Contents of Chapter 33

- Stars and Galaxies
- Stellar Evolution: Birth and Death of Stars, Nucleosynthesis
- Distance Measurements
- General Relativity: Gravity and the Curvature of Space
- The Expanding Universe: Redshift and Hubble’s Law
- The Big Bang and the Cosmic Microwave Background
Contents of Chapter 33

• The Standard Cosmological Model: the Early History of the Universe
• Inflation: Explaining Flatness, Uniformity, and Structure
• Dark Matter and Dark Energy
• Large-Scale Structure of the Universe
• Finally…
33-1 Stars and Galaxies

The universe is vast; we define new units to make distances easier to measure.

A light-year (ly) is the distance light travels in a year:

\[
1 \text{ ly} = (2.998 \times 10^8 \text{ m/s})(3.156 \times 10^7 \text{ s/yr})
\]

\[
= 9.46 \times 10^{15} \text{ m} \approx 10^{13} \text{ km}
\]

Pluto is about \(6 \times 10^{-4}\) ly from us. The next nearest star is 4.3 ly away. (Proxima Centauri)

Earth-Sun: 8.3 light-minutes, Earth-Moon: 1.28 light-sec
33-1 Stars and Galaxies

On a dark moonless night, a band of stars can be seen traversing the sky. Ancients called it the Milky Way; we now know that it is our view of our galaxy.
33-1 Stars and Galaxies

We still call our galaxy the Milky Way; it is a spiral galaxy, disc-shaped with spiral arms.

It is about 100,000 ly in diameter and about 2000 ly thick, and contains some 100 billion stars.
These two drawings show what our galaxy would look like from the outside; the photograph was taken in the infrared.
• 400 billion stars
• Sun’s orbit: 250 million years, 200km/s
Many faint cloudy patches can be seen in the sky, some with the naked eye and some with simple telescopes. They are of several types:

Star clusters—large groups of stars within our galaxy

Nebulae—glowing clouds of gas and dust

Galaxies—other than our own, at varying distances from us
33-1 Stars and Galaxies

The next nearest galaxy, Andromeda, is some 2 million light-years away.

It is estimated that there are about as many galaxies in the universe as there are stars in our own galaxy—100 billion or so.

Many galaxies occur in gravitationally bound clusters, some of which have only a few galaxies and others of which have thousands.
This table gives some idea of the vast distances between objects in the universe.

<table>
<thead>
<tr>
<th>Table 33–1 Astronomical Distances</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Object</strong></td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Moon</td>
</tr>
<tr>
<td>Sun</td>
</tr>
<tr>
<td>Size of solar system (distance to Pluto)</td>
</tr>
<tr>
<td>Nearest star (Proxima Centauri)</td>
</tr>
<tr>
<td>Center of our Galaxy</td>
</tr>
<tr>
<td>Nearest large galaxy</td>
</tr>
<tr>
<td>Farthest galaxies</td>
</tr>
</tbody>
</table>
The absolute luminosity, $L$, of a star is the power it radiates, in watts.

The apparent brightness, $b$, is the power per unit area at the Earth, a distance $d$ away.

They are related:

$$b = \frac{L}{4\pi d^2}. \quad (33-1)$$
More massive stars are also more luminous. The surface temperature of a star can be measured from its spectrum; surface temperatures range from about 3500 K to 50,000 K.
An especially useful way of comparing stars is the Hertzsprung-Russell (H-R) diagram, which plots absolute luminosity vs. temperature.
Most stars fall along the main sequence line in the H-R diagram. There are also some outliers:

Red giants, with low temperature and high luminosity

White dwarfs, with high temperature and low luminosity
Wein’s Law

• Temperature, \( T = \frac{2.9 \times 10^{-3}}{\lambda} \)
Stellar evolution cannot be observed directly, but can be inferred from observations of stars at different points in their lifetimes:

• Star formation begins when interstellar cloud of gas and dust begins to contract

• As it contracts, mass collects in the center and begins to heat up

• When the core is hot enough, about $10^7$ K, hydrogen fusion begins
For a sun-like star, time from beginning to stable fusion is about 30 million years; stable fusion (during which star is on Main Sequence) continues for about 10 billion years.

- Eventually core is mostly helium; outer layers of star once again begin to collapse and heat.
Eventually, next layer of hydrogen becomes hot enough for fusion
• Hotter still and the helium can fuse to carbon; this is as far as a Sun-like star gets.

• Carbon core again collapses and heats; outer layers of star expand and are ejected

• Star is now a white dwarf

• More massive stars will fuse elements up to iron, then collapse in a supernova to a neutron star or black hole
Novae and supernovae are violent eruptions; besides the massive-star supernova, a nova or supernova can occur in a binary star system.

This example would result in a nova; if there were a neutron star instead of the white dwarf it would be a supernova:
Space is curved around massive objects:
In the extreme limit, a black hole is formed—the curvature is so strong that even light cannot escape if it gets too close.

“Too close” means inside the Schwarzschild radius:

\[ R = \frac{2GM}{c^2}, \]
The expansion of the universe was proposed to explain the correlation between distance and recessional velocity for distant galaxies.

The recessional velocity causes spectra to be shifted to longer wavelengths, due to the Doppler effect:

\[
\lambda_{\text{obs}} = \lambda_{\text{rest}} \sqrt{\frac{1 + v/c}{1 - v/c}}, \quad \text{[source and observer moving away from each other]} \tag{33-3}
\]
Hubble’s law relates the recessional velocity to the distance:

\[ v = H_0 d. \]  (33-4)

The constant \( H_0 \) is called the Hubble constant, and is measured experimentally.

\[ H_0 = 67 \text{ km/s/Mpc} \]

(One parsec is the distance at which one astronomical unit subtends an angle of one arcsecond. A parsec is equal to about 3.26 light-years (31 trillion kilometres or 19 trillion miles) in length.)
If all galaxies are moving away from us, are we at the center of the expansion?

No—think of the surface of an expanding balloon. Every point on the surface is moving away from every other point; there is no center.

The age of the universe can be calculated by the Hubble constant:

\[ t = \frac{d}{v} = \frac{d}{H_0 d} = \frac{1}{H_0} \approx \frac{(10^6 \text{ ly})(0.95 \times 10^{13} \text{ km/ly})}{(21 \text{ km/s})(3.16 \times 10^7 \text{ s/yr})} \approx 14 \times 10^9 \text{ yr}, \]
The Big Bang and the Cosmic Microwave Background

Projecting universal expansion backwards—universe must have been very tiny at the beginning.

Big Bang—not an explosion, but an expansion of spacetime itself.

Cosmic microwave background radiation—comes from every direction, has spectrum of black-body radiation with a temperature of 2.725 K.
This background radiation has been mapped in great detail, and is very strong evidence in support of the Big Bang.
This is the outline of the beginning of the universe, as we currently understand it:
The four physical forces were initially a single force. This symmetry was broken as the universe expanded and cooled. This figure shows the time and temperature of the universe when the forces separated from each other.
33-7 The Standard Cosmological Model: the Early History of the Universe

- Before $10^{-43}$ s, all four forces were unified, in a way we don’t understand.
- Grand unified era—no distinction between quarks and leptons.
- Around $10^{-35}$ s the strong force separates from the others.
- Hadron era—lepton-quark soup at first, the quarks become confined.
- Inflation.
Around $10^{-6}$ s most hadrons have disappeared; once average kinetic energy dropped below nucleon mass, nucleon creation stopped, leaving a slight excess of matter over antimatter.

Once the kinetic energy was below the pion mass, no more hadrons could be formed.

This happened around $10^{-4}$ s, beginning the lepton era.
After about 10 s electron-positron pairs could no longer be formed.

This begins the radiation era; universe consists mostly of photons and neutrinos, and is opaque.

At about 3 minutes, nuclear fusion begins, creating deuterium, helium, and some lithium.

After about 380,000 years the photons decouple from matter—the universe is now transparent.
33-7 The Standard Cosmological Model: the Early History of the Universe

- The cosmic background radiation is these photons, cooled through further expansion
- At 200 million years, stars begin to form
- Galaxies begin to form around 1 billion years
Percentages of the Major Components of the Universe

- Dark energy: 72.2%
- Dark matter: 23.2%
- Normal matter: 4.5%
- Electromagnetic radiation: 0.005%
- Neutrinos: 0.10%
- Other: 4.6%
It has been known for some time, by studying galactic rotation curves and gravitational lensing, that more matter must be present than can be seen. This dark matter is now thought to make up about 23% of the total density.

More recently, astronomers were surprised to discover that the expansion of the universe is accelerating. This cannot be explained by any known force.

What is causing the acceleration is not known; generically this is referred to as dark energy.
33-9 Dark Matter and Dark Energy

This dark energy is found to contribute 73% to the density, bringing it to the critical density.

To summarize, the universe’s mass-energy comes from:

Dark energy, 73%

Matter, 27%, which is

23% dark matter

4% ordinary matter
Summary of Chapter 33

• Milky Way is our galaxy; disc-shaped, contains 100 billion stars
• Astronomical distances are measured in light-years
• Stars begin as collapsing dust clouds; they contract and heat
• Hydrogen fusion begins; some heavier elements are formed
• Star is stable—on Main Sequence
Summary of Chapter 33

• When core is exhausted, star expands and cools while core contracts and heats
• Solar-mass star becomes white dwarf
• More massive stars explode as supernovae, leaving neutron star or black hole behind
• Equivalence principle—gravitational field and acceleration are indistinguishable
• Gravity is a curvature of spacetime
Summary of Chapter 33

- Distant galaxies are redshifted, due to Doppler effect of recession velocity
- Universe is expanding, and is about 13.7 billion years old
- Created in Big Bang
- Cosmic microwave background radiation is remnant of Big Bang
- Standard Big Bang model has universe beginning as very hot and dense; as it expands it cools, and various reactions cease to occur
Summary of Chapter 33

• Hydrogen, deuterium, helium, and a tiny amount of lithium are created as universe cools

• Once atoms could form, stars and galaxies became possible

• Must be more than visible matter to account for observed motions—dark matter

• Expansion of universe is accelerating—dark energy

• Dark energy, dark matter, and ordinary matter combine to give universe critical density