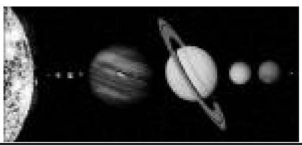
Chapter 6: The Solar System

An Introduction to Comparative Planetology

- What's in the solar system?
- Where's "the what" in the solar system?
- What makes up "the what" in the solar system?
- How do we know the answers to these questions?



Discovering our Solar System

- Discovered more in last 30 years than in all the years past.
  - new, powerful telescopes
  - spacecraft
    - flown past or around every planet except Pluto
    - investigated dozens of moons, 4 ring systems, 4 asteroids, and two comets
  - probes
    - penetrated atmospheres of Venus, Mars and Jupiter
    - landed on surface of Venus, Mars, Moon, and asteroid Eros
  - humans
    - stepped on the Moon and returned soil samples

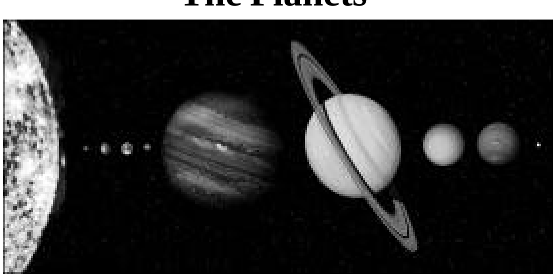
Exploring the Solar System

Solar System Object	Flyby	Orbit	Probe	Lander	Sample Return	Human
Mercury	*					
Venus	*	*	*	*		
Moon	*	*	*	*	*	*
Mars	*	*	*	*		
Jupiter	*	*	*			
Saturn	*	*	*			
Uranus	*					
Neptune	*					
Pluto						
Asteroid	*	*		*		
Comet	*				*	

Space Exploration of the Planets

- Mercury: *Mariner 10*
- Venus: *Mariner* missions; *Venera* missions; *Pioneer Venus; Magellan*
- Mars: *Mariner 4,6,7,9; Viking 1,2; Mars Observer; Mars Global Surveyor; Mars Pathfinder, Mars Odyssey*
- Jupiter: *Pioneer* and *Voyager* missions; *Galileo*
- Saturn: *Voyager 1, Voyager 2; Cassini*
- Uranus: *Voyager 2*
- Neptune: *Voyager 2*

The Planets



- Mercury, Venus, Earth, Mars, Jupiter, Saturn known to ancients
- Uranus, Neptune, Pluto discovered since invention of telescope

What's in the Solar System?

- Sun
- 9 planets
- 91 moons orbiting planets
  (at last count 6 months ago)
- asteroids
  - 6 (>300 km diameter)
  - >7000 (<300 km diameter)
- comets (a few km diameter)
- meteoroids (<100 meters diameter)
- dust

Distribution of Mass in the Solar System

Object	% of Mass
Sun	99.8
Jupiter	0.10
Comets	0.05
All other planets	0.04
Satellites and rings	0.00005
Asteroids	0.000002
Meteoroids and dust	0.0000001

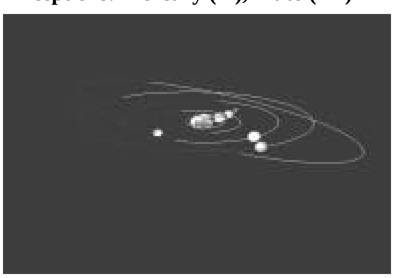
General Motions

- All nine planets revolve in the same direction around the equator of the Sun.
- They orbit in approximately the same plane.
- Each planet rotates about an axis running through it and, in most cases, the direction of rotation is the same as that of revolution about the Sun.
  - exceptions
    - Venus rotates very slowly backwards
    - Uranus and Pluto each spin about an axis tipped nearly on its side

Solar System-Side View

Planets orbit Sun in same sense and nearly in same plane (ecliptic)

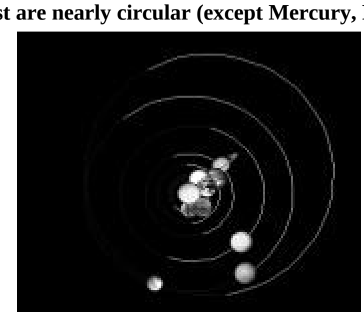
Exceptions: Mercury (7^0), Pluto (17^0)



Solar System-Top View

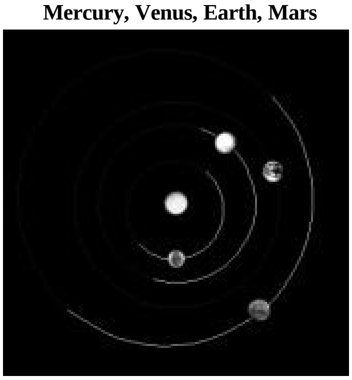
Planets orbit the Sun in elliptical orbits.

Most are nearly circular (except Mercury, Pluto)

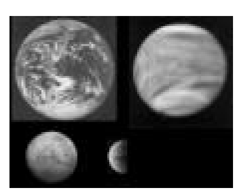


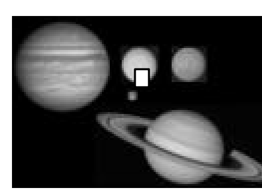
Inner Planets

Mercury, Venus, Earth, Mars



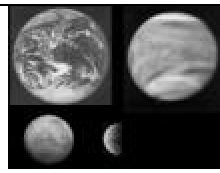
Classifying the Planets





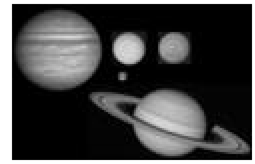
- Two distinct groups of planets when classifying by structure and composition.
  - Terrestrial planets
    - Mercury, Venus, Earth, Mars
  - Jovian planets
    - Jupiter, Saturn, Uranus, Neptune

Mercury, Venus, Earth, Mars:
The Terrestrial Planets



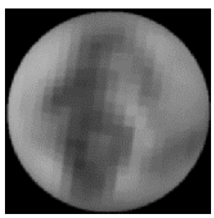
- Four planets closest to Sun are called inner or terrestrial planets.
- Earth's satellite, the Moon is also discussed as part of this group.
- All are relatively small objects composed of primarily rock and metal.
- All have solid surfaces the record their geological history in craters, mountains, and volcanoes.

Jupiter, Saturn, Uranus, Neptune:
The Jovian Planets



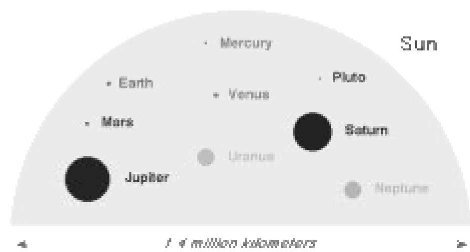
- Next four planets are called outer or giant or jovian planets.
  - Over 1400 Earths could fit inside Jupiter.
- Composed primarily of lighter ices, liquids, gases.
- Do not have solid surfaces;
  more like vast, ball-shaped oceans with
  much smaller, dense cores at their centers.

Pluto:
The Outermost Planet

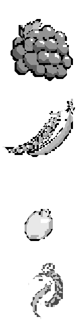


- Last planet to be discovered (1930).
- Mass measured when its satellite Charon was discovered (1978).
- Neither terrestrial nor jovian.
- Most similar to satellites of outer planets.
  - Possibly more representative of objects in Kupier Belt.

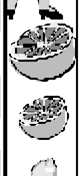
Planet Properties: Relative Size of Planets



Scale Model of the Solar System
Scale factor = 10^9 = 1 billion

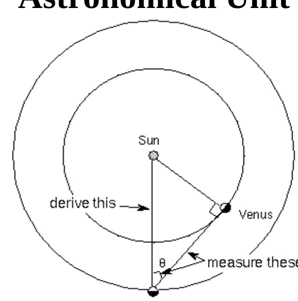


	SIZE (CM)	OBJECT	DISTANCE (CITY BLOCK)
Earth	1.3	Grape	0
Moon	0.35	Pea	40 cm
Sun	150	Adult	1 (=150 meters)
Jupiter	15	Grapefruit large	5
Saturn	12	Grapefruit small	10
Uranus	5	Lemon	20
Neptune	5	Lemon	~30
Pluto	0.26	Pea, small	~30



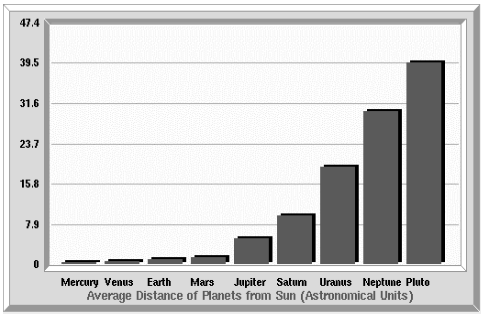
video

Astronomical Unit



Measuring the angle θ between Venus and the Sun and the distance between Earth and Venus enables us to find the distance between the Earth and the Sun using trigonometry.

Planet Properties
Average Distance from Sun



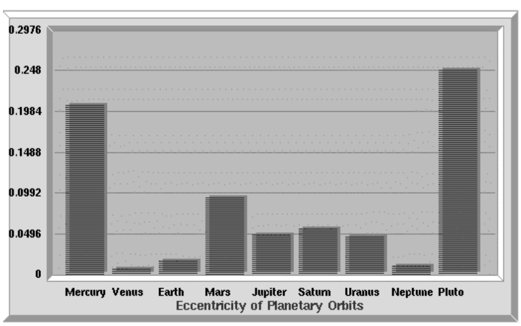
Titius-Bode "Law"

Predicted Planet Distance From Sun

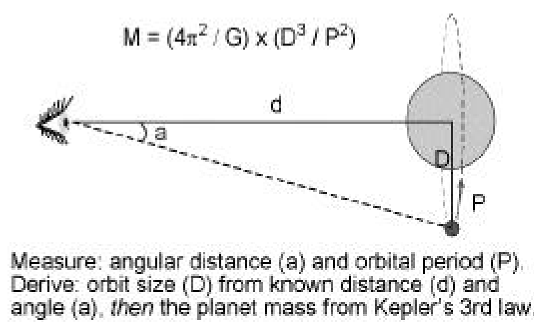
$a_n = 0.4 + 0.3 \times 2^{n-2}$ for n = 2,3,4,...

			Observed location	
• Planet 1:		0.4 AU	• 0.39 AU	Mercury
• Planet 2:	$[0.4 + (0.3 \times 2^0)]$ AU =	0.7 AU	• 0.72 AU	Venus
• Planet 3:	$[0.4 + (0.3 \times 2^1)]$ AU =	1.0 AU	• 1.0 AU	Earth
• Planet 4:	$[0.4 + (0.3 \times 2^2)]$ AU =	1.6 AU	• 1.5 AU	Mars
• Planet 5:	$[0.4 + (0.3 \times 2^3)]$ AU =	2.8 AU	• 2.8 AU	Ceres
• Planet 6:	$[0.4 + (0.3 \times 2^4)]$ AU =	5.2 AU	• 5.2 AU	Jupiter
• Planet 7:	$[0.4 + (0.3 \times 2^5)]$ AU =	10.0 AU	• 9.5 AU	Saturn
• Planet 8:	$[0.4 + (0.3 \times 2^6)]$ AU =	19.6 AU	• 19.2 AU	Uranus
• Planet 9:	$[0.4 + (0.3 \times 2^7)]$ AU =	38.8 AU	• 30.1 AU	Neptune
			• 39.5 AU	Pluto

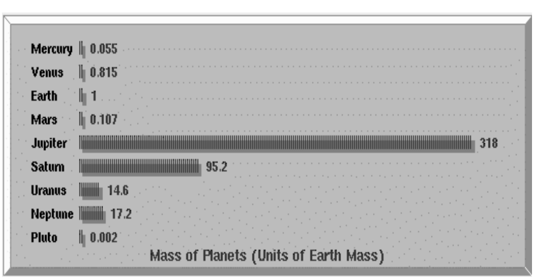
Planet Properties:
Orbit Eccentricities



Planetary Mass Measurement



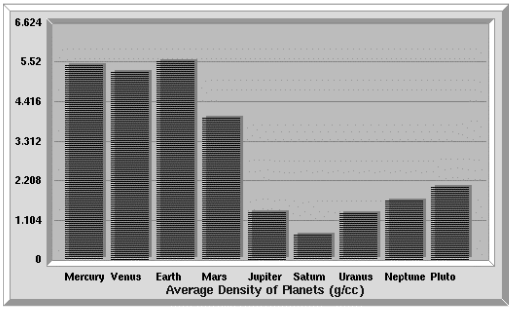
Planet Properties:
Relative Mass of Planets



Density

- **Density measures the "compactness" of matter.**
  - **Density = mass/volume**
- **units = gram/cubic centimeter = g/cm^3**
- **For a planet:**
  - **If know the diameter,**
  - **can calculate volume.**
  - **If also know the mass,**
  - **can calculate average density.**

Planet Properties: Planetary Densities



How do we know what we know?

- Distance from Sun and orbital period about Sun?
  - observe orbital period and correct for motion of Earth/Sun,
  - apply Kepler's Laws for relative spacing,
  - radar ranging for absolute distance to Venus
- Mass of planet w/ moons?
  - observe moons' orbits,apply Newton's laws of motion and gravity
- Mass of planet w/o moons?
  - measure planet's influence on other planets/nearby objects
- Size of orbits and/or planets?
  - measure angular size and apply geometry
- Rotation period?
  - observe surface features appear and disappear or
  - use radar ranging to measure Doppler shift due to rotation
- Average density of planet?
  - Compute from (total mass)/volume

Composition and Structure of Solar System Objects

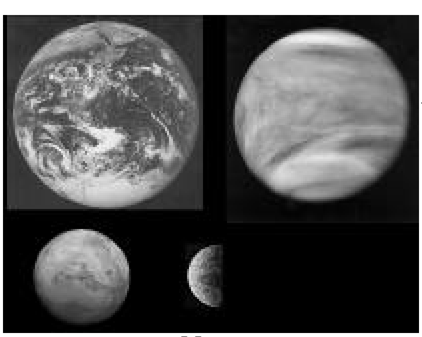
Chemistry
Internal Structure
Surface Features

Chemistry of the Planets

- Under planetary conditions, atoms often form molecules and minerals.
- The primary forms of matter in our planetary system are solid and liquid.
- Two dominate classes of elements:
  - Refractory: relatively heavy with high boiling points
    - Metals (e.g., iron and nickel)
    - Rock (compounds of silicon, oxygen, magnesium, aluminum, iron, sulfur, and other elements)
  - Volatiles: relatively light with low boiling points
    - Solids or ices (water, carbon dioxide, ammonia, methane)
    - Liquids
    - Gases

Terrestrial Planets: Views from Space

Earth



Venus

Mars Mercury

Terrestrial Planets

- Much smaller than giant planets, but more dense.
- Composed primarily of rock and metal
  - made of elements that are not as common in universe
    - most abundant rocks: silicates (silicon and oxygen)
    - most abundant metal: iron
- Earth, Venus, Mars have similar bulk compositions by mass
  - 1/3 iron-nickel or iron-sulfur combinations
  - 2/3 silicates
  - little hydrogen, many oxygen compounds
- Oxidized chemistry

Terrestrial Planets: Internal Structure

- Observed and inferred internal structure
  - densest metals in central core
  - lighter silicates near surface
- Process that organizes planet into layers of different compositions and densities is called differentiation.
- Requires planet to be molten so that heaviest materials "sink" to interior and lightest material "float" to surface.
- As planet cools, layered structure is preserved.
- Melting point of rocks >1300K.

Surfaces as Records of Geological Activity

- Crusts of terrestrial planets and many of larger moons have been modified by both internal and external forces.
  - internal: deform crust, build mountain ranges, volcanic eruptions
  - external: projectiles from space create craters
- Geological activity is a result of hot interior.
  - Small objects cool more quickly than large ones.

Determining the Age of a Surface

- Counting craters
  - yields estimate of time since surface underwent major change
  - comparison between regions can imply relative age of surfaces
- Radioactive dating of rock samples
  - provides nuclear clock to measure time since formation of rock

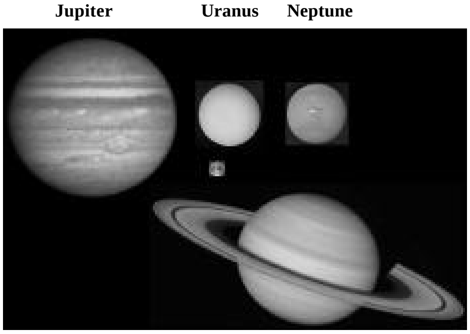
Surface of the Moon

Terrestrial Planets: Summary

- within 1.5 AU of Sun
- small
- low mass
- high density
- rocky composition (but each different from others)
- solid surfaces
- atmospheres (from near vacuum to dense hot gas)
- rotation rate: Earth, Mars ~ 24 hrs,
  Mercury ~ 2 months
  Venus ~ 8 months
  video
- moons: Earth - 1
  Mars - 2
  Mercury and Venus - 0
- magnetic field: Earth, Mercury - yes
  Mars, Venus - no

Jovian Planets: Earth Comparison

Jupiter Uranus Neptune



Saturn

Giant Planets

- Jupiter and Saturn have nearly the same chemical makeup as the Sun.
  - primarily hydrogen and helium
  - by mass: 75% hydrogen, 25% helium
  - gas compressed in interior until hydrogen becomes a liquid.
- Uranus and Neptune are smaller, attracted less hydrogen and helium.
- All have interior core composed of rock, metal, and ice.
  - approximately 10x mass of Earth.
- Chemistry dominated by hydrogen, oxygen in form of H_2O (water and water ice)
  - reducing chemistry

Jovian Planets: Summary
Jupiter, Saturn, Uranus, Neptune

- large size
- high mass
- low density
- gaseous composition: predominately hydrogen and helium
- no solid surfaces - atmosphere thickens and merges with liquid interior over a small rock/metal core
- atmospheres - dense, varying composition
- large ring systems
- rotation rates: rapid compared to terrestrial, (0.38 to 0.72) x rotation rate of Earth
- moons: numerous and varied in composition
- magnetic field: all have strong fields

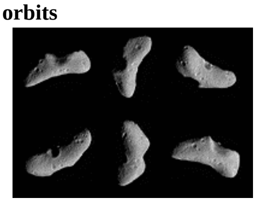
video

Moons, Asteroids, and Comets

- **Earth's Moon**
  - chemically and structurally like terrestrial planets.
- **Other Large Moons**
  - Most moons in solar system far from Sun with compositions similar to cores of giant planets they orbit.
  - Largest are half frozen water, half rock and metal.
  - Differentiated during formation, but only to melting point of ice, not rock.
- **Small moons, Asteroids, and Comets**
  - probably never heated to melting point and retain original composition and structure.
  - "fossils" of very early solar system

Asteroids

- **Relatively small, rocky objects that revolve around Sun.**
- **Probably remnants of common solar system objects from time before planets formed.**
- **Most move in very eccentric orbits between Mars and Jupiter.**
  - orbit eccentricity: 0.05-0.3



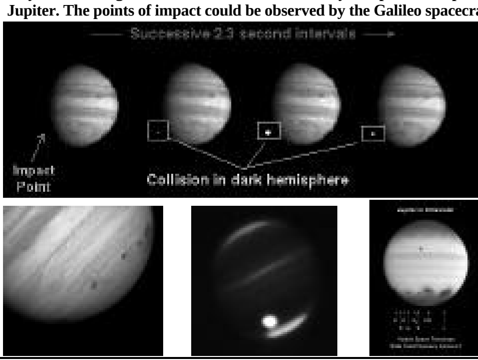
- **Largest known: Ceres**
  - 940 km diameter (480 miles)
  - 1/10,000 mass of Earth
- **A few have orbits that cross Earth's orbit and are known as *Earth-crossing asteroids*.**
  - Recently studied by NEAR spacecraft.

Comets

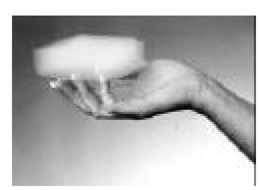
- **Travel in highly elliptical orbits with Sun at one focus.**
- **Orbital periods range from tens of years to several million years.**
- **Structure**
  - Nucleus: a few km across
  - Primarily frozen ices w/ rock and metallic particles.
  - Near Sun, surface too warm to be stable.
  - Forms coma, hydrogen envelope, and tail.
- **Remnants from formation of solar system.**

Comet Shoemaker-Levy 9

In July of 1994, fragments of Comet Shoemaker-Levy 9 impacted the planet Jupiter. The points of impact could be observed by the Galileo spacecraft.

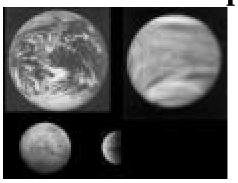


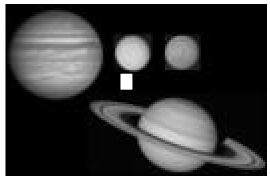
In Search of Stardust and Clues to Life



- **Stardust -**
  - unmanned probe
  - planned 7 year mission
    - rendezvous with comet,
    - collect
      - microscopic particles from comet Wild-2 and
      - interstellar dust from between Mars and Jupiter
    - return to Earth with samples

Implications of Structure and Composition





- The distinct differences in structure and composition of solar system objects implies that each of the classes of objects formed under different conditions.

The Origin of Our Solar System

- Knowledge of solar system’s formation emerging from studies of objects other than Earth.
  - Earth’s surface constantly changing through erosion.
  - interstellar gas clouds
  - meteorites and comets
  - Moon and other planets from telescope, space probes
  - extra-solar planets
- Any model must adhere to known facts.

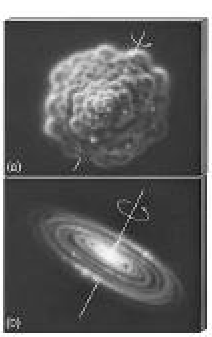
Solar System Facts

- Each planet is relatively isolated in space.
- Orbits of planets are nearly circular.
- Orbits of planets all lie in nearly the same plane.
- The direction in which planets orbit the Sun is the same direction in which the Sun rotates on its axis.
- The direction in which most planets rotate on their own axis is roughly the same as the direction the Sun rotates on its axis. (exceptions: Venus, Uranus,Pluto)
- Most of the known moons orbit their parent planet in the same direction that the planets rotate on their axes.
- Our planetary system is highly differentiated.
- Asteroids are very old and exhibit a range of properties not characteristic of inner or outer planets or their moons.
- Comets are primitive, icy fragments that do not orbit in the ecliptic plane and reside primarily at large distances from Sun.

Clues to the Origin of the Solar System

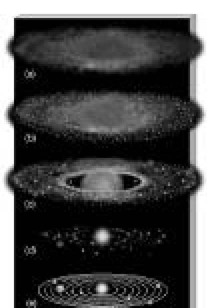
- Many observations suggest that the Sun and planets formed together from a spinning cloud of dust and gas (called a solar nebula).
  - Patterns in motions of solar system objects
    - Planets revolve about Sun in same direction.
    - Planets revolve about Sun in a common plane.
    - Sun also rotates in the same direction.
  - Composition
    - Sun, Jupiter, and Saturn have same hydrogen dominated composition implying they formed from the same materials.
    - Terrestrial planets and satellites are deficient in light gases and ices.
      - Formed too close to Sun for gases/ices to remain, leaving heavier rock and metal.
  - Planetary systems around other stars.

Formation of Solar System



- Objects in solar system formed together with the Sun about 4.6 billion years ago.
- Represent aggregations of material condensed from cloud of dust and gas.
- Central part of cloud became the Sun and a small fraction of material in outer part of cloud eventually formed other objects.

Formation of Planets: Condensation Theory



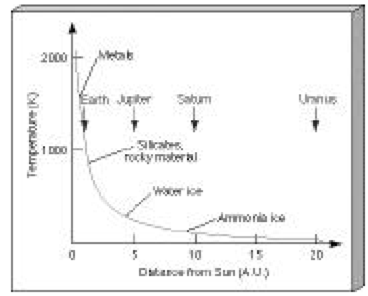
- Solar nebula modeled as large rotating disks of dust and gas.
- Dust grains act as condensation nuclei, creating clumps of material.
- Lumps grow by accretion until large enough to gravitationally attract materials. Begin to coalesce by forming small moon-sized objects called planetesimals.
- Most planetesimal material swept up to form protoplanets.
- Competing process is fragmentation, breaking up of small bodies following collisions with larger objects.
- Eventually, only a few planet-sized objects remain.
- Rest left as comets and asteroids.

Temperature and Distance

- In general, the further from Sun, the cooler the planet or satellite.
  - Mercury >500K (cleaning cycle on electric oven)
  - Pluto 50K (colder than liquid air)
- Temperatures decrease approximately in proportion to square root of distance from Sun.

  $T \propto (\text{distance from Sun})^{1/2}$
  - $\text{distance}_{Mercury} = 0.4$ AU
  - $\text{distance}_{Pluto} = 40$ AU
  - factor of 100 in distance; factor of 10 in temperature.
  - Earth only planet with surface temperature in range between freezing and boiling point of water.

Solar Nebula Temperature and Condensation



Formation Models: Terrestrial and Jovian Planets

- Terrestrial planets
  - Accretion model
- Jovian planets
  - Two models
    - Accretion model to form proto-planets. Then, four largest proto-planets became massive enough to gravitationally attract and hold gases from the solar nebula.
    - Instabilities in original solar nebula formed giant planets without accretion phase. Mimics initial collapse of interstellar cloud on small scale to form proto-planets massive enough to gather gas and dust from solar nebula.

Extra-Solar Planets

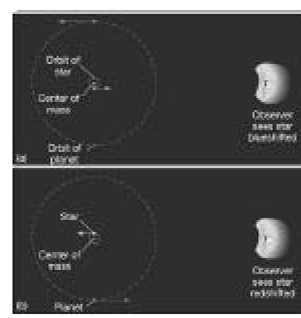
Known number of extra-solar planets is approximately 70.

Discovered by observation of parent star's

wobble from gravitational effects

or

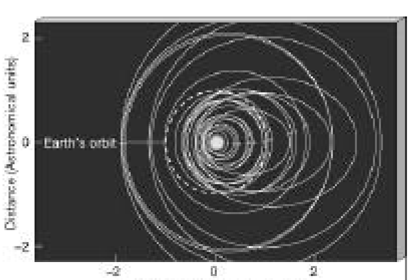
brightness variation as the planet orbits.



Extra-solar Planets

None like our planetary system.

Most have one massive planet (comparable to Jupiter) in orbits that take the planet close to its star.



Summary of Chapter 6 Comparative Planetology

- Solar System
  - What's in it?
  - How are the things in it alike/different?
  - Relative size, position, density
- How do we gather the information to make comparisons?
  - Measurements from Earth
  - Missions to the planets, asteroids, and comets.

Review

- THE SUN
  - A star; contains most of the mass of the Solar System.
  - Gaseous nuclear power plant, providing most of the energy in the Solar System.
- THE PLANETS
  - Planets orbit the Sun directly.
  - Terrestrial and jovian types.
- MOONS
  - Orbit the planets.
  - Some are as large as small planets.
  - Some are as small as small asteroids.
- ASTEROIDS
  - Small, rocky & metallic, minor planets.
  - Many orbit in the asteroid belt.
  - Some cross Earth's orbit.
  - Meteoroids are small pieces of asteroids.
- COMETS
  - Small, icy bodies.
  - Very eccentric orbits that are not like planetary orbits.
  - Some cross Earth's orbit.
- INTERPLANETARY GAS AND DUST
  - Gases from the Sun and planetary atmospheres.
  - Dust from cosmic collisions.

Review

- THE ORDER OF THE PLANETS FROM CLOSEST TO FARTHEST FROM THE SUN

Mercury (My)
Venus (very)
Earth (educated)
Mars (Mother)
Jupiter (just)
Saturn (served)
Uranus (us)
Neptune (nine)
Pluto (pizzas.)

Comparison of Terrestrial and Jovian Planets

TERRESTRIAL PLANETS	JOVIAN PLANETS
close to the Sun	far from the Sun
closely spaced orbits	widely spaced orbits
small masses	large masses
small radii	large radii
predominantly rocky	predominantly gaseous
solid surface	no solid surface
high density	low density
slower rotation	faster rotation
weak magnetic fields	strong magnetic fields
few moons	many moons
no rings	many rings

SIMPLIFIED SOLAR SYSTEM CHEMISTRY

- VOLATILE ELEMENTS (ICES, LIQUIDS, AND GASES)
  - Elements that are relatively light.
  - Low boiling points.
  - Generally found as liquids or gases in Earth's environment.
  - Solids state is called an "ice".
  - Carbon is considered a volatile element.
- REFRACTORY ELEMENTS (ROCKS AND METALS)
  - Elements that are relatively heavy.
  - High boiling points.
  - Generally found as solids in Earth's environment.