere, and its surface contains cold lakes of liquid ethane or methane.

In addition to moons, all four Jovian planets are orbited by vast numbers of small particles that make up their rings.

## HEAVY BOMBARDMENT



Figure 4.10 | Around 4 billion years ago, Earth, its Moon, and the other planets were heavily bombarded by leftover planetesimals. This painting shows the young Earth and Moon, with an impact in progress on Earth.

## ORIGIN OF THE MOON

A Mars-sized planetesimal crashes into the young Earth, shattering both the planetesimal and our planet.

Hours later, our planet is completely molten and rotating very rapidly. Oebris. splashed out from Earth's outer layers is now in Earth orbit. Some debris rains back down on Earth, while some will gradually acorete to become the Moon.


8

## FIGURE 7.15



Our Cratered Moon. This composite image of the Moon's surface was made from many smaller images taken between November 2009 and February 2011 by the Lunar Reconnaissance Orbiter (LRO) and shows craters of many different sizes. (credit: modification of work by NASA/GSFC/Arizona State University)


Saturn and lts Rings. This 2007 Cassini image shows Saturn and its complex system of rings, taken from a distance of about 1.2 million kilometers. This natural-color image is a composite of 36 images taken over the course of 2.5 hours. (credit: modification of work by NASA/JPL/Space Science Institute)

## FIGURE 7.12



Ganymede. This view of Jupiter's moon Ganymede was taken in June 1996 by the Galileo spacecraft. The brownish gray color of the surface indicates a dusty mixture of rocky material and ice. The bright spots are places where recent impacts have uncovered fresh ice from underneath. (credit: modification of work by NASA/JPL)

## THE AGE OF THE SOLAR SYSTEM

To go all the way back to the origin of the solar system, we must find rocks that have not melted or vaporized since they first condensed in the solar nebula.

Meteorites that have fallen to Earth are our source of such rocks. Many meteorites appear to have remained unchanged since they condensed and accreted in the early solar system.

Analysis of radioactive isotopes in meteorites shows that the oldest ones formed about 4.55 billion years ago: according to the nebular theory this marks the beginning of accretion in the solar nebula.

According to the nebular theory the planets accreted within a few tens of millions of years, and so the Earth and the other planets must have finished forming about 4.5 billion years ago.

## RADIOACTIVITY

Most of the atoms and isotopes we encounter in daily life are stable, meaning that their nuclei stay the same at all times.

For example, most of the carbon in our bodies is carbon-12, which is stable.

But some isotopes are unstable: their nuclei are prone to spontaneous change, or decay.

These unstable nuclei are said to be radioactive.

## FIGURE 7.16



Radioactive Decay. This graph shows (in pink) the amount of a radioactive sample that remains after several half-lives have passed. After one half-life, half the sample is left; after two half-lives, one half of the remainder (or one quarter) is left; and after three half-lives, one half of that (or one eighth) is left. Note that, in reality, the decay of radioactive elements in a rock sample would not cause any visible change in the appearance of the rock; the splashes of color are shown here for conceptual purposes only.

## DATING ROCKS WITH POTASSIUM-40 DECAY

The radioactive isotope potassium-40 decays into argon-40.

This process has a half-life of 1.25 billion years.

- Half the original potassium-40 would have decayed into argon- 40 by the time the rock was 1.25 billion years old.
- Half of this remaining potassium-40 would then have decayed by the end of the next 1.25 billion years...


## METEOR CRATER, AZ



## TUNGUSKA 1908 JUNE 30



Credit: Leonid Kulik Expedition, Wikipedia from http://apod.nasa.gov/apod/ap071114.html

## EXTRASOLAR PLANETS

What do observations of extrasolar planets tell us about the nebular theory?

Hot Jupiters

NASA's Kepler mission

## HOT JUPITERS



Image courtesy of Geoffrey Marcy, San Francisco State University

## KEPLER MISSION SEARCH METHOD



## FIGURE 14.16



Transiting Planets by Size. This bar graph shows the planets found so far using the transit method (the vast majority found by the Kepler mission). The orange parts of each bar indicate the planets announced by the Kepler team in May 2016. Note that the largest number of planets found so far are in two categories that we don't have in our own solar system-planets whose size is between Earth's and Neptune's. (credit: modification of work by NASA)

## FIGURE 14.17



Masses of Exoplanets Discovered by Year. Horizontal lines are drawn to reference the masses of Jupiter, Saturn, Neptune, and Earth. The gray dots indicate planets discovered by measuring the radial velocity of the star, and the red dots are for planets that transit their stars. In the early years, the only planets that could be detected were similar in mass to Jupiter. Improvements in technology and observing strategies enabled the detection of lower mass planets as time went on, and now even smaller worlds are being found. (Note that this tally ends in 2014.)

## Current Potential Habitable Exoplanets



