CESAR BOOKLET

The Secrets of Galaxies

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Introduction

Using large telescopes, you can see clouds of dust and gas inside the Galaxy. You can also see other peculiar milky nebulae scattered among the stars. Some of these milky nebulae have spiral shapes to them and others look like squashed spheres or tortured messes of material. Three of the milky nebulae are visible as fuzzy patches to the naked eye: one is in the constellation Andromeda and two others (called the Large and Small Magellanic Clouds, after the first European explorer to see them, Ferdinand Magellan) are in the southern sky in the constellations Mensa and Hydrus.

One century ago, astronomers believed that the whole Universe was comprised within the Milky Way. There was a big controversy in the 1910s and early 1920s over whether the so-called (at the time) 'spiral nebulae' were outside the Milky Way or were part of it. Until work by Edwin Hubble (1889-1953) and Milton Humason (1891-1972) in the 1920s established that each of the spiral nebulae was a huge star system, called a *galaxy*. They were able to measure the distance to some of these galaxies, proving that the Universe was much vast than previously thought, and that our Galaxy is just one of billions of galaxies in the Universe.

Since then, astronomers have learned a lot about galaxies: how many they are, what types of galaxies exist, and the stars that they contain. They have also started to figure out how galaxies formed and how they evolve. And all this thanks to the light coming from those galaxies, which is being emitted by the thousands to trillions of stars within them.

The electromagnetic spectrum

The colours of light

You have surely seen a rainbow, and you are probably familiar with the explanation to this phenomenon: In very basic terms, sunlight is refracted as it gets through water droplets suspended in the Earth's atmosphere. Because white light is a mixture of six (or seven) different colours, and each colour is refracted a different angle, the result is that the colours get arranged in a given order, from violet to red through blue, green, yellow and orange. We can get the same effect in a laboratory by letting light go through a prism, as shown in Figure 1. This arrangement of colours is what we call a *spectrum*.

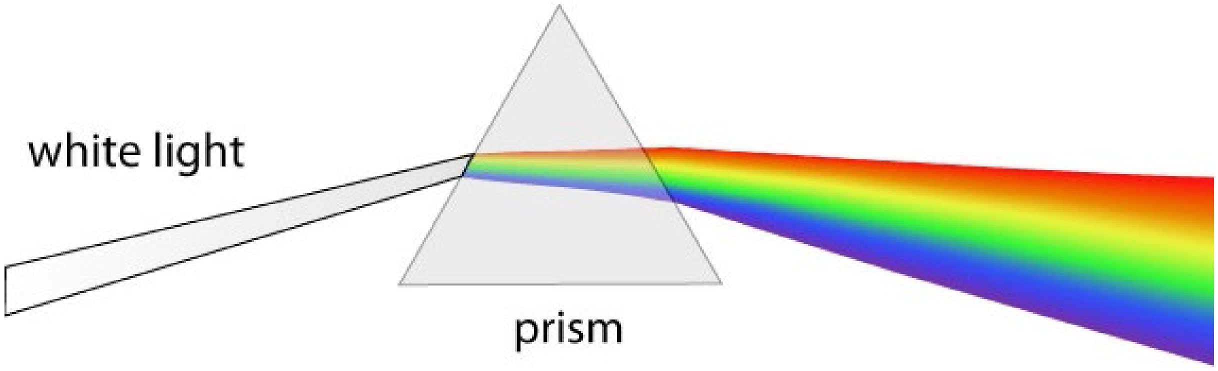

Figure 1: *White light passing through a prism creates a rainbow.* ***Credit:*** *physics.stackexchange.com*

Yet the spectrum of light is not only made of the colours we see with our eyes. There are other colours that are invisible, although they can be detected with the appropriate devices. Beyond the violet, we have ultraviolet, X-rays and gamma rays. On the other extreme, beyond the red, we have infrared and radio. Although we cannot see them, we are familiar with these other types of light: for example, we use radio waves to transmit music from one station to our car receiver, ultraviolet light from the Sun makes our skin get tanned, X-rays are used by radiography machines to check if we have a broken bone, or we change channel in our TV device by sending an infrared signal to it from the remote control.

Physicists describe light as something called *electromagnetic radiation* or *electromagnetic wave*. The word *radiation* means 'energy that is transported from one spot to another without need of direct contact between the two locations'. Light in each of these colours carries a different amount of energy: gamma rays are the most energetic, and radio is the least. Thus, when we observe gamma or X-rays from an astronomical object, we know that something really powerful is happening there. This energy is transported in the form of a wave, and each colour is related to a different wave size: The more energy the wave carries, the narrower it is –or, in technical terms, the shorter its *wavelength*. Hence, X-rays have shorter wavelengths than visible-light waves (also called 'optical waves' in Astronomy), and visible light has shorter wavelengths than radio waves.

Also, the amount of light of a given colour that is emitted by a body depends on its temperature. Contrary to what everyday experience tells us, though, most of the light emitted by the hottest objects in the universe has a colour on the 'blue side' of the spectrum (violet and ultraviolet), while the coolest objects emit most of their light in a colour in the 'red side' of the spectrum (infrared and radio). In other words, a blue star is hotter than a red star! (Note, however, that we are talking about the light that an object *emits*, and not the light it *reflects*. We see most of the things around us thanks to the light they reflect, because the light emitted by them has a colour that our eyes cannot detect.)

Figure 2 summarises the properties of the electromagnetic spectrum.

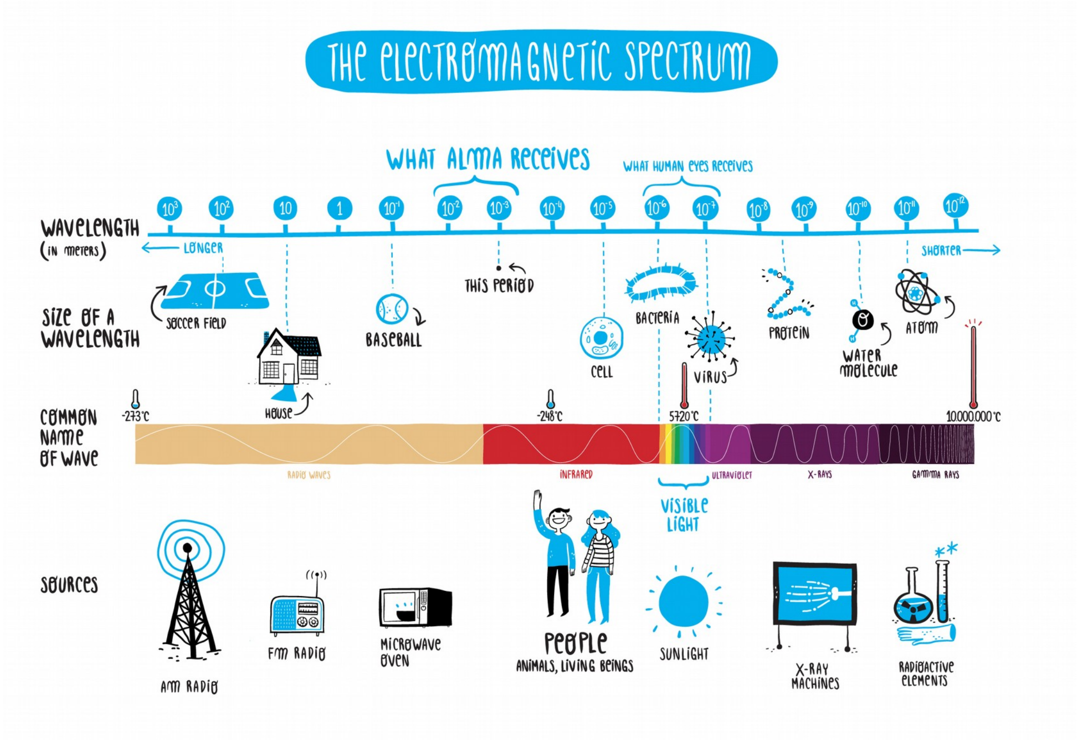

Figure 2: *Properties of the electromagnetic spectrum.* ***Credit:*** *ESO/ALMA*

Observing across the spectrum

Because astronomical objects emit light in different colours depending on their temperature and the phenomena that are going on in them, it is important to observe them in different types of light to fully understand them. As an example, Figure 3 shows the Crab Nebula, a supernova remnant about 6,000 light-years from Earth, observed by different telescopes that detect different types of light. Note how the appearance of the nebula changes depending on the wavelengths that are observed, because they are being emitted by different components or phenomena in this object. The cool gas and dust dominate the emission in the radio and infrared bands, respectively; in visible and ultraviolet light, we see the gas heated and ionised by the central neutron star (all that is left from a massive star that exploded at the end of its life); and X and gamma-rays reveal the emission from the neutron star itself, which is surrounded by a disk of very hot gas in the X-ray image.

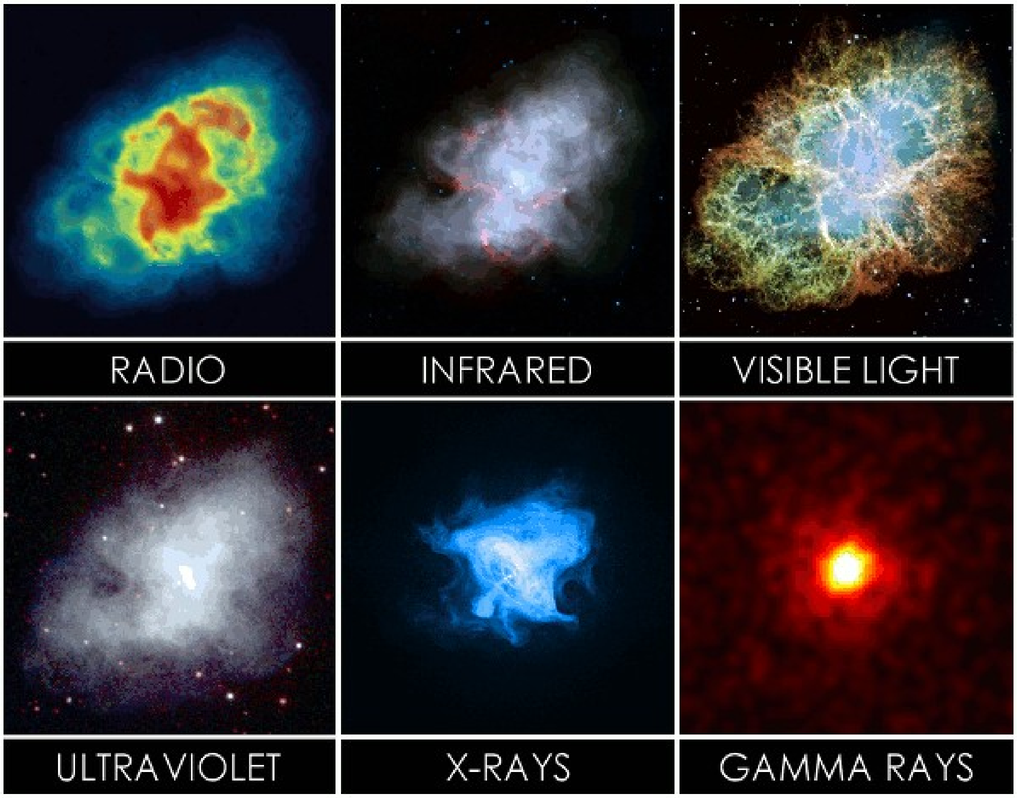

Figure 3: *The Crab Nebula observed across the electromagnetic spectrum.* ***Credits:*** *NASA/ESA/NRAO*

In Table 1, you have a list of the temperatures of sources emitting in the different colours of the electromagnetic spectrum, as well as some examples of these sources.

But observing across the full electromagnetic spectrum is not possible from Earth, as the atmosphere blocks most of the invisible light. For this reason, telescopes observing the universe in invisible colours (except part of the radio and infrared) must be placed in space. Figure 4 shows the space telescopes operated by ESA, and the part of the electromagnetic spectrum they observe.

Table 1: Examples of astronomical sources emitting in each range of the electromagnetic spectrum.

Type of radiation	**Temperature**	**Typical sources**
Gamma-rays	$>10^8$ K	Matter falling into black holes
X-rays	10^6-10^8 K	Gas in clusters of galaxies Supernova remnants Stellar coronae
Ultraviolet	10^4-10^6 K	Supernova remnants Very hot stars
Visible	10^3-10^4 K	Stars Hot planets
Infrared	10-10^3 K	Very cool stars Planets Cool clouds of dust
Radio	<10 K	Cool clouds of gas The Cosmic Microwave Background (CMB) Electrons moving in magnetic fields

Adapted from: NASA/Imagine the Universe!

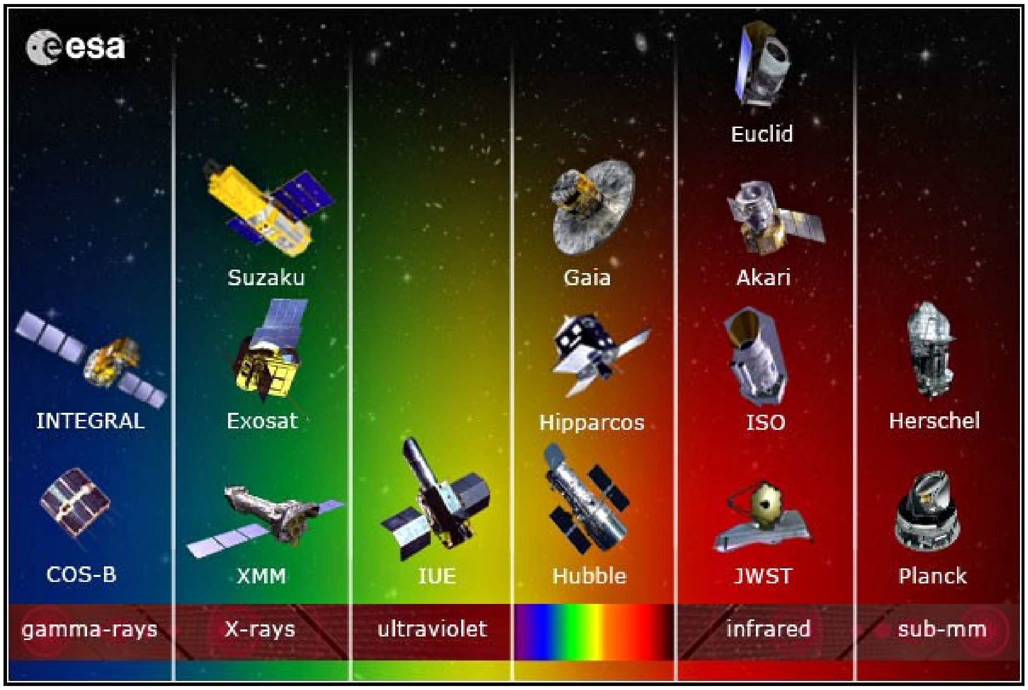

Figure 4: *ESA's fleet of telescopes across the electromagnetic spectrum. (The sub-millimetre range is part of the radio band.)* ***Credit:*** *ESA*

Lives of the stars

Stars, like people, are born, they evolve and change during their lifetime, and they die. However, the duration of their lives and the stages they go through are not the same for all stars.

The longest period of the life of any star is the so-called *main-sequence stage*. In this stage, hydrogen fusion is taking place in the core of the star, meaning that hydrogen nuclei (protons) are brought together to form nuclei of helium. This process releases a large amount of energy, preventing the star from collapsing to its centre under the effect of gravity.

The primary factor determining how a star evolves is its mass when it reaches the main sequence. Although this may seem contradictory, massive stars form faster and also evolve and die faster than stars of mass similar to the Sun or lower; this is because higher mass also means higher gravity, and fusion needs to proceed at a faster path to counterbalance that stronger gravitational force.

Figure 5 shows the main evolutionary stages of a low and a high-mass star. Both are born out of the gravitational collapse of a cool, dense interstellar cloud (also called a *nebula*). As the cloud collapses, it contracts to form a stellar core that rotates faster and increases in temperature as it condenses. Eventually, the central temperature reaches the point where nuclear fusion begins, starting the main sequence stage. In this stage, the most massive stars are large, bright and hot, and they have a bluish colour, while the least massive stars are small, dim and cool, and have a yellowish or reddish colour.

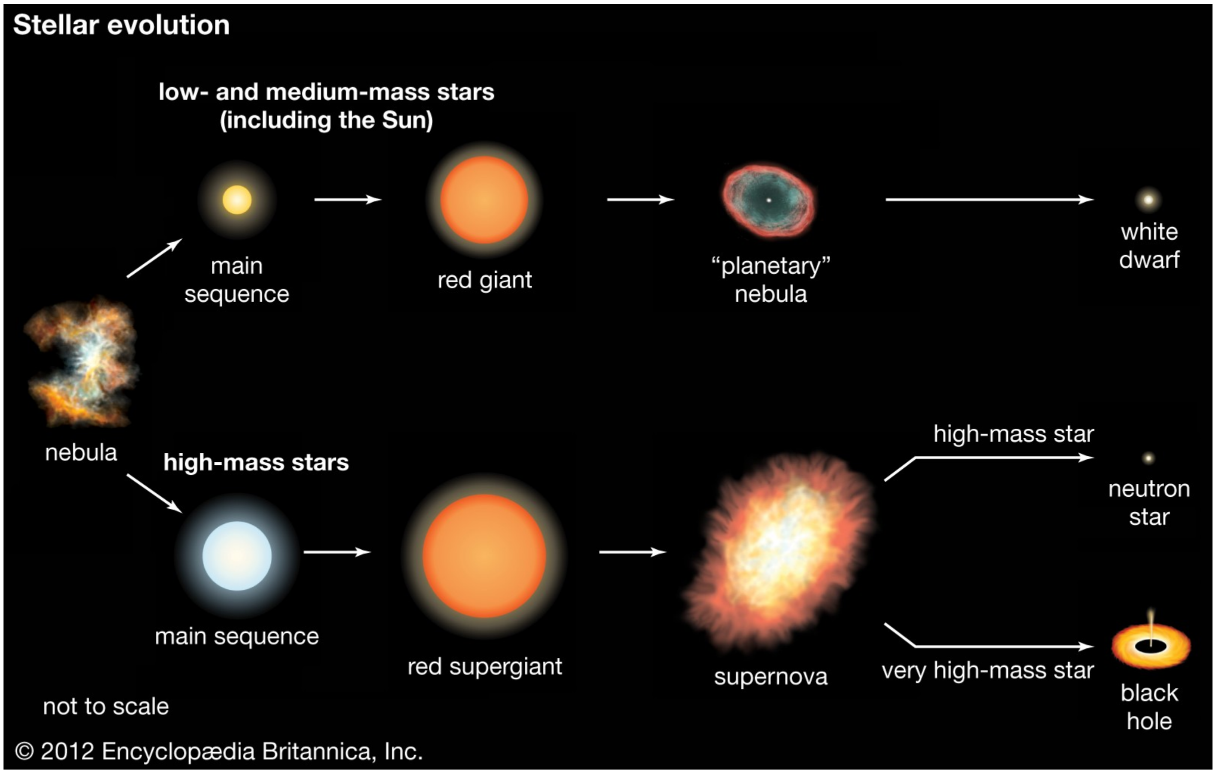

***Figure 5:** A star's evolution in time depends on its mass.* ***Credit:** Encyclopaedia Britannica*

Once the hydrogen in the core has all been burned to helium, energy generation stops and the core begins to contract. What happens now depends on the star's mass.

A low-mass star expands in size and gets redder and cooler in its surface as it leaves the main sequence; its luminosity also increases. The star is now called a *red giant*. Meanwhile, the helium core continues to contract and increase in temperature, until the conditions for helium fusion into carbon are reached. Once the helium has all been converted, the inert carbon core begins to contract and increases in temperature, but never reaching the value necessary to start carbon fusion. The outer layers of the star expand and are eventually ejected completely, glowing for a short period of time as a *planetary nebula*. Only the bare core remains, compressed into a ball of carbon we call a *white dwarf*.

If the star has a mass higher than about 8 solar masses, though, the fusion process does not stop at carbon, but it continues all the way to iron. All through these stages, the star is called a *red supergiant*: it gets even larger in size, cooler, redder and brighter. Because iron cannot be burned to heavier elements, at this point, the star has finally run out of fuel and the collapse of the core cannot be stopped. The star explodes as a *supernova*, blowing out the outer layers completely. The mass of the core determines what is left of the star after the explosion: If the core has a mass less than about 3 times the mass of the Sun, the collapse can be halted when the core has turned into a ball of neutrons, or *neutron star*. But if the core's mass is higher than 3 solar masses, nothing can withstand gravity, and only a *black hole* remains.

What is a galaxy?

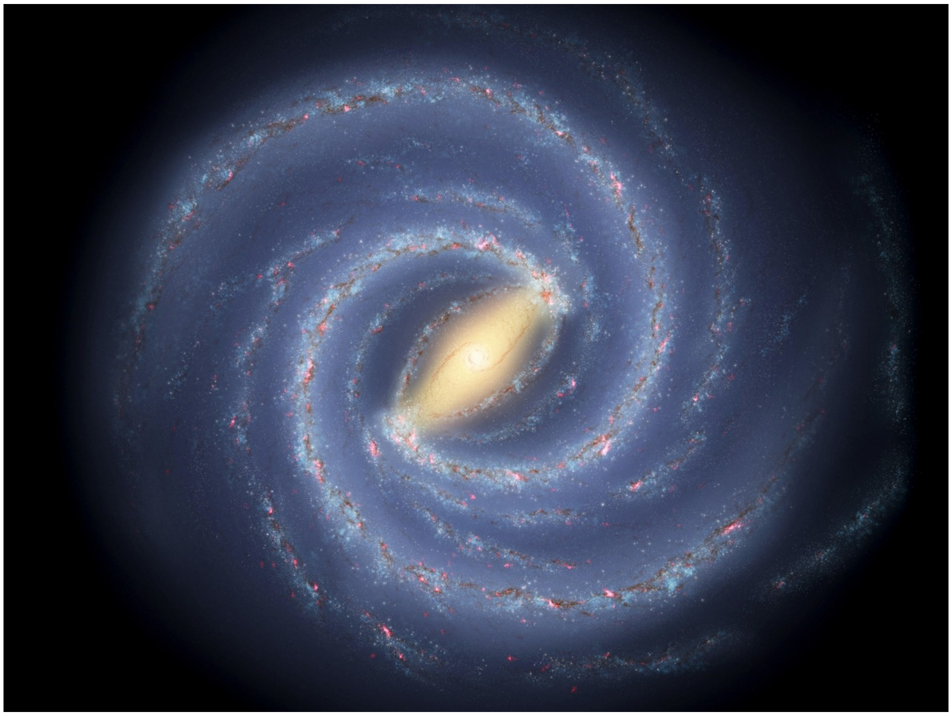

Figure 6: *A typical galaxy: our Milky Way (artist's impression).* ***Credit:*** *NASA*

A *galaxy* is a huge collection of stars and interstellar matter isolated in space and bound together by gravity. There are thought to be over 100 billion galaxies in the Universe, mainly residing in clusters and groups. The most well known galaxy is our own Milky Way –and indeed, the term *galaxy* comes from the Greek word 'gala', which means 'milk'.

Most galaxies have a total mass between 10,000 and 10 trillion solar masses, and sizes between a few to over several hundred kiloparsecs (1 kpc = $3.086 \cdot 10^{16}$ km). The Milky Way (shown in Figure 6) contains over 100 billion stars, including the Sun, and the stellar disk extends to about 30 kpc in diameter; it also has a stellar halo with a diameter of about 100 kpc, and a dark matter halo that may extend well beyond this.

Classifying galaxies: The Hubble Tuning Fork

Galaxies are classified according to their shapes in optical (visible-light) images. The most common classification scheme in use today is the Hubble classification scheme, or *Hubble tuning fork* (Figure 7). In this scheme, galaxies are classified into the following broad categories: ellipticals, spirals, and irregulars. The ellipticals are smooth and round or elliptical, the spirals are flat with a spiral pattern in their disk, and the irregulars have stars and gas in random patches. Spirals are further classified into two types: regular spirals, where the arms come right out of the galaxy centre, or *barred* spirals, with the arms starting from the ends of a bar of gas and stars going through the centre. The ellipticals are sub-divided by how round they are and the spirals are sub-divided by how loose their arms are and how big their nucleus is.

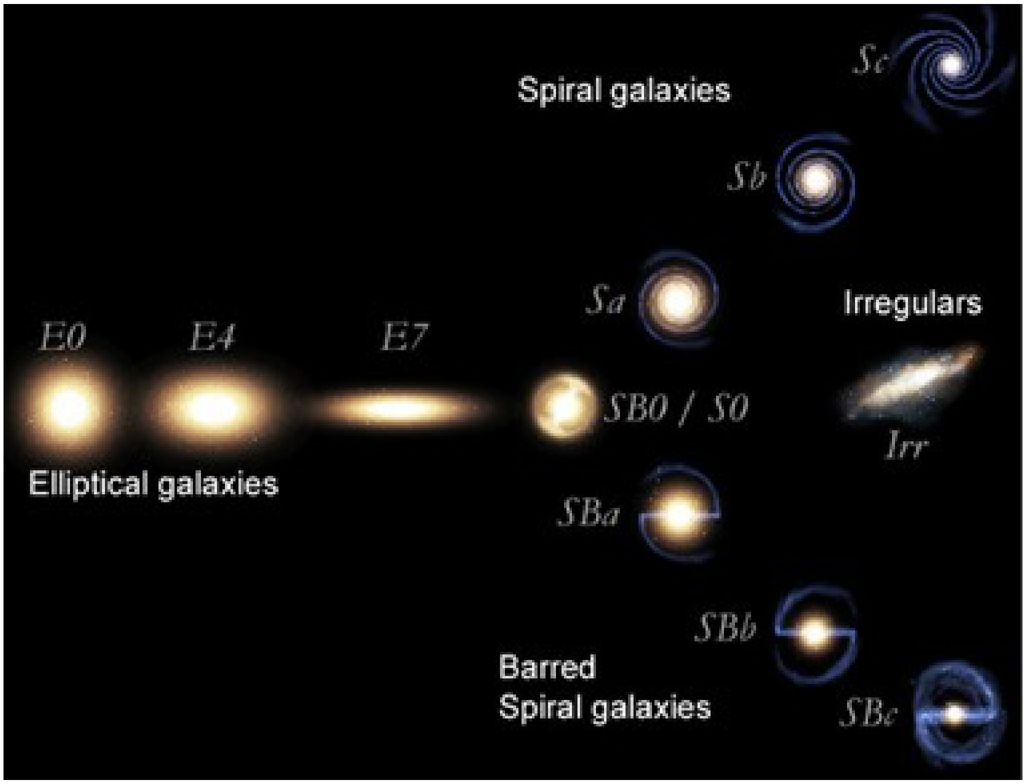

Figure 7: *The Hubble Tuning Fork.* ***Credit:*** *NASA/ESA*

Most galaxies are small and faint and are called *dwarf galaxies*; they tend to be elliptical or irregular in shape. Only the most luminous and biggest galaxies are seen at great distances; these spectacular *giant galaxies* tend to be either the elliptical or spiral type. The biggest of all are always ellipticals.

In 1936, Hubble put these groups onto a two-pronged sequence that looks like a tuning fork, because he thought that the galaxies started out as ellipticals, then changed either to regular spirals or barred spirals, and then to irregulars. However, astronomers now know that this diagram does not represent the evolution of galaxies.

The optical colours of galaxies vary depending on their types: Elliptical galaxies usually show yellowish or reddish colours, in contrast with spirals and irregulars that tend to look more bluish. Inside a spiral galaxy, the central part or *bulge* looks yellowish or reddish, while the *disk* containing the spiral arms usually glow bluish; spirals are also surrounded by a *halo* of yellowish or reddish stars, often packed in spherical *globular clusters* (see Figure 8). Astronomers relate these colour differences to the different types of stars galaxies contain: Remember that stars get reddish when they evolve off the main sequence, while young massive stars are blue. Thus, if a galaxy looks bluish, it means that it contains lots of young stars, while a yellowish or reddish galaxy will contain mostly old stars. (Note that big, massive stars are the only ones bright enough to be observed at the distances of most galaxies.)

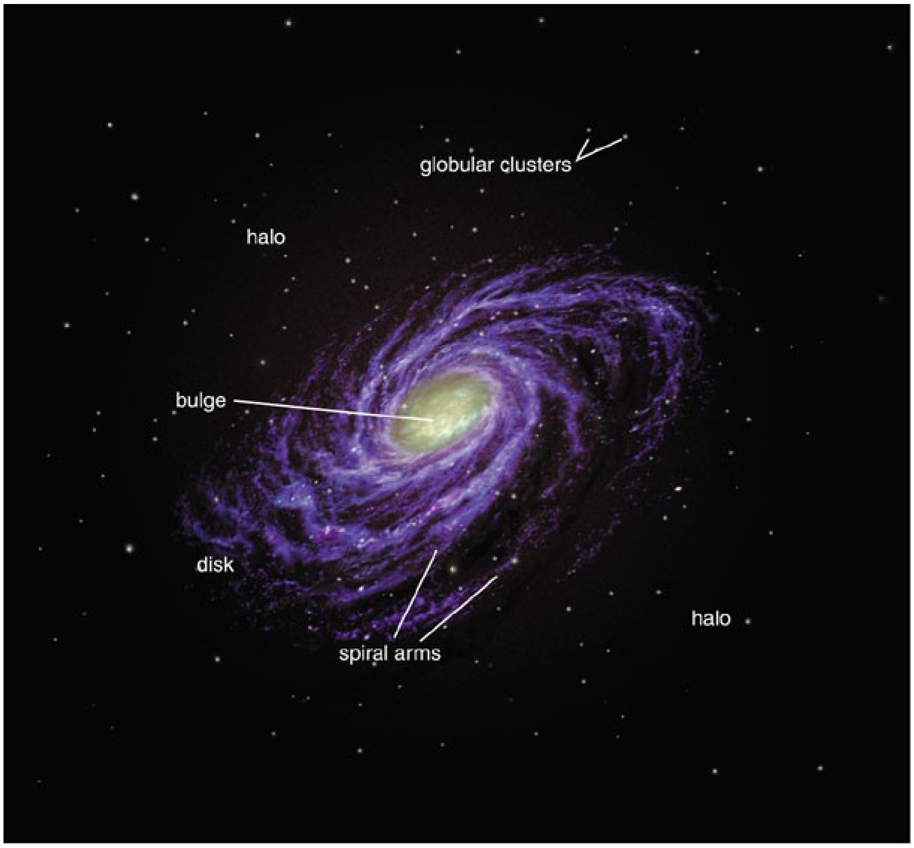

Figure 8: *Parts of a spiral galaxy.* ***Credit:*** *Pearson Education*

Since stars form from clouds of dust and gas, if a galaxy is rich in young stars, we expect it to contain large amounts of interstellar gas and dust as well; while a galaxy that does not contain much gas and dust will not have many young stars, as there is no material from which these stars can form. Therefore, we do not expect elliptical galaxies to be rich in gas and dust, and hence, they will not look very bright in infrared and radio images (as they mainly show the emission of dust and gas, respectively). On the other hand, galaxies rich in young stars, like spirals, must be very prominent in the infrared and radio.

Galaxy formation and evolution

Astronomers are just beginning to understand how galaxies form and evolve. They now think that all galaxies began forming about 13 billion years ago, when the Universe was very young. In the beginning, there were only very small clumps of stars and gas about the size of a million solar masses (the size of a globular cluster) that started collapsing, forming larger structures. Then galaxies would be drawn into clusters and superclusters by their mutual gravitational attraction.

This theory is supported by the fact that there are many more dwarf galaxies than giant galaxies; they may have originated from cloud fragments that did not get incorporated into larger galaxies. In addition, at very large distances, most galaxies are small and irregular; since the further we observe, the earlier in time (because light takes time to travel from the source galaxy to us), this means that early in the history of the universe, only small, irregular galaxies existed, as the ones shown in Figure 9.

Another fact supporting this theory of galaxy formation and evolution is that collisions and mergers of galaxies are still observed today. As a matter of fact, galaxy collisions do happen quite often.

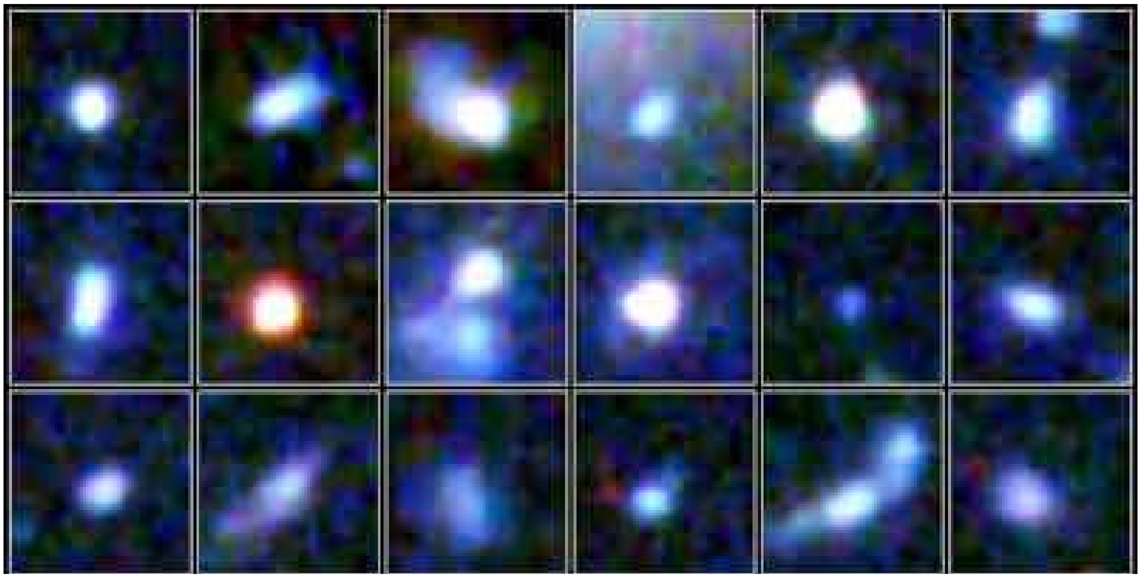

Figure 9: *Small, irregular galaxies like the ones in these images from the Hubble Space Telescope are observed at large distances. They are thought to be the 'building blocks' of current giant galaxies.*

Credit: *NASA/ESA*

Interacting galaxies

The distances between galaxies are large, but not extremely large compared to their sizes: only a few times bigger. Thus galaxy collisions do happen quite often. The shapes of galaxies may get remarkably distorted in the collision, as in the example shown in Figure 10. The two galaxies can even merge to form a larger galaxy. The giant elliptical galaxies usually found close to the centres of galaxy clusters most likely formed from the collision and merging of smaller galaxies.

Stars inside a galaxy do not collide because the distances between them are hundreds of thousands to millions of times larger than the sizes of stars; for the same reason, when two galaxies collide, the stars will pass right on by each other without colliding, although their orbits can be radically changed.

On the contrary, the gas clouds in galaxies are much larger than stars, so they will likely hit the clouds in another galaxy when the galaxies collide. As a consequence, the clouds compress and collapse to form a lot of stars in a short time. Galaxies undergoing such a process are called *starburst galaxies*.

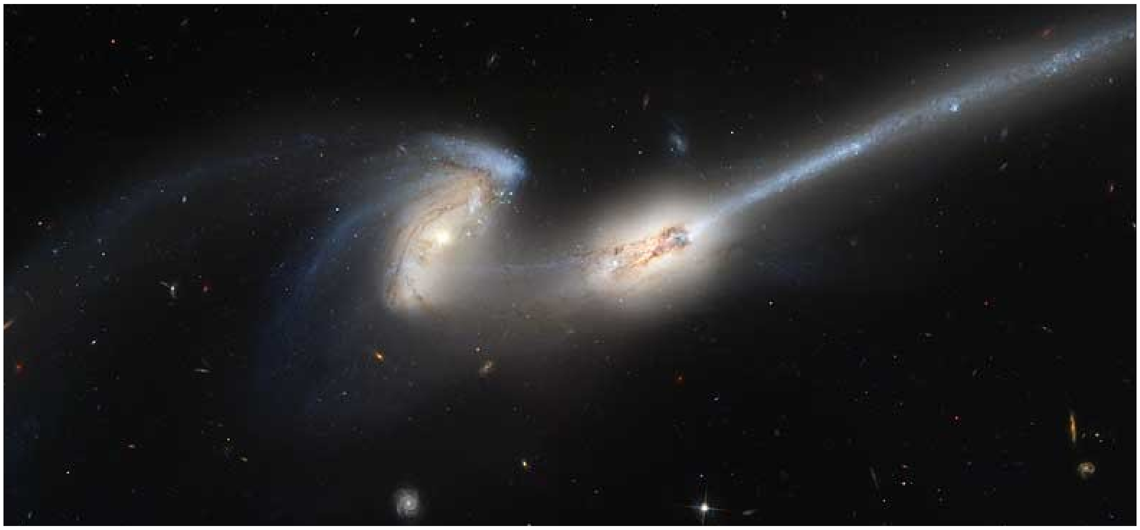

Figure 10: *The Mice, two colliding galaxies, as observed by the Hubble Space Telescope.* ***Credit:*** *NASA/ESA*

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