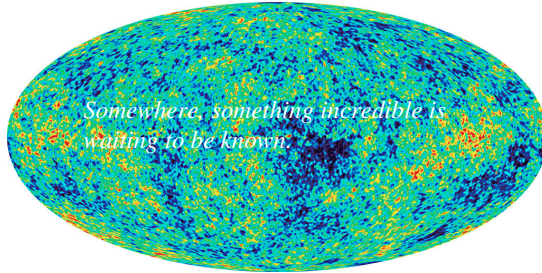


23. The Beginning of Time

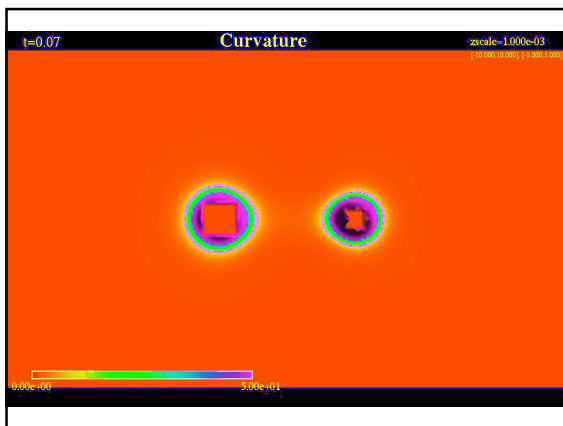


Somewhere, something incredible is waiting to be known.

Carl Sagan (1934 – 1996)
American astronomer

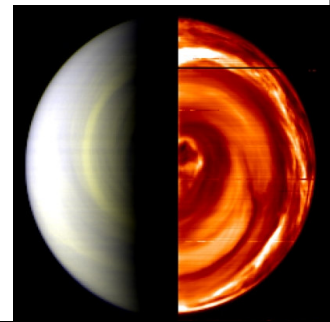
Agenda

- Announce:
 - Solar Altitude Lab (#2) due today
 - Read Ch. 24 for Thursday
 - Observation make-up next week
 - Project Presentations two weeks from today (last day of class)
- Extra Credit Presentations
- Finish Ch. 23



ESA's Venus Express

- Arrived April 11
- Picture from April 12
- Southern Hemisphere
- Left side: day/visible
- Right side: night/IR



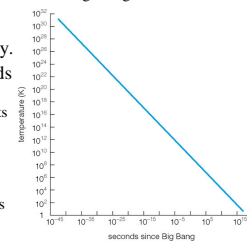
23.1 Running the Expansion Backward

Our goals for learning:

- How can we presume to understand the conditions that existed in the early universe?

Conditions in the Early Universe

- The most distant galaxies we observe come from a time when the Universe was a few billion years old.
- The cosmic microwave background prevents us viewing light from before the Universe was 380,000 years old.
- So how do we know what conditions were like at the beginning of time?
- We know the conditions & expansion rate of the Universe today.
- By running the expansion backwards
 - we can predict the temperature & density of the Universe at anytime in its history using basic physics
 - we study how matter behaves at high temperatures & densities in laboratory experiments
 - current experimental evidence provides info on conditions as early as 10^{-10} sec after the Big Bang



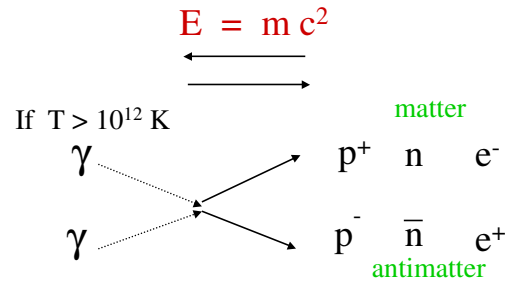
23.2 A Scientific History of the Universe

Our goals for learning:

- What was the Universe made of during its earliest moments?
- Briefly describe the various eras of the universe since the Big Bang.

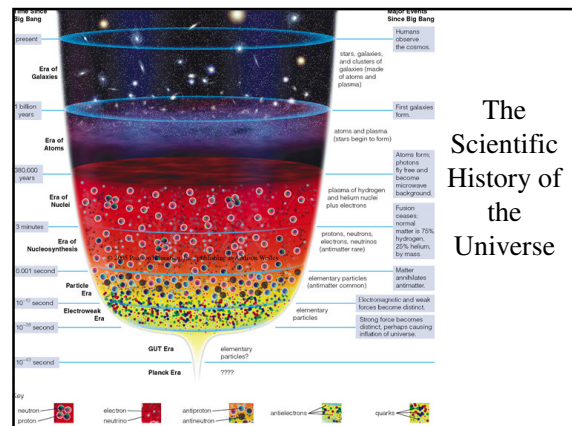
The Creation of Matter

- The early Universe was filled with radiation & subatomic particles.
- We've seen matter converted to energy...
 - but Einstein's famous equation is a two-way street!



The Destruction of Matter

- When two partner particles of matter & antimatter collide
 - they annihilate each other and form gamma photons
- During the very first few moments of the Universe...
 - matter and radiation (energy) were continually converting into each other
 - the total amount of mass-energy remained constant



BANG!

Planck Era ($t < 10^{-43}$ sec)

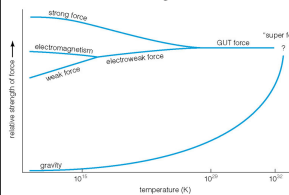
- This era, the “first instant”, lasted for 10^{-43} sec.
- Because we are as yet unable to link...
 - quantum mechanics (our successful theory of the very small)
 - general relativity (our successful theory of the very large/massive)
- ...we are powerless to describe what happened in this era.
- 10^{-43} sec after the Big Bang is as far back as our current science will allow us to go.
- We *suppose* that all four natural forces were unified during this era.

GUT Era ($10^{-43} < t < 10^{-38}$ sec)

- The Universe contained two natural forces:
 - gravity
 - Grand Unified Theory (GUT) force
 - electromagnetic + strong (nuclear) + weak forces unified
- This lasted until the Universe was 10^{-38} sec old.
 - at this time, the Universe had cooled to 10^{29} K
 - the strong force “froze out” of the GUT force
 - the energy released by this caused a sudden and dramatic **inflation** of the size of the Universe

Electroweak Era ($10^{-38} < t < 10^{-10}$ sec)

- The Universe contained three natural forces:
 - gravity, strong, & electroweak
- This lasted until the Universe was 10^{-10} sec old.
 - at this time, the Universe had cooled to 10^{15} K
 - the electromagnetic & weak forces separated



W&Z particles predicted in '68, Nobel Prize in '79...

Experimentally verified in 1983:

- discovery of W & Z bosons
- electroweak particles predicted to exist above 10^{15} K

Particle Era ($10^{-10} < t < 10^{-3}$ sec)

- The four natural forces were now distinct.
- Particles were as numerous as photons.
- When the Universe was 10^{-4} sec old...
 - quarks combined to form protons, neutrons, & their anti-particles
- At 10^{-3} sec old, the Universe cooled to 10^{12} K.
 - protons, antiprotons, neutrons, & antineutrons could no longer be created from two photons (radiation)
 - the remaining particles & antiparticles annihilated each other into radiation
 - slight imbalance in number of protons & neutrons allowed matter to remain
- Electrons & positrons are still being created from photons.

Era of Nucleosynthesis (10^{-3} sec $< t < 3$ min)

- During this era, protons & neutrons started fusing...
 - but new nuclei were also torn apart by the high temperatures
- When the Universe was 3 min old, it had cooled to 10^9 K.
 - at this point, the fusion stopped
- Afterwards, the baryonic matter leftover in the Universe was:
 - 75% Hydrogen nuclei (i.e. individual protons)
 - 25% Helium nuclei
 - trace amounts of Deuterium (H isotope) & Lithium nuclei

Era of Nuclei (3 min $< t < 3.8 \times 10^5$ yr)

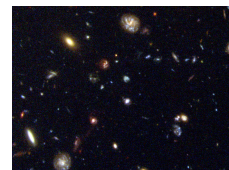
- The Universe was a hot plasma of H & He nuclei and electrons.
 - photons bounced from electron to electron, not traveling very far
 - the Universe was opaque
- When the Universe was 380,000 yrs old...
 - it had cooled to a temperature of 3,000 K
 - electrons combined with nuclei to form stable atoms of H & He
 - the photons were free to stream across the Universe
 - the Universe became transparent

Era of Atoms ($3.8 \times 10^5 < t < 10^9$ yr)

- The Universe was filled with atomic gas.
 - sometimes referred to as the "Cosmic Dark Ages"
- Density enhancements in the gas and gravitational attraction by dark matter...
 - eventually form protogalactic clouds
 - the first star formation lights up the Universe
 - which provokes the formation of galaxies

Era of Galaxies ($t > 10^9$ yr)

- The first galaxies came into existence about 1 billion years after the Big Bang.
- This is the current era of the Universe.



23.3 Evidence for the Big Bang

Our goals for learning:

- What two key lines of evidence support the Big Bang model?
- What is the cosmic microwave background?
- How does the Big Bang theory predict the Helium abundance of the Universe?
- How does the cosmic deuterium abundance argue in favor of dark matter being made of WIMPs?

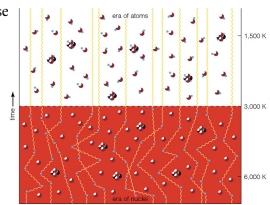
Evidence for the Big Bang Theory

- A good scientific model should make predictions which can be verified.
- The Big Bang model makes two predictions which have been verified since the 1960s:
 - the existence and characteristics of the cosmic microwave background
 - the expected Helium abundance in the Universe
- The model predictions agree with current observations.

Cosmic Microwave Background

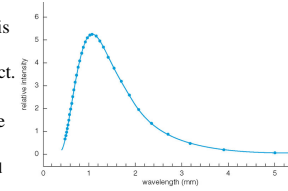
- The Universe is immersed in a sea of radiation.
- This is the same radiation which was unleashed at the end of the Era of Nuclei.
 - 380,000 years after the Big Bang, the Universe had cooled enough for free electrons to become bound into atoms of H & He
 - without electrons to scatter them, photons were able to travel unhindered throughout the Universe
 - the Universe became *transparent*

The temperature of the Universe was 3,000 K at this time.



Cosmic Microwave Background

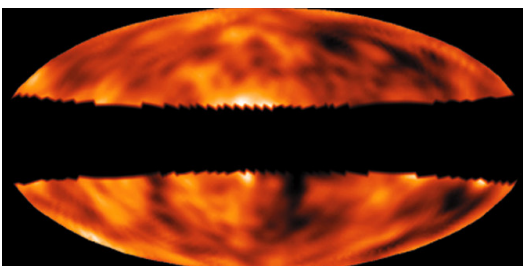
- The spectral distribution of this radiation was the same as radiation from a 3,000 K object.
 - like the surface of a red giant
- Since then, the Universe's size has expanded 1,000 times.
 - cosmological redshift has turned this radiation into microwaves.
- This Cosmic Microwave Background, predicted by theory...
 - was accidentally discovered in 1965 by Arno Penzias & Robert Wilson
 - appeared to come from every direction
 - had a perfectly thermal spectrum with a temperature of 2.73 K
 - this is the temperature one expects after expanding the Universe 1,000 times



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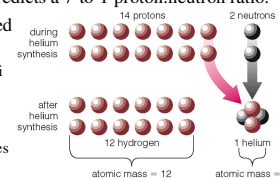
Cosmic Microwave Background...

- ...was mapped by the *Cosmic Background Explorer (COBE)* in 1990s
- While very smooth and uniform across the sky...
- COBE did find slight temperature variations from place to place on the level of a few parts in 100,000.



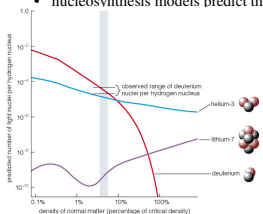
Cosmic Helium Abundance

- In the Era of Nucleosynthesis, *i.e. the first three minutes*
 - number of protons & neutrons roughly equal as long as $T > 10^{11}$ K
 - below 10^{11} K, proton-to-neutron reactions no longer occur
 - neutrons still decay into protons
 - protons begin to outnumber neutrons
- At $T < 10^{10}$ K, the products of fusion reactions no longer break up.
 - Helium, Deuterium, & Lithium remain stable
- At this time, Big Bang model predicts a 7-to-1 proton:neutron ratio.
- For every 2 n & 2 p⁺ which fused into a Helium nucleus...
 - there are 12 p⁺ or Hydrogen nuclei
- Model predicts a 3-to-1 H:He
- This what we observe:
 - minimum of 25% He in all galaxies



Abundances of Other Light Nuclei

- By the time stable ${}^4\text{He}$ formed...
 - the Universe was too cool for He to fuse into C or other heavier nuclei
 - ${}^4\text{He}$ could fuse with ${}^3\text{H}$ to form stable ${}^7\text{Li}$
- Deuterium (${}^2\text{H}$) is a "leftover" isotope.
 - if densities had been greater, fusion would have gone faster, and more neutrons would have ended up in ${}^4\text{He}$ instead of ${}^2\text{H}$
 - nucleosynthesis models predict the amount of leftover ${}^2\text{H}$ for each density



- The measured abundance of ${}^2\text{H}$ is
 - one for every 40,000 H atoms
- Compared to the model calculations
 - the density of ordinary matter is 4% of the critical density.
- Density of matter appears to be like 30% of the critical density.
- Majority of mass in the Universe is extraordinary, such as WIMPs.

23.4 Inflation

Our goals for learning:

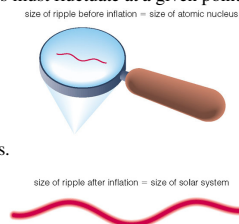
- What do we mean by "inflation" in the early Universe?
- What three questions were left unanswered by the Big Bang model prior to the time that inflation was included in the model?
- How does inflation answer the three questions?
- Is the overall density of the universe really equal to the critical density, as predicted by inflation?

Shortcomings of the Big Bang Model

- So far, we have considered the evidence which supports the Big Bang theory.
- Prior to 1980, cosmologists had identified three major questions which the theory was unable to answer:
 - Where does structure come from?
 - Why is the large-scale Universe so smooth?
 - Why is the density of matter almost critical?
- In 1981, physicist Alan Guth realized that the Grand Unified Theories could hold the answers to these questions.
- When the strong force froze out of the GUT force...
 - it should have released enough energy to expand the Universe 10^{30} times in less than 10^{-36} sec
 - we call this dramatic expansion **inflation**

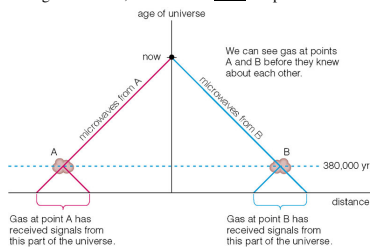
Where Does Structure Come from?

- The density of matter in the early Universe had to differ slightly from place to place.
 - otherwise, galaxies would never have formed
 - traditional Big Bang model does not tell what caused density enhancements
- Quantum Mechanics: energy fields must fluctuate at a given point.
- Energy distribution is irregular...
 - on microscopic spatial scales
- These quantum ripples would be greatly magnified by inflation.
- Large ripples in energy are the seeds for the density enhancements.
 - they imposed a pattern about which structure formed



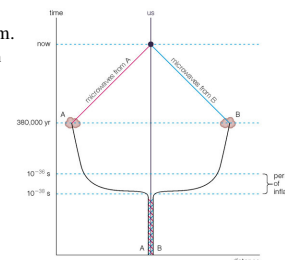
Why is the Large-Scale Universe so Smooth?

- In all directions, the Cosmic Microwave Background is uniform.
- Traditional Big Bang model can not explain...
 - how two disparate parts of the Universe, beyond each other's cosmological horizon, can have the same temperature



Why is the Large-Scale Universe so Smooth?

- Inflation can solve this problem.
 - the entire Universe was less than 10^{-38} light-second across
 - radiation signals could reach all points in the Universe
 - temperatures were equalized
 - then inflation expanded the Universe so quickly
 - that many points in the Universe went out of communication with each other

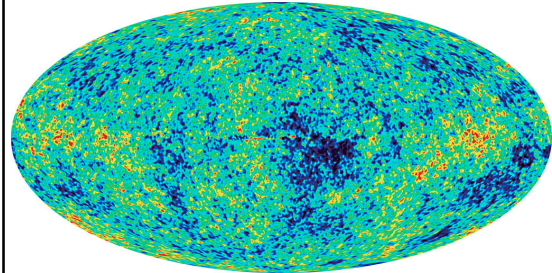


Why is the Density of Matter Almost Critical?

- The gravitational pull of the Universe almost balances the kinetic energy of its expansion... Why?
 - if matter were at least 10% denser, Universe would have already collapsed
 - if matter were at least 10% less dense, galaxies would have never formed
- According to General Relativity, an imbalance of these energies imposes a curvature of spacetime.
 - but when they balance, we say that spacetime is "flat"
- The effect of rapid inflation is to flatten spacetime.
 - thus, inflation imposed the balance of these energies

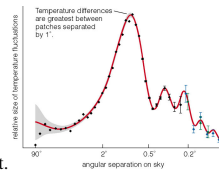
New Evidence for Inflation

- In 2002, the *Wilkinson Microwave Anisotropy Probe* (WMAP) measured the Cosmic Microwave Background with much more precision than COBE.
- It detected far more subtle, small-scale temperature variations.



New Evidence for Inflation

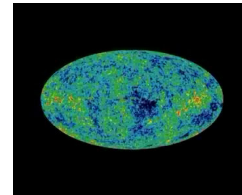
- A Big Bang model with inflation was fitted to:
 - temperature variations plotted as angular separation on the sky
 - the data are shown here →



- Overall geometry of the Universe is flat.
- Total matter density is 27% of the critical density.
 - in agreement with *M/L* in clusters of galaxies
- Density of baryonic (ordinary) matter is 4.4% of critical density.
 - in agreement with observed abundance of Deuterium
- Flat geometry + matter density < critical implies dark energy.
 - in agreement with accelerating expansion from white dwarf supernovae
- Age of the Universe is 13.7 billion years.

Evolution of a Universe

- Temperature variations in the 380,000 year-old Universe serve as a "genetic code" for the structure of the Universe today!



Movie. Click to launch.

23.5 Did the Big Bang Really Happen?

Our goals for learning:

- What is Olber's paradox?
- How does the Big Bang theory solve the paradox?

Olber's Paradox

- If the Universe is infinite and filled with stars, then why is the night sky **black**?
 - in every direction we look, we should eventually see a star
 - the sky should be ablaze with light
- This paradox can be solved with an expanding Universe.
 - Starlight gets redshifted out of the visible range
 - Since light travels at a finite speed, if the Universe had a beginning, then there would be a limit on the number of visible stars

What have we learned?

- How can we presume to understand the conditions that existed in the early universe?
 - By imagining running the expansion backward, we can use fundamental physical principles to predict the temperature and density of the universe at various times past. We can then study how matter behaves at various temperatures and densities with laboratory experiments, including experiments in particle accelerators. Today, we have experimental evidence telling us about conditions presumed to exist as early as one ten-billionth of a second after the Big Bang.

What have we learned?

- What was the universe made of during its earliest moments?
 - The early universe was filled with radiation and elementary particles. Because reactions involving matter and antimatter can turn matter into radiation and vice versa, matter and energy were continually converted back and forth during the first few moments, but the total amount of mass-energy remained the same.

What have we learned?

- Briefly describe the various eras of the universe since the Big Bang.
 - Plank era: The earliest time in the universe (10^{-43} seconds) when all four forces—gravity, electromagnetism, the strong force, and the weak force—are thought to have been indistinguishable. GUT era: the next moment in time, when gravity was distinct from the other three forces, which together formed the GUT force. At the end of this era, when the strong force became distinct, a period of inflation may have caused an enormous expansion of the universe. Electroweak era: Three forces — the strong force, the electroweak force, and gravity — operated until electromagnetism and the weak force became distinct. Particle era: the universe consisted of four distinct forces and elementary particles of both matter and antimatter. This era ended when all antimatter was annihilated at 0.001 second, leaving a tiny bit of matter and a huge amount of radiation...

What have we learned?

- Briefly describe the various eras of the universe since the Big Bang, cont'd.
 - ...Era of nucleosynthesis: During this three-minute era protons and neutrons fused to form deuterium and helium, producing about 75% hydrogen and 25% helium by mass. Era of nuclei: the era during the universe consisted of a plasma of free nuclei and electrons, during which photons bounced rapidly from one particle to the next. This era ended about 500,000 years after the Big Bang, when complete atoms formed for the first time and photons could stream freely through the universe. Era of atoms: The era in which the universe consisted of a mixture of neutral atoms and plasma, before galaxies formed. This era lasted about a billion years. Era of galaxies: The current era, in which galaxies are the most prominent structures in the universe.

What have we learned?

- What are the two key lines of evidence supporting the Big Bang model?
 - The Big Bang model predicts: (1) the existence and characteristics of the cosmic microwave background; and (2) the expected helium abundance in the cosmos. Both predictions agree with observations.
- What is the cosmic microwave background?
 - It is microwave radiation that comes from all directions in space and thus seems to be the radiation of the universe itself. Its spectrum matches the characteristics expected of the radiation released at the end of the era of nuclei, thereby providing spectacular confirmation of a key prediction of the Big Bang theory.

What have we learned?

- How does the Big Bang theory predict the helium abundance of the universe?
 - The theory predicts the temperature and density of the early universe, so we can use these conditions to predict when and how much hydrogen should have fused into helium. The prediction matches observations of the cosmic helium abundance.
- How does the cosmic deuterium abundance argue in favor of dark matter being made of WIMPs?
 - The deuterium abundance can be used to estimate the density of ordinary (baryonic) matter in the universe. Because this density turns out to be smaller than the overall matter density of the universe, we conclude that at least some — and probably most — of the matter in the universe must be extraordinary (nonbaryonic) matter such as WIMPs.

What have we learned?

- **What do we mean by “inflation” in the early universe?**
 - A dramatic growth in the size of the universe, thought to have been driven by energy released as the strong force froze out at the end of the GUT era. The universe is thought to have grown by a factor of 10^{30} in less than 10^{-36} second.
- **List three questions left unanswered by the Big Bang model prior to the time that inflation was included in the model.**
 - (1) Where does structure come from? (2) Why is the large-scale universe so smooth? (3) Why is the density of the universe almost the critical density?

What have we learned?

- **How does inflation answer the three questions?**
 - (1) Structure arises because the enormous growth of inflation stretches random quantum fluctuations into seeds for the density enhancements around which structure formed. (2) The universe is smooth on large scales because, prior to inflation, everything was close enough together for temperatures and densities to equalize. (3) The growth that occurred with inflation ensure that the universe is geometrically flat, with a matter density close to the critical density for most of its history.

What have we learned?

- **Is the overall density of the universe really equal to the critical density, as predicted by inflation?**
 - The density of matter in the universe appears to be well below the critical density (about 30% of the critical density). However, detailed studies of the cosmic microwave background suggest that the universe is indeed flat, as predicted by inflation. In that case, the remaining density needed to reach the critical density must exist in the universe in the form of energy — presumably as the mysterious energy driving the acceleration of the expansion of the universe.

What have we learned?

- **What is Olbers’ paradox?**
 - If the universe were infinite, unchanging, and filled with stars, the sky would everywhere be as bright as the surface as the Sun and it would not be dark at night. Kepler was probably the first person to notice this contradiction between belief in an infinite, unchanging universe and the darkness of the night sky. However, this paradox has come to be named after Heinrich Olbers, a later astronomer of the 1800s.
- **How does the Big Bang theory solve the paradox?**
 - The Big Bang theory tells us that the sky is dark at night because the universe changes with time: Because the universe has a finite age, we can see only a finite number stars in the sky, which is why the sky is not everywhere bright.

Can the spectrum of the cosmic microwave background be explained by being due to the combined light of many stars and galaxies?

- a. Yes, the red-shifted light from the very first stars and galaxies in the universe can explain the observations of the cosmic microwave background.
- b. Yes, but astronomers prefer the explanation that the cosmic microwave background resulted from the Big Bang.
- c. No, stars and galaxies have different temperatures and would not produce a perfect thermal spectrum at a single temperature as observed.
- d. No, the light from stars and galaxies would be much brighter than the cosmic microwave background.
- e. No, stars produce mainly optical, not microwave radiation.

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Why should it not be surprising that some galaxies contain little more than 25% helium, but it would be very surprising if some galaxies contained less.

- a. Because a star converts about 25% of its hydrogen into helium before it dies. Galaxies with multiple generations of star formation can have a higher percentage.
- b. Because the Big Bang fused 25% of normal matter in the universe into helium and stellar nucleosynthesis can increase, but not decrease, this amount.
- c. The helium fraction decreases with age so younger galaxies have more than 25%, but galaxies with less helium would be older than the estimated age of the universe.
- d. Helium is more massive than hydrogen so it cannot readily escape the gravitational field of a galaxy. A percentage lower than 25% would indicate that the galaxy had no dark matter.

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Although the universe today appears to be made mostly of matter and not antimatter, the Big Bang theory suggests that the early universe had nearly equal amounts of matter and antimatter.

- a. Yes, the Big Bang theory predicts that high temperatures in the early universe generated matter-antimatter pairs, and the amounts of each were therefore virtually equal.
- b. Yes, the Big Bang was started by the mutual annihilation of virtually equal numbers of matter and antimatter particles.
- c. No, the amount of matter and antimatter in the early universe should be exactly the same as it is today.
- d. No, the amount of matter and antimatter in the early universe should be in the same proportion as it is today.

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The theory of inflation suggests that the structure of the universe may have originated as tiny quantum fluctuations.

- a. Yes, tiny quantum fluctuations were stretched to enormous sizes by inflation and became large enough to grow into galaxies and galaxy clusters.
- b. Yes, quantum uncertainty meant that some regions of the universe expanded more slowly than other regions and these slower moving regions eventually became galaxies and galaxy clusters.
- c. No, the theory of inflation suggests that the structure of the universe arose when radiation decoupled from matter.
- d. No, quantum fluctuations are on an atomic scale and the structure of the universe is on the scale of galaxies.

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The fact that the night sky is dark tells us that the universe cannot be infinite, unchanging, and the same everywhere.

- a. Yes, the dark night sky shows that the Big Bang theory must be modified by allowing for an initial period of massive inflation.
- b. Yes, if the universe were infinite, unchanging, and the same everywhere, the night sky would be as bright as the surface as the Sun.
- c. No, the night sky is dark at optical wavelengths but is blazing at microwave wavelengths.
- d. No, the night sky is dark simply because the Sun is on the opposite side of the Earth!

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