Preview of Period 13: Astrophysics

13.1 What is the origin of matter?

How did matter form following the Big Bang?

13.2 How did galaxies form?

Why did matter clump together into galaxies?

13.3 What is composition of stars?

How can the chemical composition of stars be determined?

13.4 What is the age of the Universe?

What is the Hubble constant? How can it be used to estimate the age of the Universe?

Energy in the Early Universe

- Energy in the early Universe was in the form of radiation, rather than matter.
- As in the case of gases, the energy content of the radiation is proportional to its temperature.
- The temperature of the early Universe is estimated to have been 10^{32} kelvin
- The energy per photon can be found from

$$E = 3\,k\,T$$

with

E = energy (in joules or electron volts eV)

k = Boltzman's constant $= 1.38 \times 10^{-23}$ J/K (or 8.62×10^{-5} eV/K)

T = temperature (in kelvin)

Temperature of Stable Particles

Over time, the Universe expanded and cooled.

To calculate the temperature at the time of formation of a particular type of particle,

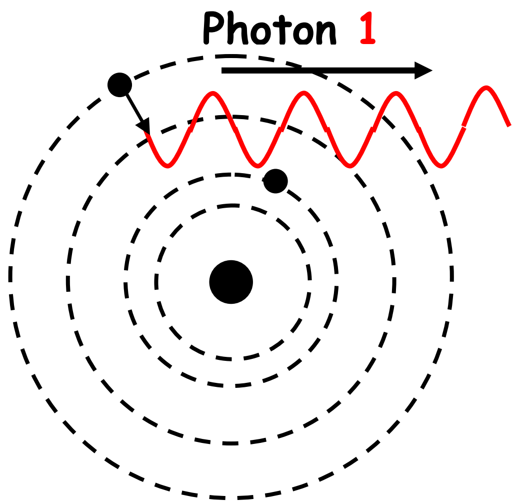
1) Convert the particle's restmass from megaelectron volts (MeV) into electron volts (eV)

   $(1 \text{ MeV} = 1 \times 10^6 \text{ eV})$

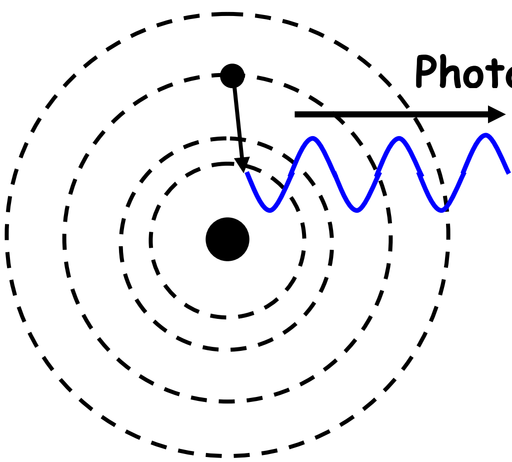
2) Solve $E = 3\,kT$ for T.

   Since the restmass is given in electron volts, use $k = 8.62 \times 10^{-5}$ eV/K.

Photon Emission



An electron drops one energy level and emits a photon of visible light.



Another electron drops two energy levels and emits a more energetic photon of visible light.

Emission spectra are bright lines light from the photons emitted by nuclei.

Each chemical element has a characteristic pattern of spectral emission lines.

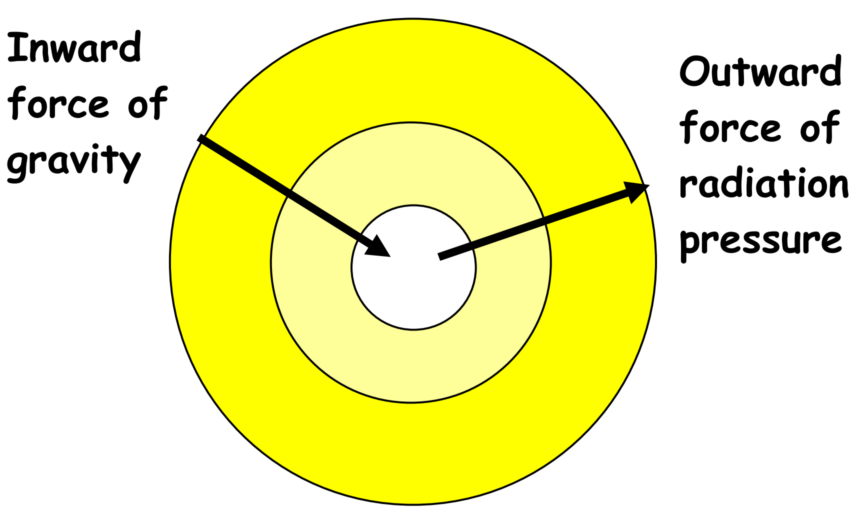
What Holds a Star in a Spherical Shape?

The gravitational force exerts an inward pressure on the core of the star.

If the pressure from the gravitational force is great enough to raise the temperature of the matter in the core to at least 15,000,000 K, nuclear fusion begins.

Thermal energy from the core is transferred out to the star surface, which produces radiation pressure.

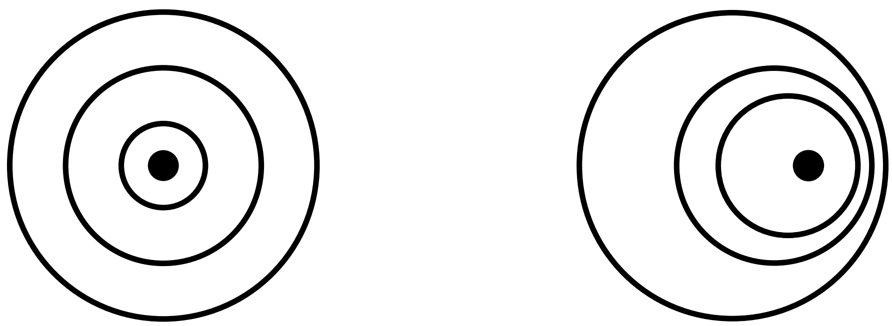
In a stable star, the outward radiation pressure of the hot gas is balanced by the inward force of gravity.



Doppler Shift of Waves from a Moving Source

A stationery light source emits waves of light uniformly in all directions.

If the same light source moves to the right, the motion of the source means that the wavelengths are no longer evenly spaced.



Spread of waves over time

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).

> 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.

The Hubble Constant

The Hubble constant (H_o) is the amount of redshift of light from a galaxy per distance of the galaxy.

The constant can be estimated from the slope of a graph of redshift versus distance of a galaxy.

The inverse of the Hubble constant, ($1/H_o$) gives an estimate of the age of the Universe in seconds.

This method of estimating the age of the Universe assumes that the Universe has expanded at a constant rate.

Einstein's Theory of General Relativity

- **Light travels between points in the Universe as if the points were each on a flat surface.**
- **Einstein's general theory of relativity predicts that gravity bends the flat-line paths of the Universe, and the motion of particles is along these warped paths.**
- **The gravitational attraction of a star bends light passing near the star and changes the orbits or planets about the star.**
- **The cosmological constant is a term in the equation describing the law of general relativity. A value other than zero for this constant implies that the Universe has a center.**
- **If the constant is given the correct sign and size, general relativity can correctly predict a Universe that is expanding at an ever faster rate.**

Period 13 Summary

13.1 Origin and evolution of the Universe

Scientists believe that the Universe began with a tremendous explosion called the Big Bang. The universe was initially incredibly hot and condensed into an extremely small space. Since the Big Bang, the Universe has expanded and cooled.

The equation for black-body radiation, $E = 3\ kT$, describes the average energy of photons in the Universe.

The condensation of the gravitational force occurred as early as 10^{-43} seconds after the Big Bang. Energy going into the gravitational force took energy away from the photons. The less energetic photons had a lower average temperature, and the cooling process of the Universe began.

Between 10^{-43} and 10^{-35} seconds after the Big Bang, quarks and leptons began to condense.

The temperature of the Universe dropped to about 10^{27}K and the average energy of photons dropped to 10^{16} GeV, allowing the condensation of the strong nuclear force, the weak nuclear force, and the electromagnetic force.

13.1 Origin and evolution of the Universe, Continued

With quarks, antiquarks, and gluons in existence and the force between quarks or antiquarks so strong, quarks condensed into hadrons and antihadrons. Hadrons and antihadrons are any particles held together by gluons (the strong nuclear force).

At this point, the Universe underwent a tremendous expansion, increasing from a diameter of 1 cm to as much as 10^{45} kilometers in as little as 10^{-34} seconds. This expansion cooled the Universe and overshadowed the huge amount of binding energy released by the formation of hadrons.

Following the sudden expansion of the Universe, expansion and cooling continued to about 10^{13} K, or an average energy of about 1 GeV. The process of nucleon-antinucleon formation continued. Over time, a preponderance of matter over antimatter occurred.

Leptons interact only by means of the weak force and the electromagnetic force. The weak force is not sufficiently strong to bind leptons together, so only electron-antielectron annihilations took place at this time.

13.1 Origin and evolution of the Universe, Continued

The lepton era saw the stabilization of the number of electrons. At this point the Universe was still only a few seconds old!

By this time, the Universe had cooled to 10^9 K, the temperature at which protons and neutrons could combine into nuclei of deuterium (one proton plus one neutron).

Two deuterium nuclei can fuse into one helium nucleus ($^4_2\mathrm{He}$).

As the Universe continued to expand and cool, collisions between protons were too weak to overcome their electrical repulsion, and fusion ceased. Most of the total helium in the Universe was formed in the first half hour of its existence.

After 400,000 years, photons had cooled to a mean temperature of 3000 K and no longer could ionize atoms. These photons continued to cool and drift throughout space and formed the cosmic microwave background radiation (CMB), with a mean temperature now of only 2.7 Kelvin.

13.2 Formation of Galaxies and Stars

Over time, matter in the Universe accreted into clumps due to fluctuations in the cosmic microwave background radiation.

Gravitational forces among particles bound matter together into galaxies and stars.

Slowly-spinning giant gas clouds composed primarily of molecular hydrogen (H_2) collapsed into disk shapes. Some giant molecular clouds broke up into smaller clouds that collapsed into disks, creating binary (double) stars and star clusters.

During the collapse of matter into a star, gravitational potential energy is converted into particle kinetic energy. The core density and temperature rise until nuclear fusion is initiated and a star is born.

Five billion years ago, one such core in one gas cloud collapsed to become our Sun and its solar system.

13.2 Formation of Galaxies and Stars, continued

After fusion starts in a star, the collapse of matter slows and eventually ceases when outward radiation pressure from nuclear fusion balances inward pressure due to gravitational attraction.

The intense pressure at the center of a rotating disk of matter causes the disk to have a dense and hot gas core. In the centers of galaxies this intense pressure is believed to create a black hole. The gravitational force in a black hole is so great that matter entering the hole cannot escape.

Spiral galaxies rotate as if they were more like a solid spinning disk than like a solar system. Scientists believe this is due to undetected mass in galaxies, known as dark energy.

Possible explanations for this missing matter are mass-energy that has not coalesced into the form of particles, particles that give off no detectable radiant energy, particles that give off radiant energy that is being absorbed by something, or very many neutrinos.

13.4 Estimating Distances to Galaxies and Stars

Distances to shining objects are given in light years, LY (1 LY = 9.46 X 10^{12} kilometers) or in parsecs, pc (1 parsec = 3.26 LY or 1 LY = 0.307 pc).

For close stars, distances can be measured using parallax by observing the apparent motion of a star against the background sky at two different times.

Distance to a star can be calculated by comparing its apparent intensity (the amount of light energy per square meter per second that reaches the Earth) to the star's intrinsic luminosity (total light per second given off).

The apparent brightness of Cepheid variable stars give a good distance measure since the apparent brightness of Cepheids is the inverse of their period of light-intensity oscillation; the longer the period, the brighter the star.

Type Ia supernovae, the explosion of white dwarf stars that had been part of a binary star system, give good distance measurements because all Type Ia supernovae have very nearly the same luminosity.

13.5 Info about the Universe from Galaxies and Stars

An absorption spectrum has dark lines missing in the continuous spectrum where light from a star has been absorbed by cool gas forming the outer layer of the star.

Light from stars exhibits dark line absorption spectra characteristic of the elements in the stars, but with lines Doppler red shifted toward longer wavelengths.

Doppler shift is the change in the frequency of waves from a moving source.

If the light source moves toward the observer, the space between waves is reduced (the wavelengths are shortened). Light is shifted toward the blue end of the visible spectrum.

Light from a receding source has longer wavelengths, and the light is shifted to the red end of the spectrum.

$$\text{redshift} = Z = (L_{obs} - L_{rest})/L_{rest}$$

The redshift of distance stars and galaxies shows they are moving away from the Earth at an appreciable fraction of the speed of light. The more distant the star or galaxy, the faster the motion away from Earth.

13.6 Hubble Constant and the Age of the Universe

The Hubble constant (H) is the slope of a graph of redshift versus distance of galaxies.

The inverse of Hubble's constant, 1/H, times a factor of 2/3 estimates the age of the Universe at 13 billion years.

13.7 Einstein's Theory of General Relativity

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Einstein's general theory of relativity predicts that gravity bends the flat-line paths of the Universe, and the motion of particles is along these warped paths.

The gravitational attraction of a star bends light passing near the star and changes the orbits or planets about the star.

The cosmological constant is a term in the equation describing the law of general relativity. A value other than zero for this constant implies that the Universe has a center.

If the constant is given the correct sign and size, general relativity can correctly predict a Universe that is expanding at an ever faster rate.

Period 13 Review Questions

R.1 **Arrange the following events in the early Universe in chronological order starting with the earliest event:**

1. **sudden expansion of the Universe**
2. **condensation of quarks and leptons**
3. **condensation of the strong, weak, and electromagnetic forces**
4. **fusion reactions of helium**
5. **the Big Bang**
6. **condensation of the gravitational force**
7. **formation of photons**

R.2 **What are three methods of measuring the distance to stars and galaxies?**

R.3 **What is Doppler shift? Give some common examples of Doppler shift.**

R.4 **What is the Hubble constant? How can it be calculated? What can it tell us about the Universe?**

R.5 **What is the cosmological constant? What can it tell us about the Universe?**