7.2 Cosmology

Cosmology is the study of the entire universe, its origin and future. Many cultures and religions provide their own answers to the questions such as 'Where did the universe come from?' and 'How will the universe end?' The answers given by scientists must match observable evidence such as the composition and structure of the universe around us.

Galaxies

Our modern understanding of the structure of the universe began with the Ancient Greek philosopher Democritus. In the fourth century BCE, he suggested that the **Milky Way** could be made up of many distant stars. This idea was rejected by other philosophers of his time, who believed the Milky Way was an atmospheric phenomenon. It was not until the 17th century CE, when the astronomer Galileo Gallilei turned his newly invented telescope onto the Milky Way, that Democritus' theory was confirmed.

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Astronomers now know that the Milky Way is just one of billions of galaxies in the observable universe. Some of the shapes galaxies can take are shown in Figure 7.2.1. This has caused scientists to dramatically reassess our understanding of the size of the universe. The Milky Way is estimated to contain between 200 and 400 billion stars and be about 100 000 light-years across. The Canis Major Dwarf galaxy is the closest galaxy to us and 25 000 light-years away from the Milky Way. Only four galaxies are closer than 2 million light-years away. Most galaxies are many millions of light-years away. Recent estimates put the number of observable galaxies at around 500 billion. This makes the universe unimaginably large.

Measuring distances to galaxies

The distances to other galaxies are far too big to be measured by parallax methods. One of the best techniques for measuring the distance to another galaxy uses a special type of star known as a Cepheid variable. A Cepheid is a type of star that has variable brightness—over a certain period of time, it changes from bright to dark and back to bright again (Figure 7.2.2). The period of this variation is directly related to the absolute magnitude of the star.

To measure the distance to another galaxy, an astronomer must first identify a Cepheid variable inside the galaxy. Then, by measuring the period of variation of the Cepheid, the absolute magnitude of the star can be determined. By comparing this to the star's apparent magnitude, the distance to the star (and the galaxy that contains it) can be calculated.

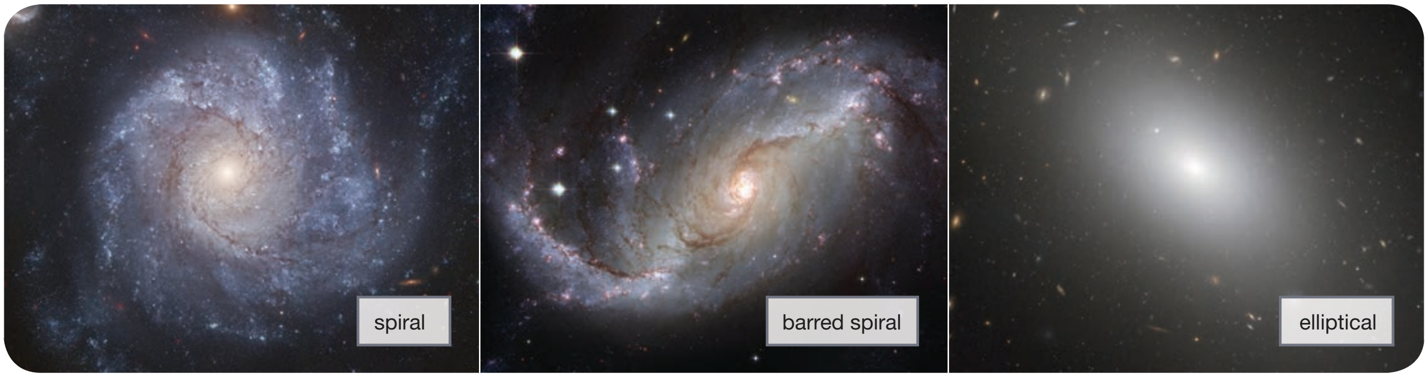

Figure 7.2.1 Galaxies can take various shapes including spiral, barred spiral and elliptical.

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Figure 7.2.2 This series of images shows the change in brightness of a Cepheid variable over a period of almost 40 days. (The variable star is in the centre of each frame.)

Steady state model

Fifty years ago, the most popular cosmological model was the **steady state** or infinite universe theory. This theory suggested that the universe is infinite in extent and has always existed in roughly the same form as observed today. This theory matches the fact that galaxies seem to be spread relatively evenly across the sky, as shown in Figure 7.2.3. This theory was expressed in its most complete form by English astrophysicist Sir Fred Hoyle in 1948 (Figure 7.2.4 on page 232). Although it enjoyed great favour through the 1950s and early 1960s, by the 1970s most scientists had rejected it.

Figure 7.2.3 Galaxies appear to be relatively evenly distributed throughout space. This was used as evidence of a steady state universe.

Big Bang

The term *Big Bang* was actually first used by Fred Hoyle, a key defender of the steady state theory. He meant it negatively, as term of ridicule, but the name caught the imagination of the public and has been linked closely with cosmology ever since.

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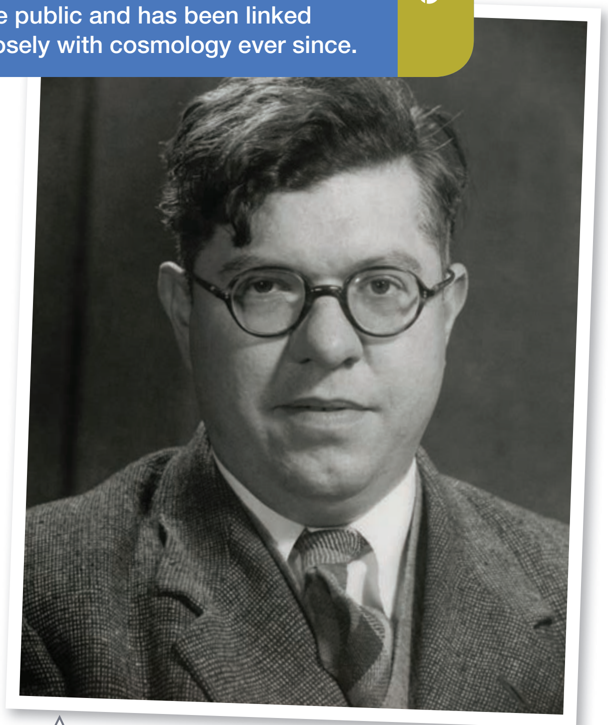

Figure 7.2.4 Astrophysicist Sir Fred Hoyle

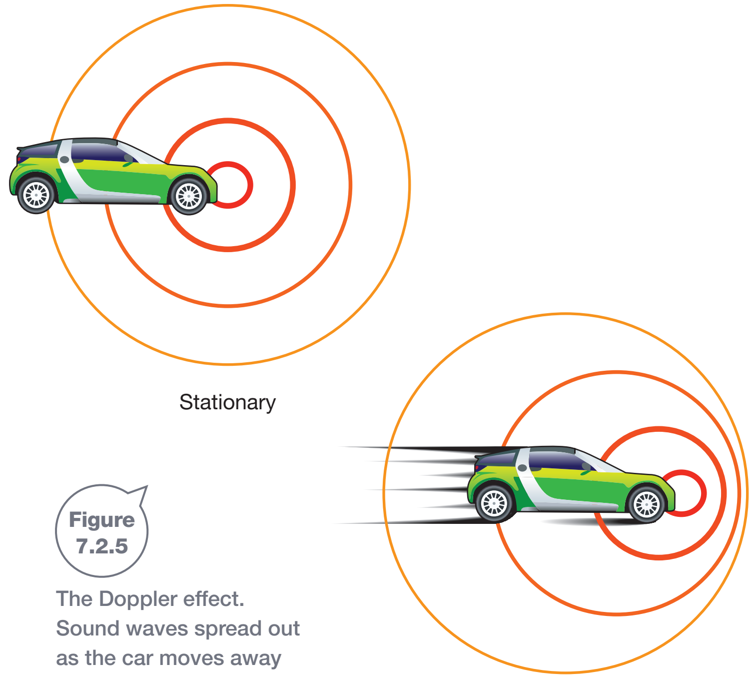

Figure 7.2.5 The Doppler effect. Sound waves spread out as the car moves away and bunch together as the car gets closer.

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Cosmological red-shift

Cosmological red-shift is *not* caused by the Doppler effect since light waves do not travel through a medium as sound waves do through air. The expansion of the universe should not be visualised as stars expanding out into empty space. Instead, it is the space between stars that expands. It is the expansion of space itself that causes electromagnetic radiation to be stretched and, therefore, red-shifted.

Big Bang theory

Red-shift

The first evidence to undermine the steady state model was American astronomer Edwin Hubble's discovery that the universe is expanding. Hubble used Cepheid variables to measure the distance to a number of galaxies. He then carefully observed the spectrum of light from these galaxies and discovered that, in almost every case, it was distorted in a manner known as **red-shift**. This means that wavelengths of the light rays were all lengthened slightly, making the light appear redder than it should.

Red-shift is similar to a phenomenon known as the **Doppler effect**, in which waves produced by a moving source are either lengthened or shortened due to the motion of the source.

Consider the stationary car in Figure 7.2.5. As it is not moving, the sound waves produced by the engine extend out in all directions. Now consider the moving car. For an observer in front of the car, the sound waves produced by the engine will be compressed by the motion of the car. This means that the wavelength of the waves will be shorter than usual and the engine will sound as though it has a higher pitch. However, for an observer behind the car, the sound waves will be lengthened and the engine's pitch will sound lower and deeper.

A similar effect can be observed with light waves emitted by stars and nearby galaxies. Light from stars moving towards us will be compressed (**blue-shifted**). Light from stars moving away from us will be shifted towards the red end of the spectrum.

Hubble's measurement of the red-shift of light from distant galaxies contained two important observations:

- Almost all galaxies in the universe are moving away from the Milky Way galaxy.
- The further away a galaxy is, the more its light is red-shifted. This means that the more distant galaxies are moving away from the Milky Way faster than the closer galaxies are.

Taken together, these observations suggested that the universe is expanding.

This conclusion has important implications. If the universe is expanding, then it is reasonable to assume that at some point all the matter in the universe was condensed into one point. This represents the birth of the universe, the moment of an enormous explosion of energy now known as the 'Big Bang'.

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Einstein's big mistake

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When Albert Einstein was working on his theory of general relativity, he realised that it suggested that the universe was expanding. He disliked the idea of an expanding universe so much that he added a 'cosmological constant' to his theory to ensure that it matched the steady state model. Einstein later described this as the 'biggest blunder' (mistake) of his life.

Cosmic microwave background radiation

In 1965, two American astronomers, Arno Penzias and Robert Wilson, were trying to study radio signals from the Milky Way. They kept finding an annoying background signal coming from all directions in the sky that interfered with their measurements. By chance, they called a cosmologist, Bob Dicke, who realised that this background signal was the 'afterglow' of the Big Bang. It was radiation emitted approximately 400 000 years after the Big Bang.

This afterglow is now known as the **cosmic microwave background radiation**. You can see an image of the cosmic background radiation in Figure 7.2.6. It is consistent with predictions that radiation from the early universe should have been red-shifted into the microwave part of the spectrum by the expansion of the universe since the Big Bang.

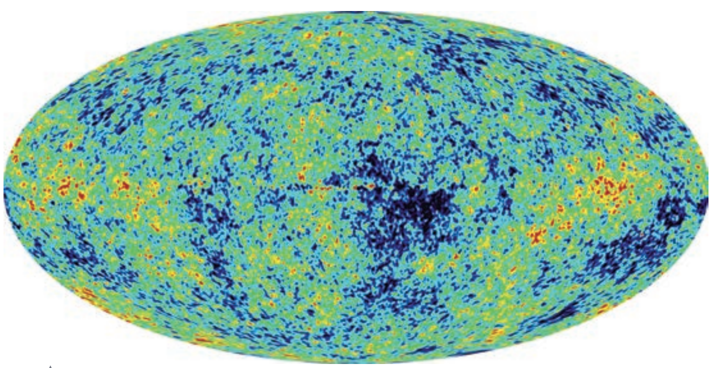

Figure 7.2.6 This image taken by the Wilkinson Microwave Anisotropy Probe (WMAP) maps the cosmic microwave background radiation. Different colours show slight variations in the temperature of the universe.

It was this discovery, in conjunction with Hubble's demonstration of the expansion of the universe, that convinced most scientists to accept the Big Bang model.

A brief history of the universe

Once the rate of expansion of the universe is accurately measured, it is possible to extrapolate back through time to the Big Bang. Astronomers currently estimate that the Big Bang occurred just under 14 billion years ago. They have also been able to suggest a rough outline of the history of the universe, as shown in Table 7.2.1 and Figure 7.2.7.

Table 7.2.1 History of the universe

Time from the Big Bang	Events
0	Big Bang—space and time come into existence along with all the energy that will ever exist. The universe undergoes a period of rapid inflation.
0.000 001 s	The universe expands and cools. Basic forces of nature come into existence. Protons, neutrons and electrons come into existence.
3 s	Protons and neutrons start to combine to form the nuclei of simple atoms—hydrogen (75%), helium (25%) and lithium (trace amounts).
10 000 years	The universe cools as high energy forms of electromagnetic radiation (X-rays and gamma) stretch into light and microwaves.
300 000 years	Electrons start to be captured by atomic nuclei to form simple atoms.
300 million years	Pockets of gas start to condense into the earliest stars and galaxies.
9 billion years	Our solar system begins to form.
13.7 billion years	Today's universe

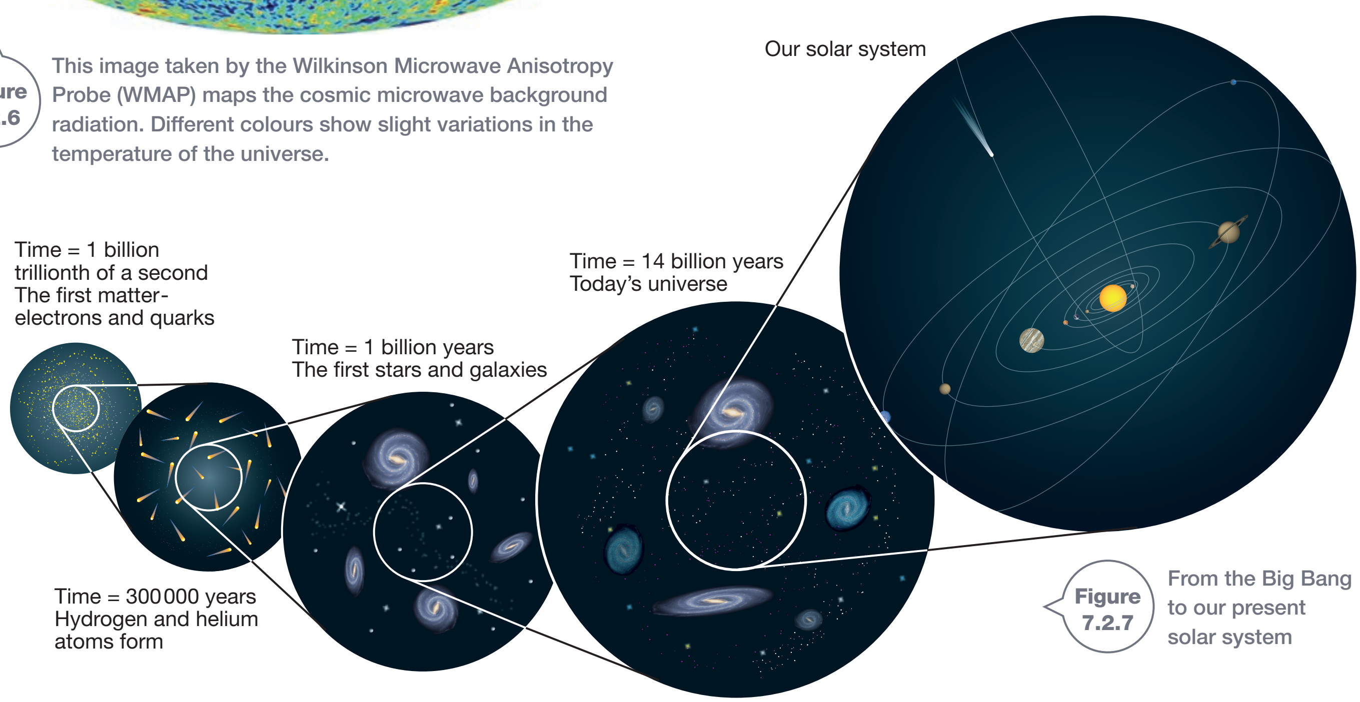

Figure 7.2.7 From the Big Bang to our present solar system

SCIENCE AS A HUMAN ENDEAVOUR

Use and influence of science

The Large Hadron Collider

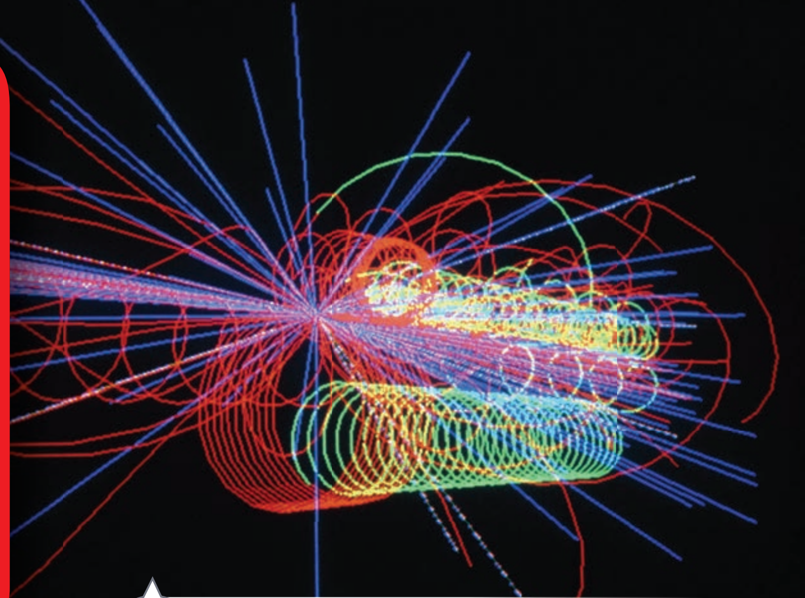

Figure 7.2.8 A computer simulation of a subparticle collision

One of the challenges faced by cosmologists is that many of the objects and processes they study are very different from those found in a standard laboratory. The conditions in the centre of a star or in the early moments of the Big Bang involve extremes of pressure and temperatures that are hard to physically recreate on Earth.

One way to explore the extraordinary conditions of the Big Bang on a microscopic scale is to use an instrument known as a particle accelerator. This takes tiny subatomic particles such as protons and electrons and uses magnetic fields to accelerate them to within 0.01% of the speed of light. Two beams of these particles can then be made to collide with each other (Figure 7.2.8). Scientists study the debris produced by these collisions, hoping to observe the sort of particles and interactions that might have occurred in the very early moments of the universe's existence.

Particle accelerators are also fundamental to scientists' pursuit of a grand unified theory, sometimes known as a 'theory of everything'. One of the great puzzles of science is that the theory used to explain the universe on the smallest scale (called *quantum mechanics*) and the theory used to explain the structure of the universe as a whole (*general relativity*) are very different and incompatible. Scientists hope that by studying the high-energy systems generated inside a particle accelerator, they can find a single mathematical model that will fit any situation, large or small.

By far the biggest particle accelerator ever built is the Large Hadron Collider or LHC (Figure 7.2.9). (Hadrons are the group of particles that include protons and neutrons.) Completed in 2008, it is not only one of the most complex scientific instruments ever constructed, but it is also one of the most significant examples of international scientific cooperation and collaboration.

The LHC consists of a ring-shaped tunnel 27 km long buried beneath the border between France and Switzerland. It has a staff of over 1800 scientists from 35 countries, including Australia. Collaboration is required at every stage of the LHC's operation, even to process the 1.7 million DVD of data it produces each year. Rather than try to process this on a single computer, the Worldwide LHC Computing Grid consists of a network of over 100 000 computers in 34 different countries.

A venture of this size and complexity could not operate without challenges. Shortly after the first beam was circulated on 10 September 2008, researchers were disappointed to discover a problem in two of the giant superconducting magnets that accelerate and guide the charged particles. It was over a year before the beams could be successfully circulated again. In the lead-up to the first particle collision there were also suggestions from some people that the high energies of the LHC might create a microscopic black hole that would eventually grow in size until it destroyed the Earth. These fears were shown to be incorrect when the first collisions took place on 30 March 2010.

7.5

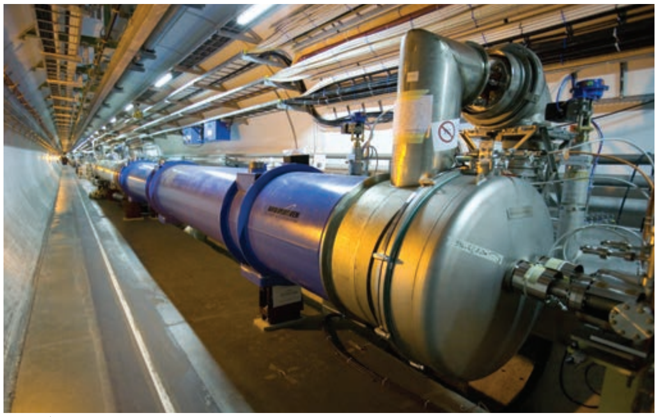

Figure 7.2.9 A section of the Large Hadron Collider

7.2 Unit review

Remembering

1 **Name** the first person to suggest that the Milky Way was made up of stars.

2 **Name** the type of star used by Hubble to measure the distance to other galaxies.

3 **State** two pieces of evidence that support the Big Bang theory.

Understanding

4 **Define** the term *cosmology*.

5 a **Outline** the two main characteristics of Hubble's red-shift data.

b **Explain** why these are significant.

6 **Describe** the cosmic microwave background radiation.

Applying

7 **Identify** an adjustment that was made to the steady state model of the universe to make it fit Hubble's observations.

8 The table below shows the distance to a number of galaxies and the speed at which each galaxy is moving away from us (i.e. recession velocity).

Galaxy	Distance (billions of light-years)	Recession velocity (× 1000 km/s)
A	4.50	114
B	1.80	46
C	2.40	61
D	1.10	28
E	0.85	22
F	3.30	84

a **Use** the data in this table to draw a graph showing the relationship between distance and recession velocity.

b **Identify** a mathematical relationship between distance and recession velocity.

c **Use** the graph to **predict** the recession velocity of a galaxy 2.8 billion light-years away.

d **Use** the graph to **determine** the distance of a galaxy if the red-shift of its light indicates it has a recession velocity of 13 000 km/s.

Analysing

9 **Contrast** red-shift with blue-shift.

10 **Contrast** the Big Bang theory with the steady state model of the universe.

11 Scientists define the *observable universe* as anything within 13.7 billion light-years of Earth. **Analyse** why it is impossible for us to observe anything further away than this.

Evaluating

12 Some scientists believe that in the distant future the universe may start to contract. **Propose** an observation that scientists could make that would indicate that this has started to occur.

13 The Magellanic Clouds are not widely visible in the northern hemisphere. **Assess** whether or not you think European astronomers would have developed the idea of galaxies outside the Milky Way if they had been able to see the Magellanic Clouds.

Creating

14 **Construct** a diagram to show how the motion of a star produces red-shift.

15 **Use** information provided in this chapter to **construct** a timeline showing the history of the universe up until today. Carefully consider what scale should be used to meaningfully show each important event.

Inquiring

1 Research the work done at Australia's only particle accelerator, the Australian Synchrotron.

2 Research the following cosmological concepts.

a the multiverse

b the anthropic principle

c string theory

d dark matter

e heat death

f big crunch

7.2 Practical activities

1 Classifying galaxies

Purpose

To develop a system for classifying galaxies on the basis of their shape.

Materials

- astronomy reference book or internet
- paper
- pencil
- cardboard
- tape

Procedure

1. Search for pictures of at least eight different galaxies including the Milky Way, Andromeda, Large Magellanic Cloud and Small Magellanic Cloud.
2. Sketch or print out the image of each galaxy on a small sheet of paper. Write the name of the galaxy on the back of the piece of paper.
3. Arrange the images into three or four groups according to their shape. Think of a name that describes the shape of each group.
4. Stick all the images from one group of galaxies onto a piece of cardboard to create a poster. Write the name of the group on the poster.
5. Repeat step 4 for each group of galaxies.
6. Copy a table like that shown in the results section to summarise your results.

Results

Copy and complete the following table or construct a similar one.

Shape	Distinctive features	Examples

Discussion

1. Scientists classify galaxies into the following groups: spiral, barred spiral, elliptical and irregular. **Discuss** how your groups compare with these, and then **classify** the galaxies in this investigation into the scientific groups.
2. **Identify** the advantages and disadvantages of each system of classification.

2 An expanding universe

Purpose

To model the expanding universe.

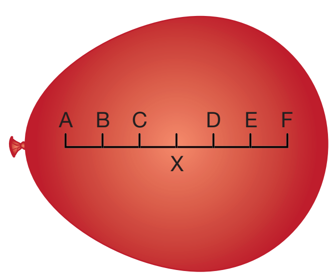

Figure 7.2.10 A balloon can be used to model the expansion of the universe.

Materials

- balloon
- felt-tip pen
- ruler or measuring tape

Procedure

1. Copy the table from the results section into your workbook.
2. Partially inflate a round balloon. Mark seven points in a line, each 1 cm apart. Each point represents a galaxy. Label the points as shown in Figure 7.2.10.
3. Inflate the balloon to its maximum size. Measure the distance between the central galaxy X and each of the other galaxies.

Results

Copy and complete the following table.

Galaxy	Initial distance from galaxy X (cm)	Final distance from galaxy X (cm)	Change in distance (cm)
A	3		
B	2		
C	1		
D	1		
E	2		
F	3		

Discussion

1. **Construct** a graph of change in distance against initial distance.
2. **Compare** this with Hubble's data on stellar red-shift.