Period 13 Solutions: Energy and Matter in the Universe

13.1 Origin of Matter in the Universe- the Big Bang

1) The Big Bang Theory and the Early Universe

a) How do scientists believe that the Universe began?

The big bang theory states that all of the energy now in the Universe was initially very hot and was condensed into an extremely small space.

b) In what form was the energy of the early Universe?

Early in the Universe, radiation, rather than matter, dominated. Energy and matter did not explode into empty space. Rather, space itself has expanded over time. Since the Big Bang, the Universe has expanded and cooled.

c) How much energy was contained in the initial Universe as compared to the amount of energy and energy that has condensed into matter in the Universe today?

The Law of Conservation of Energy tells us that the amount of matter and energy that exists today is the same as the amount of energy that was present at the beginning of the Universe.

d) Any source of radiation is characterized by a temperature.

i) What temperature characterizes radiation from the Sun? **6,000 Kelvin**

ii) What temperature characterizes radiation from the Earth? **300 K**

iii) What temperature is believed to have characterized the early Universe? **10^{32} K**

e) In our study of gases, we saw that the average energy and temperature of gases are related by the constant k. (k = 1.38×10^{-23} J/Kelvin or 8.62×10^{-5} eV/Kelvin). Use this relationship to find the average energy per photon in the early Universe in units of joules and in electron volts.

In the early Universe, where there was no matter, the average energy E of a photon was proportional to the amount of energy present.

$$E = 3\ k\,T = 3\ (1.38 \times 10^{-23}\ J/K) \times (10^{32}\ K) = 4.14 \times 10^{9}\ J$$

In terms of electron volts, this is

$$E = 3\ k\,T = 3\ (8.62 \times 10^{-5}\ eV/K) \times (10^{32}\ K) = 2.59 \times 10^{28}\ eV$$

f) Group Discussion Question: How does the energy of an early Universe photon compare to the energy of a visible light photon from the Sun?

2) The Expanding Universe

Following the Big Bang, the Universe began expanding. We will represent the expanding Universe with an inflating balloon.

a) Mark several large dots several centimeters apart on a deflated balloon. Blow up the balloon. If each dot represents a galaxy, what happens to the galaxies as the universe expands?

The galaxies move farther apart.

b) Consider the view of the Universe as seen by an observer on each galaxy. Do **all** the galaxies appear to be receding from the observer as the Universe expands? **Yes**

c) An elastic band attached to a board can illustrate the rate of expansion of the Universe. Initially the distance between marks on the unstretched elastic band is 1 inch. Stretch the elastic band until the 1 inch mark on the band lines up with the 2 inch mark on the ruler.

When the 1 inch mark on the band is stretched to 2 inches, how far has the 2 inch mark on the band stretched? **to the 4 inch mark on the ruler**

If this band represented the expansion of the Universe, how would the rate of expansion of distant galaxies compare to the rate of expansion of closer galaxies?

More distant objects appear to be moving away at a faster rate than closer objects.

d) The size of astronomical objects is measured in light years – the distance photons of light travel in one year. If the speed of a photon is 3×10^8 m/s, how many meters does a photon travel in one year?

S = D/t so D = S x t

D = 3×10^8 m/sec x (3,600 sec/hr x 24 hr/day x 365 days/yr)

D = 9.5×10^{15} meters/yr

e) Light from objects at the edge of the expanding Universe takes an estimated 13 billion years to reach the Earth. Approximately how many meters is this?

(9.5×10^{15} meters/yr) x (1.3×10^{10} yr) = 1.2×10^{26} meters

f) Group Discussion Question: The radius of the very early Universe is estimated to have been 10^{-35} meters. By how many factors of ten has the Universe expanded?

3) Formation of Matter in the Early Universe

a) What happens to the temperature of the Universe as it expands?

We know from our study of thermal energy that as a substance expands, it cools. As the Universe expands, it cools.

b) As the early Universe cooled, the first particles to form were quarks and antiquarks. With further cooling, these particles combined to form protons, neutrons, antiprotons, and antineutrons.

The rest mass of a proton is 938.3 MeV. To what temperature must the Universe have cooled for the conversion of energy into protons to stop?

E = 3 k T or T = E/3 k Convert 938.3 MeV to 938.3×10^6 eV

$T = 938.3 \times 10^6 \text{ eV} / 3 (8.62 \times 10^{-5} \text{ eV/K}) = 3.63 \times 10^{12}$ K

c) When the temperature of the Universe cooled further, protons and neutrons combined into nuclei of deuterium. If the binding energy of deuterium is 2.22 MeV, at what temperature did deuterium nuclei become stable?

$T = 2.22 \times 10^6 \text{ eV} / 3 (8.62 \times 10^{-5} \text{ eV/K}) = 8.58 \times 10^9$ K

d) How long did it take for the Universe to cool to this temperature?

Just several seconds

e) In the early Universe, both matter and antimatter where formed. When a proton and an antiproton collide, they are annihilated and their mass is converted into energy. What form did much of this energy take?

The annihilation of matter and antimatter resulted in the formation of photons.

4) Remnants of the Big Bang

a) What remnants of the Big Bang can we detect?

Can sound waves from the Big Bang be detected? **No** Why or why not?

Sound waves cannot travel through a vacuum, such as empty space. Sound waves must travel through a medium, such as air or water.

Can waves of electromagnetic radiation from the Big Bang be detected? **Yes** Why or why not?

Electromagnetic radiation can travel through a vacuum.

b) Visible light from a distant star be observed on Earth. Hold a small lens up to one of your eyes. Place a large lens in front of the small lens. Move the large lens away from your eye until objects in the room come into focus. How do the lenses change an image?

The lenses focus light reflected from an object. The object appears larger and upside down. These lenses act like a telescope.

c) Which forms of radiant energy from stars, in addition to visible light, are detected on Earth?

In addition to visible light, radiant energy from stars in the form of radio waves, microwaves, infrared radiation, ultraviolet light, X-rays, and gamma rays are detected on Earth.

d) What evidence of microwave radiation do we observe?

Microwave radiation of a wavelength corresponding to a temperature of 2.7 K can be observed uniformly in every direction. This cosmic microwave background radiation is a remnant of the photons created in the early Universe. The temperature of these photons has cooled from 10^{32} K to 2.7 K.

13.2 Formation of Galaxies

5) Clumping of matter into galaxies

a) At the time of the Big Bang, energy was distributed fairly uniformly in a very small volume. How is energy and matter distributed throughout the Universe today?

Matter has clumped into galaxies. Within galaxies, stars and planets have formed.

b) Which force caused matter to form clumps that became galaxies?

the gravitational force

c) Which force binds protons and electrons into atoms?

the electromagnetic force

d) Observe the demonstration of the hanging cans. Which force is stronger – the gravitational attraction or the electromagnetic attraction between the cans?

The electromagnetic force is much stronger than the gravitational force

e) Slowly pour "magic" sand from one beaker of water into a second beaker of water. What force causes the sand grains to clump together?

The electromagnetic attraction among the water molecules that coat the sand grains forces the sand grains into clumps. The gravitational force among the sand grains is too weak to force them into clumps. Because the electromagnetic force is so much stronger than the gravitational force, the concept of clumping can be demonstrated on a small scale using the electromagnetic force.

f) If the gravitational force is so weak, how can the gravitational force be responsible for binding matter into galaxies and stars?

Although the gravitational force is weak, the large amount of matter in stars and galaxies results in a large effect from the gravitational force.

13.3 Composition of Stars

6) Emission lines in the spectra of elements

a) Observe a tube of glowing gas through a diffraction grating. The lines you see are the emission lines of the photons of the gas. Draw the lines your see and indicate their colors.

Match these lines to the lines of an element on the spectral analysis chart. The first tube contains gas of which element? **hydrogen**

b) Observe a second tube of glowing gas and draw the lines your see.

Match these lines to the lines of an element on the spectral analysis chart. The second tube contains gas of which element? **helium**

c) Observe the glowing neon tube through a diffraction grating. What do you see?

The characteristic bright spectral emission lines of neon gas.

7) The chemical composition of stars

a) Observe the long filament bulb through a diffraction grating. The continuous spectrum represents the emissions from a hot object, such as a star.

What happens when you cover the diffraction grating with a blue filter?

The red photons are absorbed by the blue filter.

b) Gases in a star are very hot inside the star and cooler at the star's surface. Cool gases at the surface absorb the spectral lines characteristic of the elements within the star.

What would the spectrum of a star with hydrogen gas on its surface look like?

The bright spectral lines you would expect from hydrogen actually appear as dark absorption lines in a continuous spectrum. The hydrogen gas has absorbed its characteristic spectral lines from the continuous spectrum.

c) How can scientists tell which elements exist in a star?

By observing the absorption spectra of the star and matching the spectral line patterns to the known spectral line patterns of each element.

8) Energy source of stars

a) Which nuclear reaction is the basis of the energy of stars?

Nuclear fusion. Protons and neutrons fuse into helium.

b) What force provided the activation energy needed to begin nuclear fusion in a star?

The force of gravity exerts the greatest pressure on the matter at the center of a clump of matter. If the pressure there is great enough to raise the temperature of the matter to at least 15,000,000 K, nuclear fusion begins.

c) What holds the gas of a star into a spherical shape?

The outward radiation pressure of the hot gas is balanced by the inward force of gravity.

d) What happens to clumps of matter that do not reach an internal temperature high enough to begin fusion reactions?

Less massive gas clouds are bound together by a weaker force of gravity. If this gravitational force does not result in enough thermal energy in the core of the clump to begin nuclear fusion reactions, the clump may become a planet.

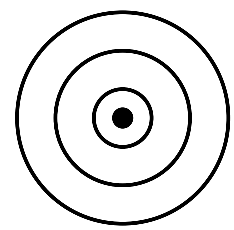
13.4 The Universe Today

9) Doppler Shift and the Expanding Universe

Your instructor will discuss the Doppler shift of light waves from a moving source.

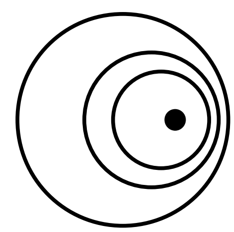
a) A stationery light source emits waves of light uniformly in all directions as shown in the diagram. How do the wavelengths of light from the right side of the diagram compare to the wavelengths of light from the left side?

The waves are the same length.



spread of waves over time

b) The same light source now moves to the right as shown in the diagram. Although the light source still emits waves uniformly in all directions, motion of the source means that the wavelengths are no longer evenly spaced. How do the wavelengths of light when viewed from the right side of the diagram compare to the wavelengths of light when viewed from the left side?



If the motion of the light source is to the right, the space between waves is reduced on the right side (the wavelengths are shorter) and the space between waves on the left side is increased (the wavelengths are longer).

c) What happens to the color of the light waves on the right side of the diagram? What happens to the color of the light waves on the left side of the diagram?

The shorter wavelengths on the right side of the light source shift the light waves to the blue end of the visible light spectrum. The longer wavelengths on the left side of the light source shift the light waves to the red end of the spectrum.

d) What information about a galaxy's motion could this change in wavelength provide?

From the change in color due to Doppler shift, the rotation speed of the parts of a galaxy can be calculated.

e) Galaxies are observed to rotate. Why would rotating matter tend to form a flattened disk?

Rotating gas clouds collapse into disk-like shapes because of gravitational attraction between molecules.

f) Based on our experience with the solar system, which portion of a rotating galaxy would you expect to rotate faster – matter closer to the galaxy center or matter toward the galaxy edge?

We would expect matter closer to the center to rotate faster.

g) In fact, the stars near the edges of a spiral galaxy rotate in tandem with the stars near the center. How can a galaxy that appears to contain much empty space act more like a solid disk than like the solar system?

It is believed that the matter telescopes can detect makes up less than 4% of the total mass of the Universe. This missing mass is known as dark matter because it is invisible to us.

10) The Hubble Constant and the Age of the Universe

Next, we consider supernovae and galaxies throughout the Universe.

a) Light from supernovae stars appears reddened as observed from the Earth. What does that indicate about the motion of the stars?

Red shifted star light indicates that the galaxy containing the star is receding from the Earth. This is evidence that the Universe is expanding.

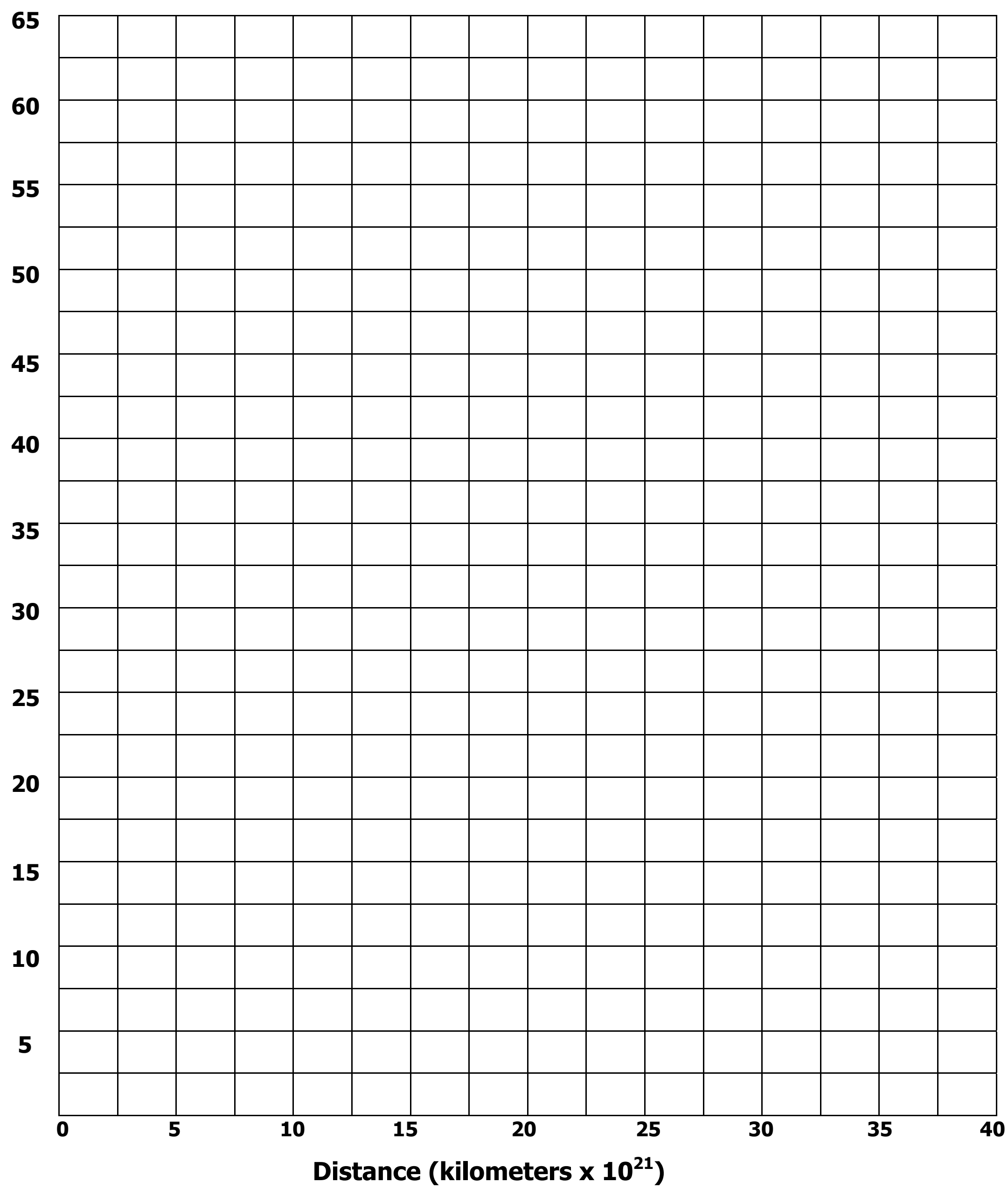
b) Light from stars further from the Earth appears more reddened than light from stars nearer to the Earth. What does this indicate about the rate of expansion of the Universe?

A greater red shift of light from more distant stars indicates that the further a star is from any point in the Universe, the faster the star is moving away from that point.

c) The data shows the velocity at which four stars in galaxies appear to be receding when viewed from the Earth and the distance of these galaxies from Earth.

Galaxy cluster in	Recessional velocity (thousands of km/sec)	Distance (km x 10^{21})
Ursa Major	15.0	9.41
Corona Borealis	21.6	13.7
Bootes	39.3	26.0
Hydra	61.2	37.6

d) Plot the recessional velocity versus distance on the grid below.



e) Find the slope of your graph. The slope of this graph is known as the Hubble constant (H_O).

slope = 1.6 x 10^{-18} 1/s

f) Estimate the age of the Universe by calculating the inverse of the Hubble constant, $1/H_O$.

$1/H_O$. = 1/(1.6 x 10^{-18} 1/s) = 6.25 x 10^{17} seconds

g) Convert your answer into years.

6.25 x 10^{17} sec x (1hr/3,600 sec) x (1 day/24 hrs) x (1 yr/365 days)

= 1.98 x 10^{10} years

h) How does your value for the age of the Universe compare to Hubble's own value of 19.6 billion years?

i) The actual age of the Universe is estimated by other means at 13.7 billion years. What could account for the difference in values?

Our calculation assumes that the Universe has always expanded at the same rate. One possible explanation for the difference in age estimates is that the rate of expansion of the Universe has slowed over time.