9. Formation of the Solar System

The evolution of the world may be compared to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a cool cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds.

George Lemaître (1894 – 1966)
Astronomer and Catholic Priest

Agenda

- What did you think of test?
- How would you rate difficulty of class?
- Go over tests
- Discuss black numbers
- COTD—Ursa Major
- Ch. 9
- Lunar, solar, Venal(!) observations

International Space Station (ISS)

- Has cost "the U.S. space agency about $23.5 billion—research costs excluded"
- ESA projections state "total cost could exceed $100 billion" for all nations
- After 5 years, still incomplete

- Compare to the cost of sending two rovers to Mars….guesses?

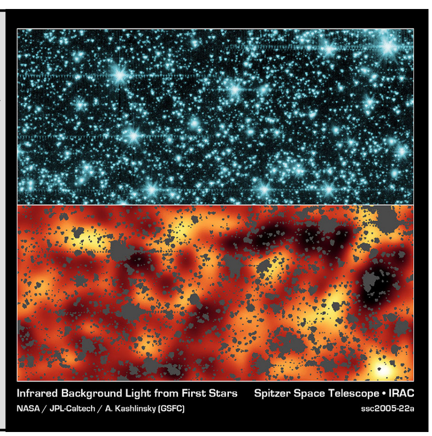
International Space Station (ISS)

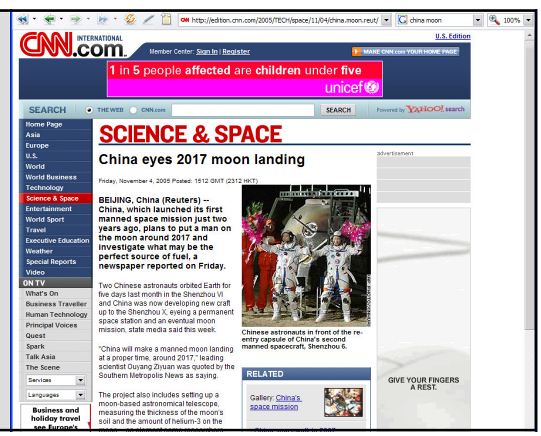
- Has cost "the U.S. space agency about $23.5 billion—research costs excluded"
- ESA projections state "total cost could exceed $100 billion" for all nations
- After 5 years, still incomplete

- Compare to the cost of sending two rovers to Mars….guesses? $820 million

Can we see light from first stars?

- Results are disputed …that's science!

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CNN INTERNATIONAL .com

SCIENCE & SPACE

China eyes 2017 moon landing

Friday, November 4, 2005 Posted: 1512 GMT (2312 HKT)

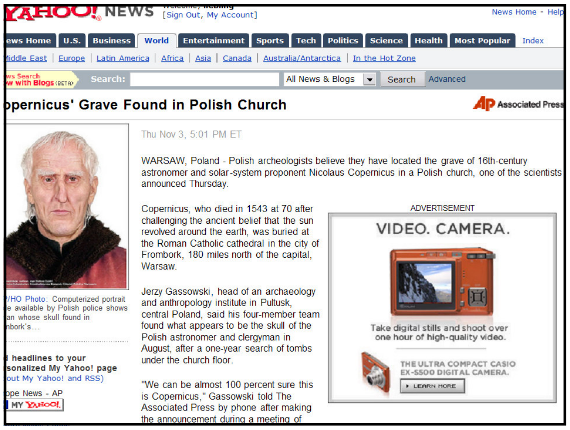
BEIJING, China (Reuters) -- China, which launched its first manned space mission just two years ago, plans to put a man on the moon around 2017 and investigate what may be the perfect source of fuel, a newspaper reported on Friday.

Two Chinese astronauts orbited Earth for five days last month in the Shenzhou VI and China was now developing new craft up to the Shenzhou X, eyeing a permanent space station and an eventual moon mission, state media said this week.

"China will make a manned moon landing at a proper time, around 2017," leading scientist Ouyang Ziyuan was quoted by the Southern Metropolis News as saying.

The project also includes setting up a moon-based astronomical telescope, measuring the thickness of the moon's soil and the amount of helium-3 on the

Chinese astronauts in front of the re-entry capsule of China's second manned spacecraft, Shenzhou 6.



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opernicus' Grave Found in Polish Church

AP Associated Press

Thu Nov 3, 5:01 PM ET

WARSAW, Poland - Polish archeologists believe they have located the grave of 16th-century astronomer and solar-system proponent Nicolaus Copernicus in a Polish church, one of the scientists announced Thursday.

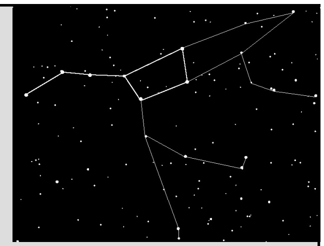
Copernicus, who died in 1543 at 70 after challenging the ancient belief that the sun revolved around the earth, was buried at the Roman Catholic cathedral in the city of Frombork, 180 miles north of the capital, Warsaw.

Jerzy Gassowski, head of an archaeology and anthropology institute in Pultusk, central Poland, said his four-member team found what appears to be the skull of the Polish astronomer and clergyman in August, after a one-year search of tombs under the church floor.

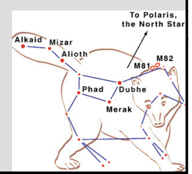
"We can be almost 100 percent sure this is Copernicus," Gassowski told The Associated Press by phone after making the announcement during a meeting of

/HO Photo: Computerized portrait e available by Polish police shows an whose skull found in nbork's...

COTD: Ursa Major



- The Great Bear
- Home of Big Dipper
- Circumpolar for northern latitudes
- Outer bowl edge points up to Polaris
- Slaves advised to "follow the drinking gourd" to freedom



9.1 The Origin of the Solar System: The Nebular Theory

Our goals for learning:

- What four characteristics of our Solar System must be explained by a formation theory?
- What is the basic idea behind the nebular theory?

Origin of the Solar System

Our theory must explain the data

1. Large bodies in the Solar System have orderly motions.
2. There are two types of planets.
   - small, rocky **terrestrial** planets
   - large, hydrogen-rich **Jovian** planets
3. Asteroids & comets exist in certain regions of the Solar System
4. There are exceptions to these patterns.

Origin of the Solar System

Nebular Theory – our Solar System formed from a giant, swirling cloud of gas & dust.

Depends on two principles of Physics:

•Law of Gravity

gravitational potential energy ⇒ heat

•Conservation of angular momentum

and

•Basic chemistry

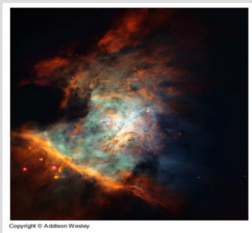
9.2 Orderly Motion in a Collapsing Nebula

Our goals for learning:

- What was the Solar nebula?
- How did gravitational collapse affect the Solar nebula?
- What produced the orderly motion we observe in the Solar System today?

The Solar Nebula

- The nebular theory holds that our Solar System formed out of a nebula which collapsed under its own gravity.
- observational evidence
  - We observe stars in the process of forming today.
  - Such forming stars are always found within interstellar clouds of gas.



newly born stars in the Orion Nebula

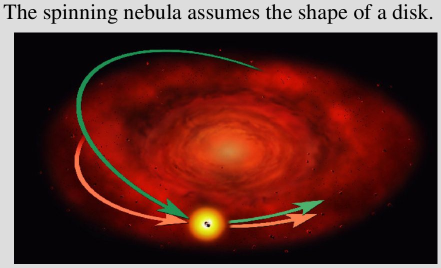
solar nebula – name given to the cloud of gas from which our own Solar System formed

Gravitational Collapse

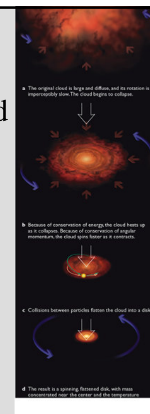
- The solar nebular was initially somewhat spherical and a few light years in diameter.
  - very cold
  - rotating slightly
- It was given a "push" by some event.
  - perhaps the shock wave from a nearby supernova
- As the nebula shrank, gravity increased, causing collapse.
- As the nebula "falls" inward, gravitational potential energy is converted to heat.
  - Conservation of Energy
- As the nebula's radius decreases, it rotates faster
  - Conservation of Angular Momentum

Flattening of the Solar Nebula

- As the nebula collapses, clumps of gas collide & merge.
- Their random velocities average out into the nebula's direction of rotation.
- The spinning nebula assumes the shape of a disk.



As the nebula collapses, it heats up, spins faster, and flattens.



Orderly Motions in the Solar System

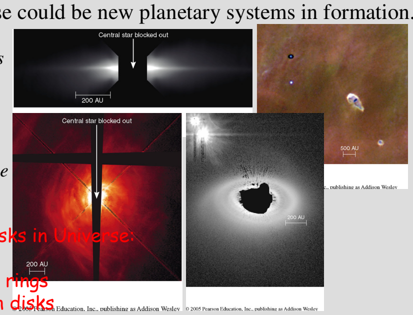
- The Sun formed in the very center of the nebula.
  - temperature & density were high enough for nuclear fusion reactions to begin
- The planets formed in the rest of the disk.
- This would explain the following:
  - all planets lie along one plane (in the disk)
  - all planets orbit in one direction (the spin direction of the disk)
  - the Sun rotates in the same direction
  - the planets would tend to rotate in this same direction
  - most moons orbit in this direction
  - most planetary orbits are near circular (collisions in the disk)

More Support for the Nebular Theory

- We have observed disks around other stars.
- These could be new planetary systems in formation.

β Pictoris

AB Aurigae



Lots of Disks in Universe:
- Galaxies
- Planetary rings
- Accretion disks

Yet More Support for the Nebular Theory

- We've detected infrared radiation from many nebulae…indicative of star formation
- Computer models of evolution of interstellar clouds reproduce general features

9.3 Creating Two Types of Planets

Our goals for learning:

- What key fact explains why there are two types of planet?
- Describe the basic steps by which the terrestrial planets formed.
- Describe the basic steps by which the Jovian planets formed.

Building the Planets

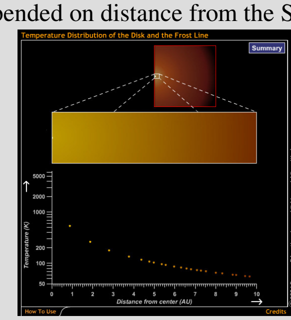
Condensation – elements & compounds began to condense (i.e. solidify) out of the nebula…. depending on temperature!

Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

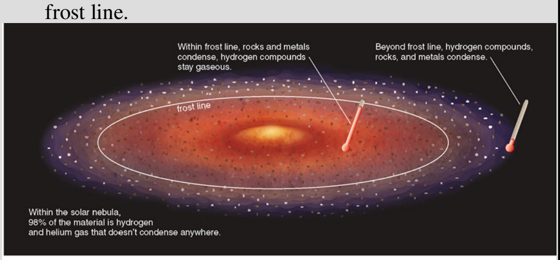
Building the Planets

…and temperature in the Solar nebula depended on distance from the Sun!



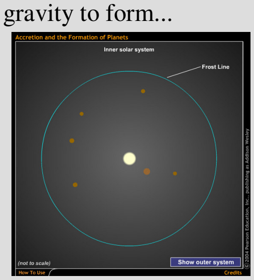
Building the Planets

So only rocks & metals condensed within 3.5 AU of the Sun… the so-called **frost line**.
Hydrogen compounds (ices) condensed beyond the frost line.



Building the Planets

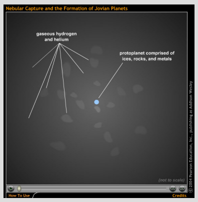
accretion -- small grains stick to one another via electromagnetic force until they are massive enough to attract via gravity to form...



Building the Planets

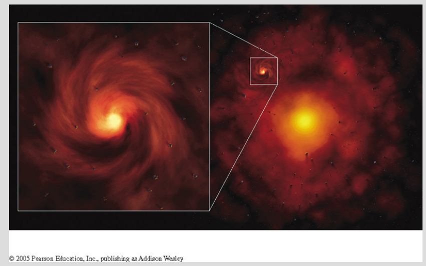
…**planetesimals** which will:

- combine near the Sun to form rocky planets
- combine beyond the frostline to form icy planetesimals which…
- capture H/He far from Sun to form gas planets



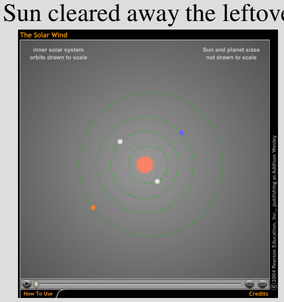
Building the Planets

- Each gas (Jovian) planet formed its own "miniature" solar nebula.
- Moons formed out of the disk.



Building the Planets

solar wind --- charged particles streaming out from the Sun cleared away the leftover gas



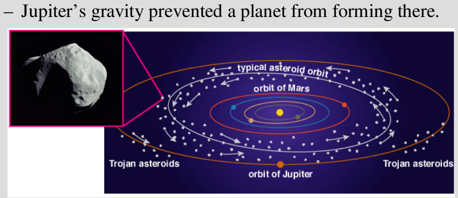
9.4 Explaining Leftovers and Exceptions to the Rules

Our goals for learning:

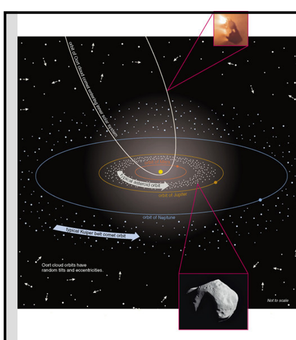
- What is the origin of asteroids and comets?
- What was the heavy bombardment?
- How do we explain the exceptions to the rules?
- How do we think that our Moon formed?

Origin of the Asteroids

- The Solar wind cleared the leftover gas, but not the leftover planetesimals.
- Those leftover rocky planetesimals which did not accrete onto a planet are the present-day **asteroids**.
- Most inhabit the **asteroid belt** between Mars & Jupiter.
  - Jupiter's gravity prevented a planet from forming there.



Origin of the Comets



The nebular theory *predicted* the existence of the Kuiper belt 40 years before it was discovered!

- The leftover icy planetesimals are the present-day **comets**.
- Those which were located between the Jovian planets, if not captured, were gravitationally flung in all directions into the **Oort cloud**.
- Those beyond Neptune's orbit remained in the ecliptic plane in what we call the **Kuiper belt**.

Exceptions to the Rules

So how does the nebular theory deal with exceptions, i.e. data which do not fit the model's predictions?

IMPACTS

- There were many more leftover planetesimals than we see today.
- Most of them collided with the newly-formed planets & moons during the first few 10^8 years of the Solar System.
- We call this the **heavy bombardment** period.

Exceptions to the Rules

Close encounters with and impacts by planetesimals could explain:

- Why some moons orbit opposite their planet's rotation
  - captured moons (e.g. Triton)
- Why rotation axes of some planets are tilted
  - impacts "knock them over" (extreme example: Uranus)
- Why some planets rotate more quickly than others
  - impacts "spin them up"
- Why Earth is the only terrestrial planet with a large Moon
  - giant impact

Formation of the Moon (Giant Impact Theory)

- The Earth was struck by a Mars-sized planetesimal
- A part of Earth's mantle was ejected
- This coalesced in the Moon.
  - it orbits in same direction as Earth rotates
  - lower density than Earth
  - Earth was "spun up"

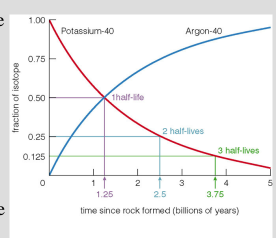
9.5 How Old is the Solar System?

Our goals for learning:

- How do we measure the age of a rock?
- How old is the Solar System and how do we know?

Radiometric Dating

- Isotopes which are unstable are said to be **radioactive**.
- They spontaneously change in to another isotope in a process called **radioactive decay**.
  - protons convert to neutrons
  - neutrons convert to protons
- The time it takes half the amount of a radioactive isotope to decay is called its **half life**.



- By knowing rock chemistry, we chose a stable isotope which does not form with the rock…its presence is due solely to decay.
- Measuring the relative amounts of the two isotopes and knowing the half life of the radioactive isotope tells us the age of the rock.

The Age of our Solar System

- Radiometric dating can only measure the age of a rock *since it solidified.*
- Geologic processes on Earth cause rock to melt and resolidify.
  - ⇒ Earth rocks can't be used to measure the Solar System's age.
- We must find rocks which have not melted or vaporized since the condensed from the Solar nebula.
  - meteorites imply an age of 4.6 billion years for Solar System
- Radioactive isotopes are formed in stars & supernovae
  - suggests that Solar System formation was triggered by supernova
  - short half lives suggest the supernova was nearby

9.6 Other Planetary Systems

Our goals for learning:

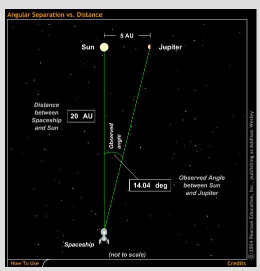
- When did we first learn of planets beyond our Solar System?
- Have we ever actually photographed an extrasolar planet?
- What new lessons have we learned from other planetary systems?

Extrasolar Planets

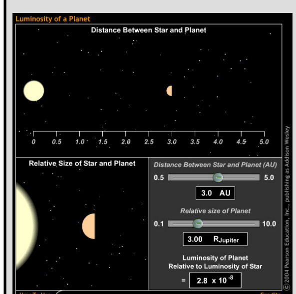
- Since our Sun has a family of planets, shouldn't other stars have them as well?
  - Planets which orbit other stars are called **extrasolar planets**.
- Over the past century, we have assumed that extrasolar planets exist, as evidenced from our science fiction.
  - The Starship *Enterprise* visits many such worlds.
  - But do they exist in fact?
- We finally obtained direct evidence of the existence of an extrasolar planet in the year 1995.
  - A planet was discovered in orbit around the star *51 Pegasi.*
  - Over 100 such extrasolar planets are now known to exist.

Detecting Extrasolar Planets

- Can we actually make images of extrasolar planets?
  - NO, this is very difficult to do.
- The distances to the nearest stars are much greater than the distances from a star to its planets.
- The angle between a star and its planets, as seen from Earth, is too small to resolve with our biggest telescopes.



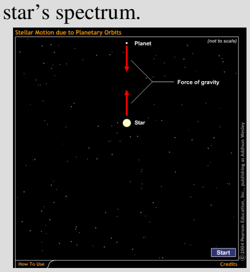
Detecting Extrasolar Planets



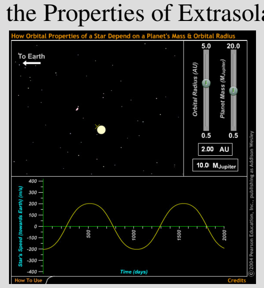
- A star like the Sun would be a billion times brighter than the light reflected off its planets.
- As a matter of contrast, the planet would be lost in the glare of the star.
- Improved techniques of interferometry may solve this problem someday.

Detecting Extrasolar Planets

- We detect the planets <u>indirectly</u> by observing the star.
- Planet gravitationally tugs the star, causing it to wobble.
- This periodic wobble is measured from the Doppler Shift of the star's spectrum.



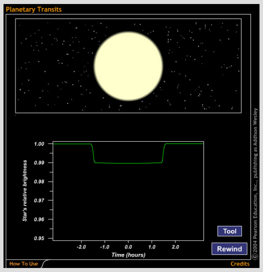
Measuring the Properties of Extrasolar Planets



- A plot of the radial velocity shifts forms a wave.
  - Its wavelength tells you the period and size of the planet's orbit.
  - Its amplitude tells you the mass of the planet.

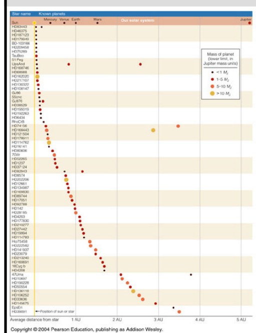
Measuring the Properties of Extrasolar Planets

- The Doppler technique yields only planet masses and orbits.
- Planet must eclipse or **transit** the star in order to measure its radius.
- Size of the planet is estimated from the amount of starlight it blocks.

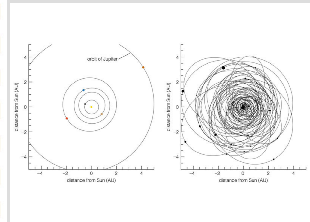


- We must view along the plane of the planet's orbit for a transit to occur.
  - transits are relatively rare
- They allow us to calculate the density of the planet.
  - extrasolar planets we have detected have Jovian-like densities.

Properties of Other Planetary Systems



- planets appear to be Jovian
- more massive than our system



- planets are close to their stars
- many more highly eccentric orbits than in our Solar System

Implications for the Nebular Theory

- Extrasolar systems have Jovian planets orbiting close to their stars.
  - Theory predicts Jovian planets form in cold, outer regions.
- Many extrasolar planets have highly eccentric orbits.
  - Theory predicts planets should have nearly circular orbits.
- Is the nebular theory *wrong*?
  - Not necessarily; it may be incomplete.
  - Perhaps planets form far from star and **migrate** towards it.
  - Doppler technique biased towards finding close Jovian planets
  - Are they the exception or the rule?
  - Migrating Jovians could prevent terrestrials from forming
  - Is our Solar Solar System rare?

What have we learned?

- What four characteristics of our Solar System must be explained by a formation theory?
  - Patterns of motion, why there are terrestrial and Jovian planets, why there are asteroids and comets, and why there are exceptions to the rules.
- What is the basic idea behind the nebular theory?
  - Our Solar System formed from a giant, swirling cloud of gas and dust.
- What was the solar nebula?
  - The piece of interstellar cloud from which our Solar System was born.

What have we learned?

- How did gravitational collapse affect the Solar nebula?
  - The nebula heated up, spun faster, and flattened into a disk.
- What produced the orderly motion we observe in the Solar System today?
  - Planets retain the motion of the spinning disk of the solar nebula.
- What key fact explains why there are two types of planet?
  - Differences in condensation at different distances from the Sun: only metal and rock condensed inside the frost line, while hydrogen compounds could also condense outside the frost line.

What have we learned?

- Describe the basic steps by which the terrestrial planets formed
  - Condensation of solid grains of metal and rock; accretion into planetesimals; growth of planetesimals into planets.
- Describe the basic steps by which the Jovian planets formed.
  - Condensation of metal, rock, & ice; accretion into icy planetesimals, making “miniature solar nebulae”; Jovian planets form at nebula centers while moons accrete from ice in the spinning disks.

What have we learned?

- What is the origin of asteroids and comets?
  - Asteroids are leftover planetesimals of the inner Solar System and comets are leftovers of the outer Solar System.
- What was the heavy bombardment?
  - The period early in our Solar System’s history during which the planets were bombarded by many leftover planetesimals.
- How do we explain the exceptions to the rules?
  - Collisions or close encounters with leftover planetesimals can explain the exceptions.

What have we learned?

- How do we think that our Moon formed?
  - A Mars-sized “leftover” slammed into Earth, blasting rock from Earth’s outer layers into orbit, where it re-accreted to form the Moon.
- How do we measure the age of a rock?
  - Radiometric dating gives the time since a rock last solidified.
- How old is the Solar System and how do we know?
  - About 4.6 billion years old, determined from radiometric dating of the oldest meteorites.

What have we learned?

- When did we first learn of planets beyond our Solar System?
  - In the mid-1990s.
- Have we ever actually photographed an extrasolar planet?
  - No; we have only detected them indirectly through their observable effects on the stars they orbit.
- What new lessons have we learned from other planetary systems?
  - Planetary systems exhibit a surprising range of layouts, suggesting that Jovian planets sometimes migrate inward from the places where they are born. This may have implications for finding other Earth-like worlds.

Could a solar system like ours have formed with the first generation of stars after the Big Bang?

1. Possibly - there is no physical reason why not.
2. No, there would not have been enough time to form planets.
3. No, the expansion of the Universe would have torn the solar system apart.
4. No, there would not have been enough metals and rock to form terrestrial planets.
5. No, the stars would have died by now.

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How much of the solar nebula condenses in the inner regions where the temperature is greater than 1300 K and in the outer regions where the temperatures are less than 150 K ?

1. Nothing in the inner region and about 2% in the outer region.
2. Nothing in the inner region and 100% in the outer region.
3. About 0.2% in the inner region and 2% in the outer region.
4. About 0.2% in the inner region and 1.4% in the outer region.
5. About 2% in both inner and outer regions.

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The dense, rocky, and metallic planets are found close to the Sun because

1. the Sun's gravity attracted the denser particles (rocks and metals) closer to it.
2. the Sun was unable to hold onto the lighter (gaseous) particles and they moved further away where they formed the giant planets.
3. a combination of (1) and (2).
4. rocks and metals condensed at the relatively high temperatures close to the Sun.
5. they were scattered inwards by close encounters with Jupiter during the early solar system.

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What age would radiometric dating give for a chunk of recently solidified lava from Kilauea, an active volcano in Hawaii?

1. Zero.
2. The half life of potassium-40 (1.25 billion years).
3. The half-life of Uranium-238 (4.5 billion years).
4. The age of the solar system.
5. The age of the volcano.

What age would radiometric dating give for a chunk of recently solidified lava from Kilauea, an active volcano in Hawaii?

1. **Zero.**
2. The half life of potassium-40 (1.25 billion years).
3. The half-life of Uranium-238 (4.5 billion years).
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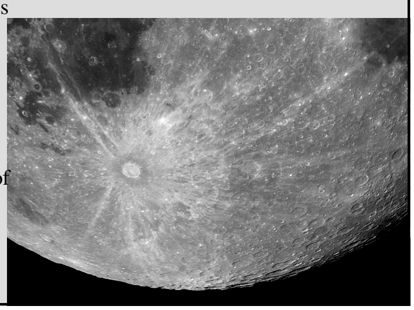
5. The age of the volcano.

Tycho Crater

- measures approximately 52 miles across
- Created by meteor impact that spewed lunar dust and rocks, called ejecta, over a large portion of the lunar surface.



Crater Plato