Chapter 1 The universe at different scales

Poets say science takes away from the beauty of the stars - mere globs of gas atoms. Nothing is "mere". I too see the stars on a desert night, and feel them. But do I see less or more? The vastness of the heavens stretches my imagination - stuck on this carousel, my little eye can catch one-million-year-old light … Or see them [the stars] with the greater eye of Palomar, rushing all apart from some common starting point when they were perhaps all together. What is the pattern, or the meaning, or the why? It does not do harm to the mystery to know a little about it. For far more marvelous is the truth than any artists of the past imagined! Why do the poets of the present not speak of it?

Richard Feynman

1.1 Units of astronomical distances

✓ **Scientific notations:** Because of the large range of scales we will encounter, we will use powers to express very large or small numbers. For examples,

$10^5 = 100{,}000$ $10^3 = 1{,}000$ $10^{-3} = 0.001$ $10^{-5} = 0.00001$

$300{,}000 = 3\times10^5$ $4{,}500 = 4.5\times10^3$ $0.000062 = 6.2\times10^{-5}$

✓ **Metric Prefixes:** These prefixes specify powers in a convenient way. For example,

kilo (k) = 10^3 = 1,000 mega (M) = 10^6 = 1,000,000

1 kilometer = 1 km = 1,000 meters 1 megaton = 1 Mton = 1,000,000 tons

✓ **Astronomical unit (AU):** The average distance between the Earth and the Sun,

$$1 \text{ AU} \approx 1.50\times10^{11} \text{ m}$$

✓ **Light year (ly):** One light year is equal to the distance travelled by light in vacuum in one year. In vacuum, light travels at a speed of 3×10^8 ms^{-1}.

$$1 \text{ ly} \approx 9.46\times10^{15} \text{ m} \approx 6.32\times10^4 \text{ AU}$$

✓ **Parsec (pc):** Another common astronomical unit for distance**.**

$$1 \text{ pc} \approx 3.08\times10^{16} \text{ m} \approx 2.06\times10^5 \text{ AU} \approx 3.26 \text{ ly}$$

1.2 A quick tour of the cosmos

To understand the universe, we must understand the *relative scales* of planets, stars, galaxies and the universe as a whole. We will journey from a campus scene to the limits of the cosmos in 13 steps. In each step we will widen our view by a factor of 100. That is, each successive picture will show a region of the universe that is 100 times wider than the preceding picture.

Step 1

We start with objects whose sizes we can understand. This helps us comprehend astronomical distances relative to ourselves.

Fig. 1-1 (16 m across): It is occupied by human being, a sidewalk, and a few trees. Only 12 steps separate this scene from the universe as a whole.

Step 2

These dimensions are also familiar. We have personal experience with such dimensions, and we can relate them to the scale of our bodies.

Fig. 1-2 (1.6×10^3 m across) [1]: We now increase our field of view by a factor of 100. Individual people, trees, and sidewalks vanish, but now we can see a college campus and the surrounding streets and houses.

[1] If case you wonder about the choice of the size of the photos, it makes more sense to know that 1.6 km is equal to 1 mile. The photos are from an American textbook, and mile instead of km is used.

Step 3

This is an infrared photograph taken from an artificial satellite. At this scale we see natural features of the Earth′s surface but not much signs of human activities.

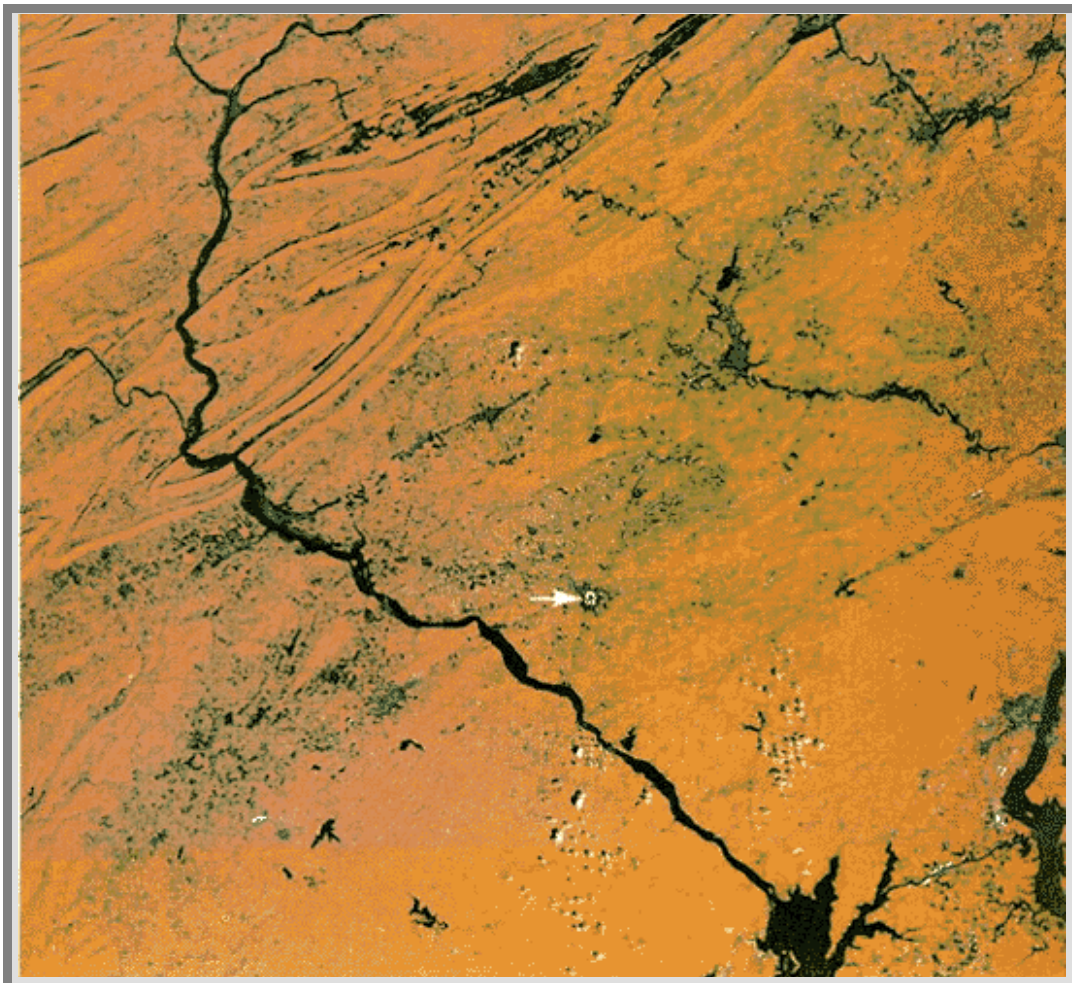

Fig. 1-3 (1.6×10^5 m across): Field of view enlarged 100 times from the previous image. Our field of view now spans 160 km. The area of the preceding photograph is shown by the small square (arrow). The college campus is invisible; cities are visible as dark blotches, and farmlands are visible as tiny rectangular shapes.

Step 4

The photograph shows most of the daylight side (illuminated by sunlight) of Earth. The rotation of the Earth carries us eastward across the daylight side, and, as we turn away from the Sun, night comes.

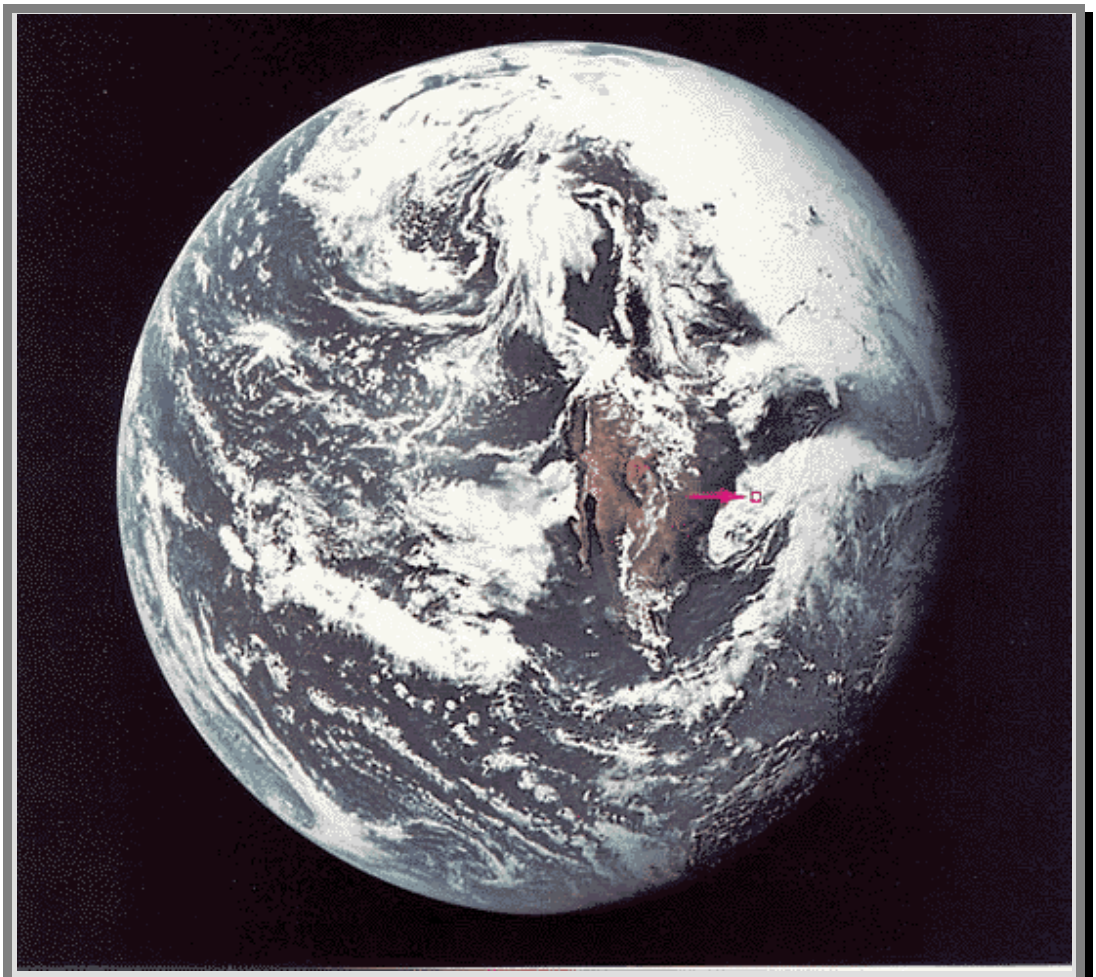

Fig. 1-4 (1.6×10^7 m across): Field of view enlarged 100 times from the previous image (NASA). This step in our journey shows our entire planet. The Earth is 12,756 km in diameter [2] and rotates on its axis once a day.

[2] The Earth is not a perfect sphere. The number quoted here is its equatorial diameter.

Step 5

At this step we meet the **Moon**, an airless, rocky **satellite** of the Earth. It shows **phases** as it orbits the Earth.[3]

Fig. 1-5: The Moon is our closest neighbour. It revolves around the Earth once in about 27 days.

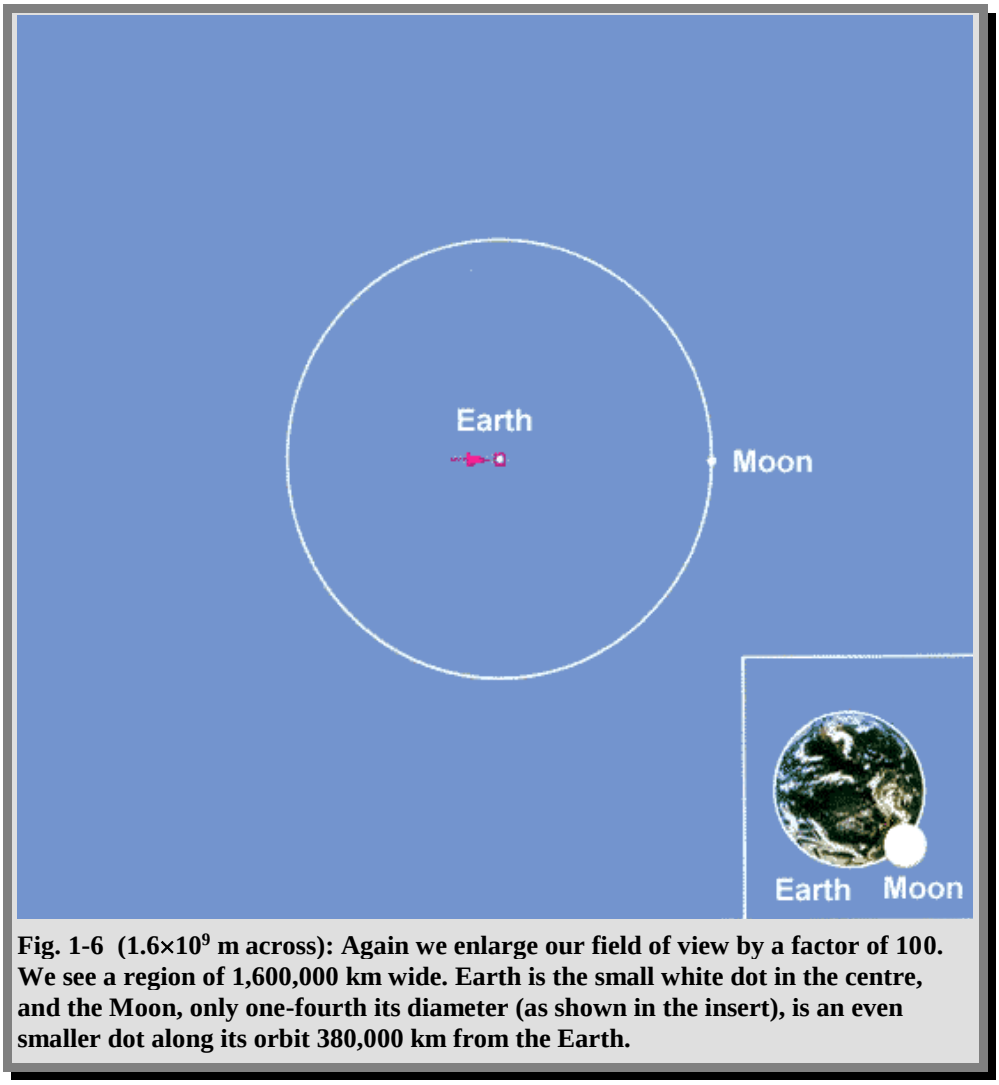

Fig. 1-6 (1.6×10^9 m across): Again we enlarge our field of view by a factor of 100. We see a region of 1,600,000 km wide. Earth is the small white dot in the centre, and the Moon, only one-fourth its diameter (as shown in the insert), is an even smaller dot along its orbit 380,000 km from the Earth.

[3] See Chapter 3 Lunar phases, tides and eclipses.

Step 6

The **Sun** is a star - it gives out light and heat. The **planets**, including our Earth, orbit the Sun and shine by reflecting sunlight. Compared to their size, the Sun and the planets are separated by very long distances. Imagine that we reduce the Sun to the size of a table tennis ball, then the Earth would be a grain of salt 4 m from it.

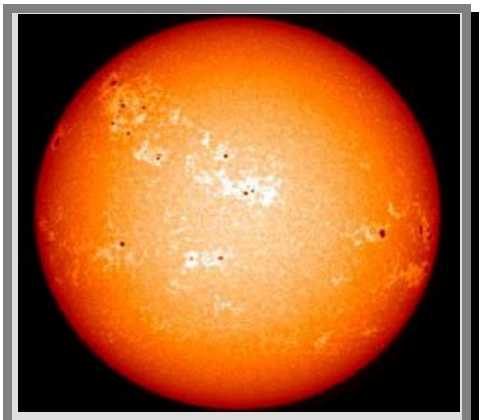

Fig. 1-7: The Sun is a star, which generates energy by nuclear reactions at its centre.

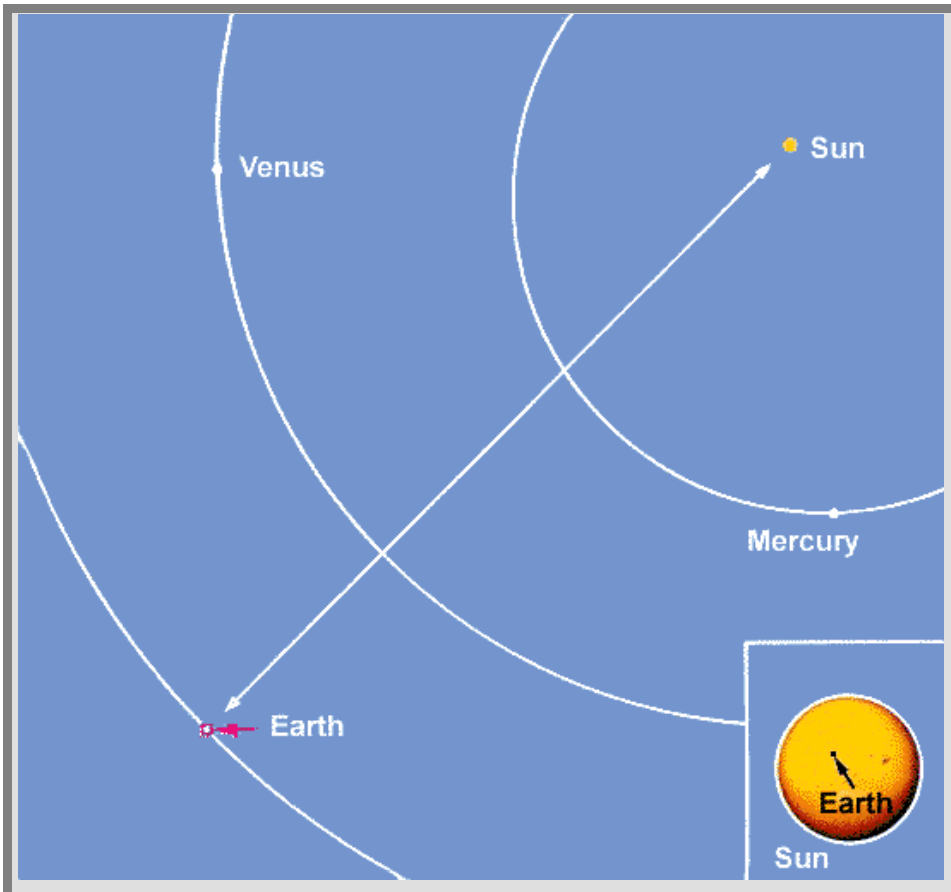

Fig. 1-8 (1.6×10^{11} m across): When we once again enlarge our field of view by a factor of 100, the Earth and the Moon lie in the small red box at lower left. We place the Earth off centre of the field of view, so that we can see the Sun and two other planets - Mercury and Venus. An AU is defined as the average distance between the Earth and the Sun.

Step 7

The **Solar System** mainly consists of the Sun and eight major planets. If we imagine that the Sun is a table tennis ball, then Jupiter, the largest planet, would be an apple seed 20m from it, and the entire Solar System would span over 230m. **Asteroids** (小行星) are "minor planets" concentrated between Mars and Jupiter. **Comets** (彗星) are small icy debris moving around the Sun in very elongated orbits. (Chapter 7)

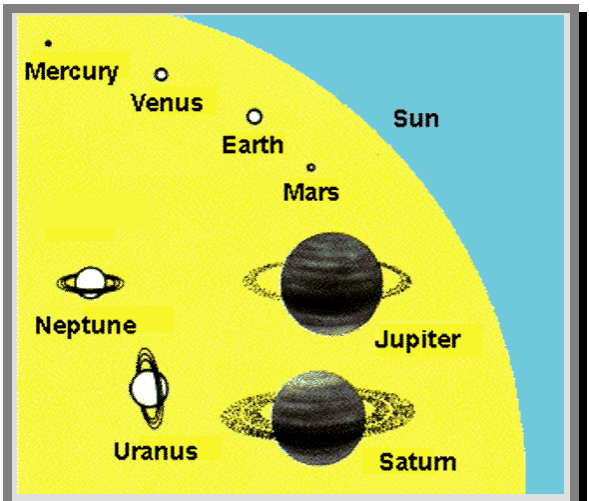

Fig. 1-9: The relative sizes of the Sun and the major planets.

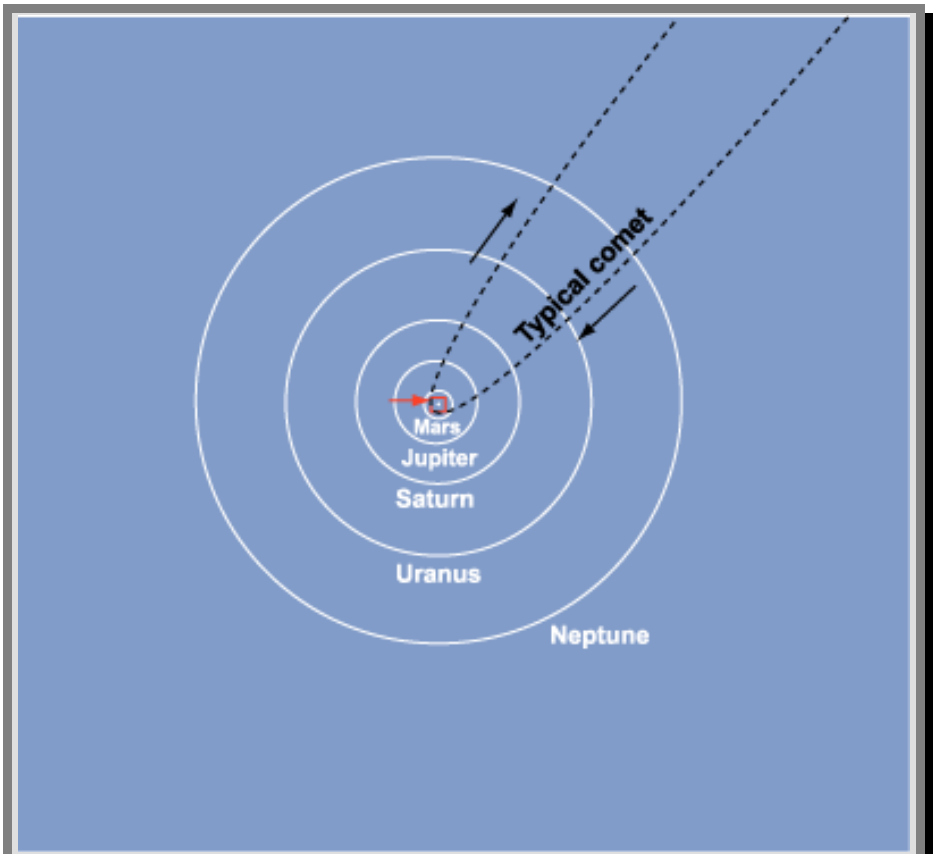

Fig. 1-10 (1.6×10^{13} m across): After only six steps of enlarging our field of view by a factor of 100 at each step, we now see the entire Solar System. The Solar System spans about 60 AU, i.e., 60 times the average distance between the Earth and the Sun.

Step 8

The distances among stars are huge. In this view we cannot see any stars except the Sun. The stars are typically separated by distances about ten times larger than this diagram.

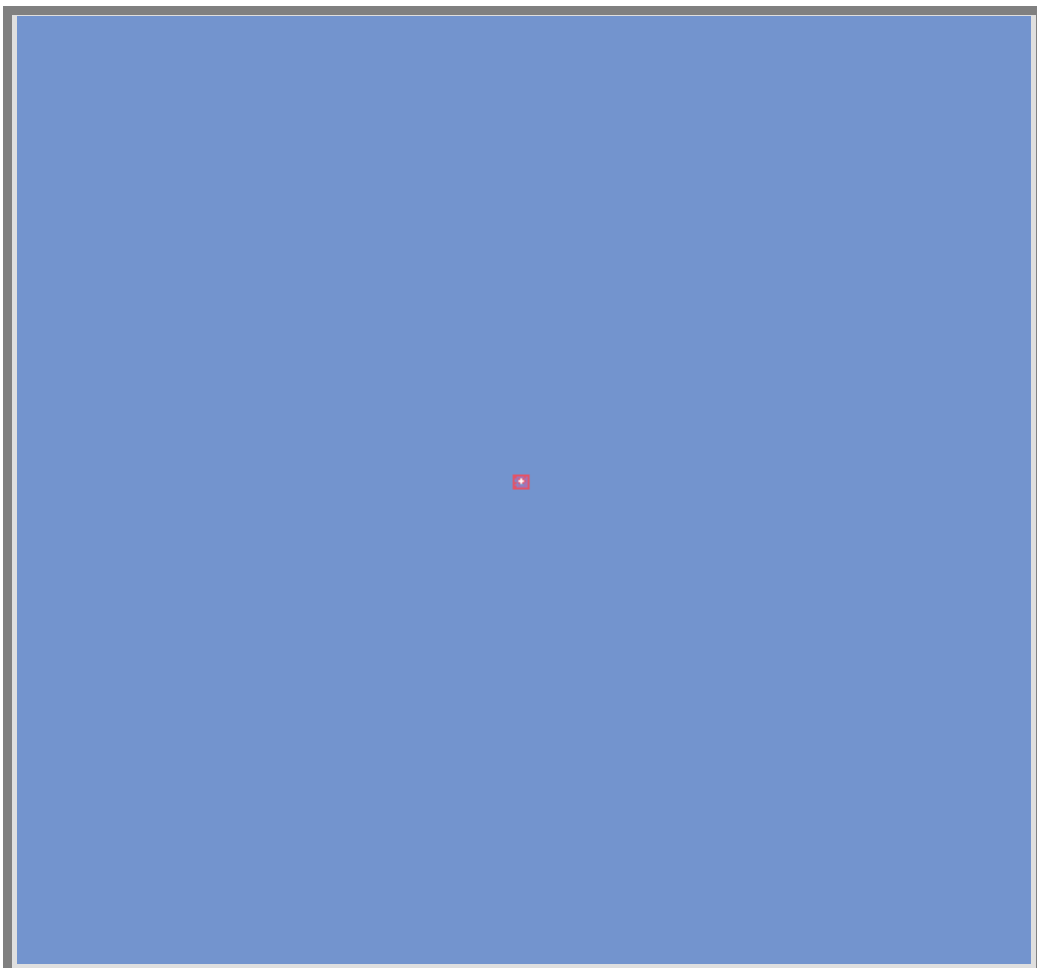

Fig. 1-11 (1.6×10^{15} m across): When we again enlarge our field of view by a factor of 100, our Solar System vanishes. The Sun is visible as a point of light, but all the planets and their orbits are now crowded into the small square at the centre.

Step 9

The nearest star (Proxima Centauri 半人馬座毗鄰星) [4] at about 4.2 ly from the Sun is observed. A **light year (ly)** is defined as a distance travelled by light (3×10^8 ms^{-1}) in vacuum in one year.

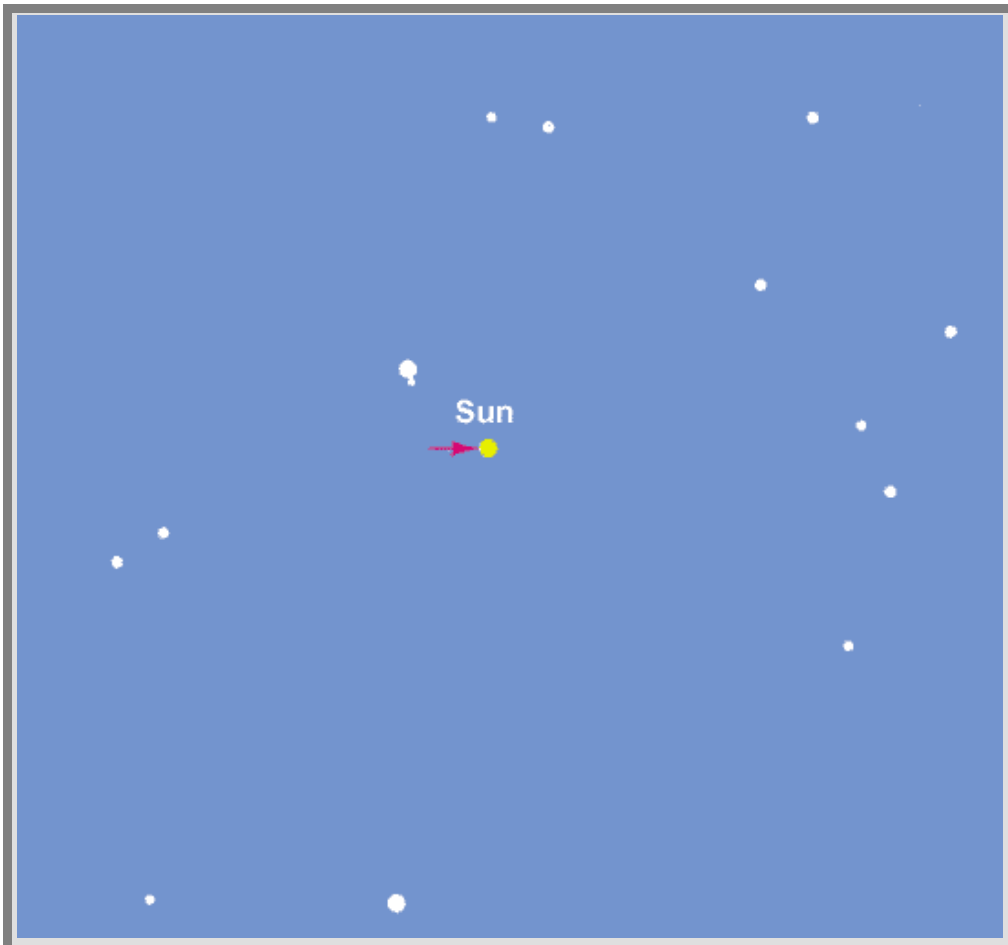

Fig. 1-12 (1.6×10^{17} m across): Our field of view has now expanded out to an area of a bit over 1 million AU across. The Solar System is located at the centre, and we see a few of the nearest stars.

[4] Proxima Centauri is part of a triple-star system, which hosts the nearest exoplanet (planet outside the Solar System) ever found (http://www.eso.org/public/news/eso1241/).

Step 10

We now see thousands of stars and their tendency form clusters. Like our Sun, they all shine by the nuclear energy generated in their cores, and many of them probably have planetary systems similar to our Solar System.

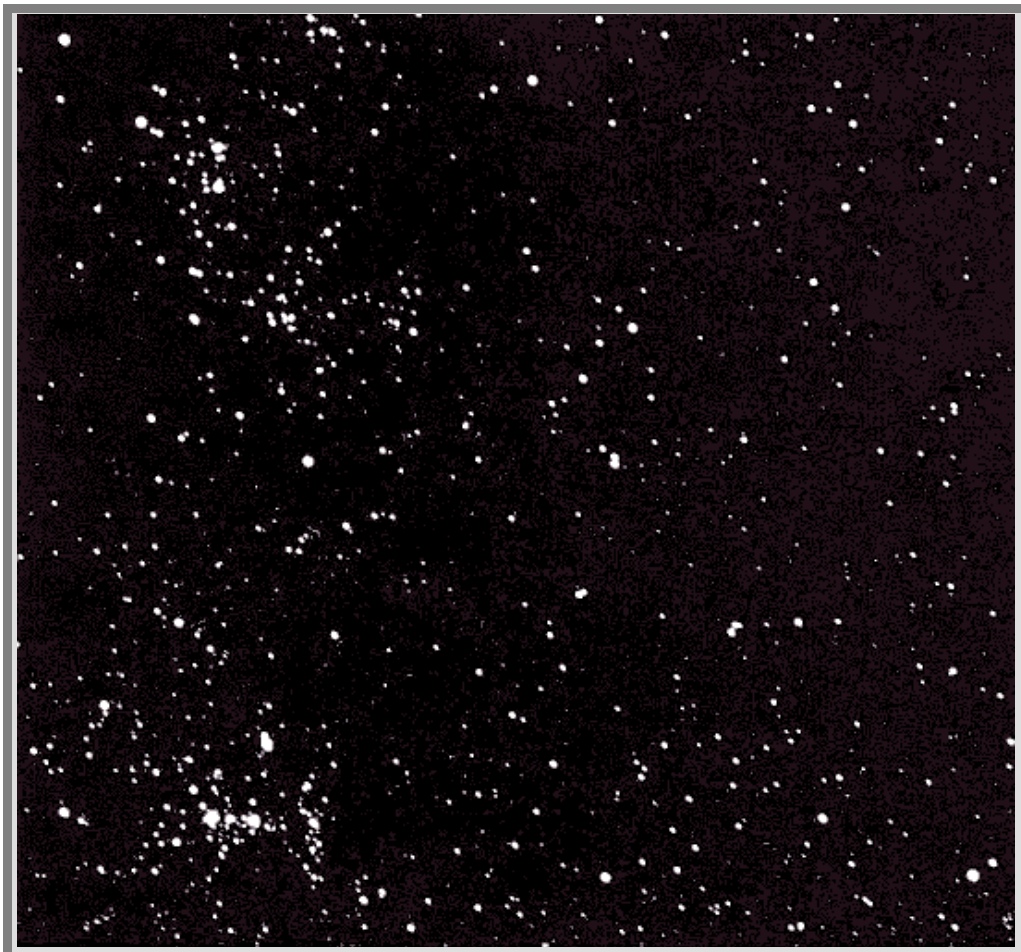

Fig. 1-13 (1.6×10^{19} m across): As we expand our field of view by another factor of 100, we find that the Sun and its neighbouring stars vanish into the background of thousands of stars. The field of view is now 1700 ly across.

Step 11

The disk of Milky Way Galaxy has a spiral structure filled with gas, dust and stars. Stars undergo a complete life cycle from birth to death, evolving into different phases at different ages - including protostars, main-sequence stars, giants, white dwarfs, neutron stars and black holes (Chapters 7-10, 12-13).

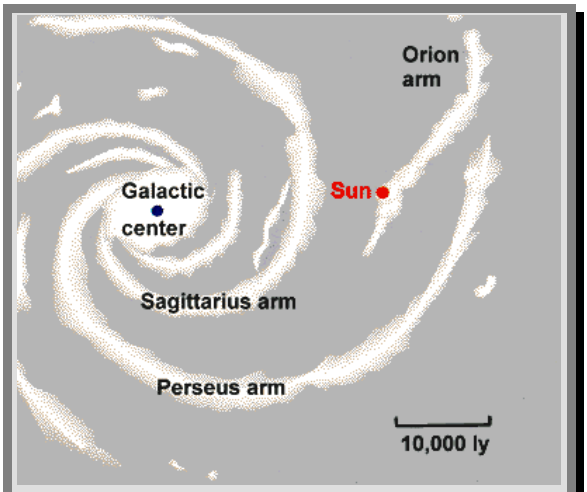

Fig. 1-14: The approximate position of the Sun in the Milky Way Galaxy. [5]

Fig. 1-15 (1.6×10^{21} m across): If we expand our field of view by another factor of 100, we can see our own Milky Way Galaxy, Our Sun and the neighbouring stars of the previous figure would be lost among the 100 billion (10^{11}) stars of the galaxy. Our galaxy spans about 100,000 ly.

[5] It is not an easy task to map the Milky Way because we are within the disk. Our picture of the Milky Way could still change with more accurate observations. In 2008, NASA's Spitzer Space Telescope identified only two spiral arms. Yet in late 2013, a 12-year study again found four arms, just as traditionally believed. See http://www.leeds.ac.uk/news/article/3470/ for details of the study.

Step 12

Galaxies are not scattered randomly in the universe but tend to form clusters. **The Local Group** is a small cluster which consists of about 50 galaxies [6] (including our Milky Way Galaxy), [7] scattering throughout a region about 6 million ly.

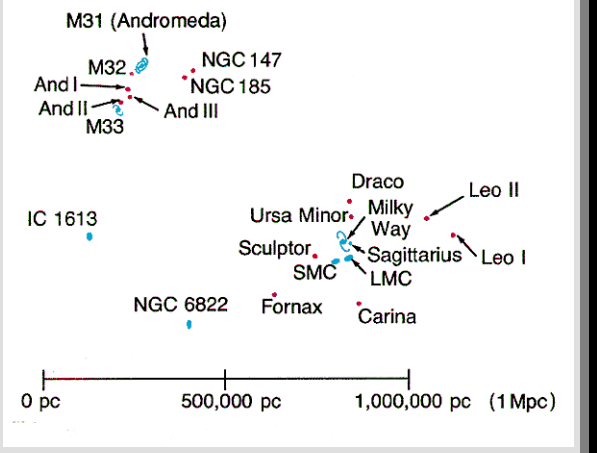

Fig. 1-16: Local Group of galaxies.

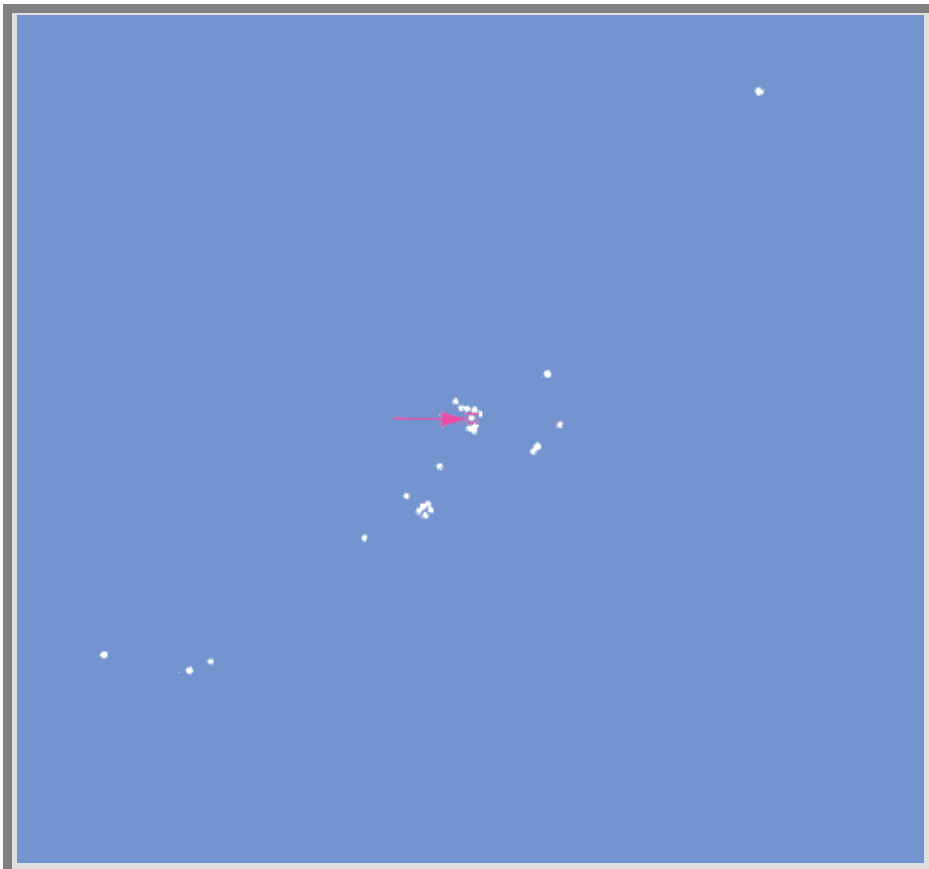

Fig. 1-17 (1.6×10^{23} m across): As we expand our field of view by another factor of 100, our Milky Way Galaxy (arrow) becomes a tiny dot surrounded by other dots, each representing a galaxy. This diagram includes a region 17 million ly across.

[6] The number is continuously increasing, as astronomers find dimmer and dimmer dwarf galaxies. For example, in older textbooks, the number could be around 20 to 30. The number quoted in *Chaisson & McMillan 14* (p. 618) has increased to 55.

[7] Consult http://messier.seds.org/more/local.html for a detailed list of the members.

Step 13

At this scale, clusters of galaxies group to form **superclusters**, which are in turn linked to form filaments outlining voids that seem nearly empty. Galaxies are recessing away from each other at high speeds, indicating that the universe is expanding.

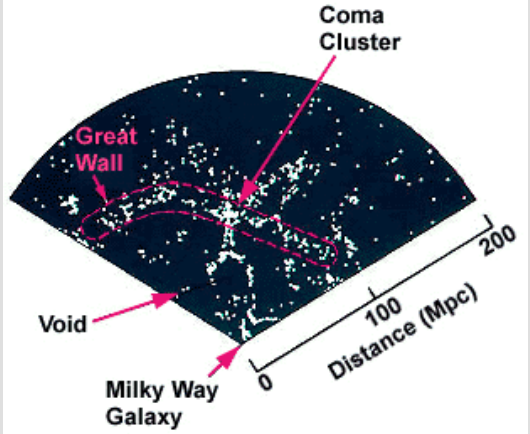

Fig. 1-18: Features like the Great Wall and the Void are the largest known structures in the universe.

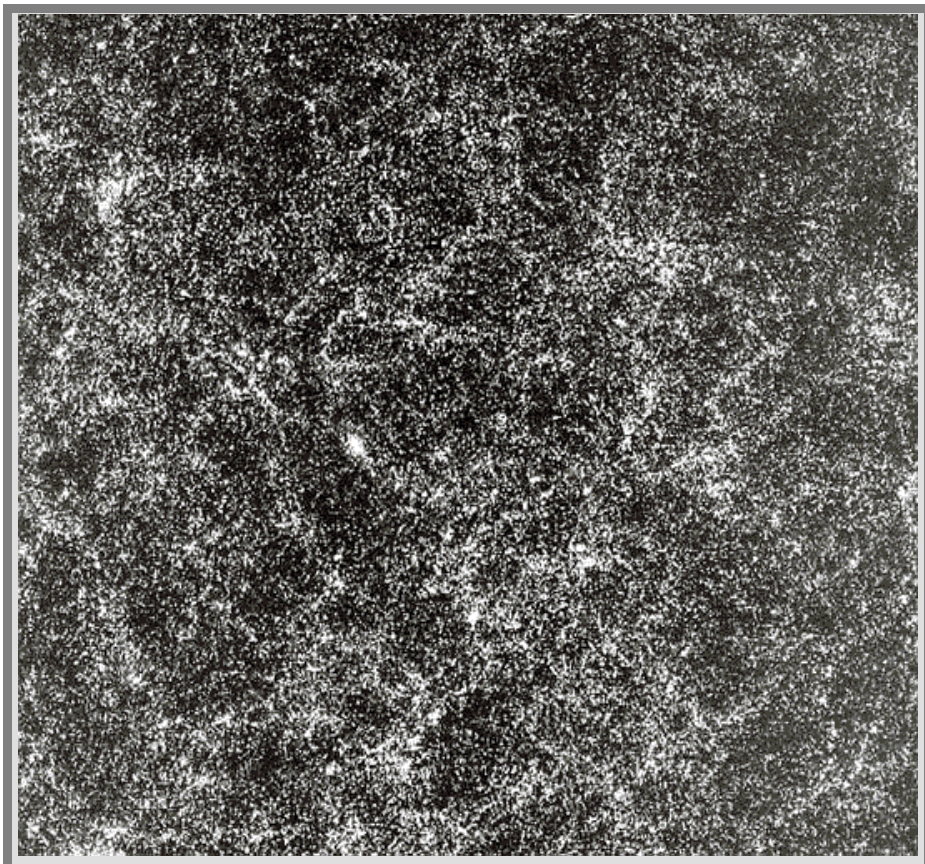

Fig. 1-19 (1.6×10^{25} m across): Were we to again expand our field of view, we would see that our Local Group of galaxies is part of a large supercluster, a cluster of clusters. Other galaxies are not scattered at random throughout the universe but lie in clusters within larger superclusters.

1.3 Summary

The following table summarizes the essential features at each step of our journey.

Systems	Sizes	Motions	Essential Features
Earth	1.3×10^4 km in diameter	Self-rotation (period: 1 day)	Day and night
Earth-Moon	Average distance: 3.8×10^5 km	Moon orbits the Earth (period ≈ 27 days)	Phases
Earth-Sun	Average distance: 1 AU ≈ 1.5×10^8 km	Earth orbits the Sun (period: 1 year); Self-rotation of the Sun (period: ≈ 25 days)	Four seasons
Solar System	Spans about 60 AU	Sun rotates about the centre of the Milky Way Galaxy (period: 2.4×10^8 years)	The Sun, eight major planets, comets and asteroids
Nearest stars	~10 ly or ~10^6 AU from the Earth		The nearest star: Proxima Centauri is 4.2 ly away
Milky Way Galaxy	Spans ~10^5 ly	Self-rotation speed: 200-300 km/s	Contains ~10^{11} stars of all ages: main-sequence stars, red giants, white dwarfs, neutron stars, black holes and clouds of gas and dust (nebulae)
Local Group	Spans ~ 2 Mpc		Cluster of galaxies (contains over 50 galaxies)
Superclusters	Extending over 100 Mpc	Expansion of the universe can be detected at this scale	Clusters of clusters of galaxies; ~100 of member clusters
Great Wall , Voids	Extending over 200 Mpc		Largest structure known!
Visible Universe	~10^{10} ly or ~10^4 Mpc		Looking into the early universe