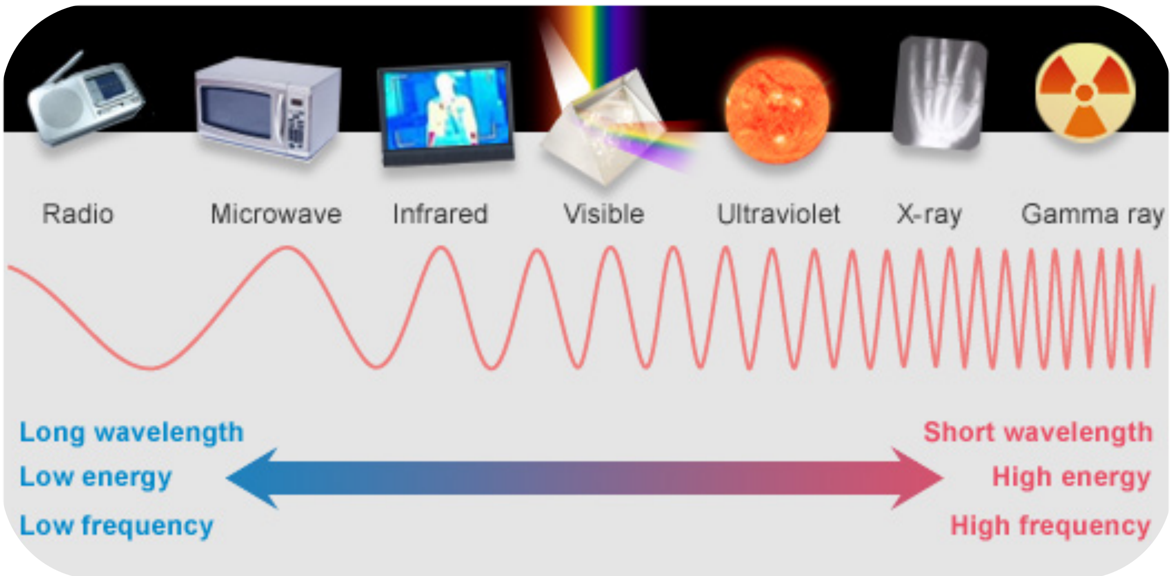
The electromagnetic spectrum

CESAR's Booklet



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*.

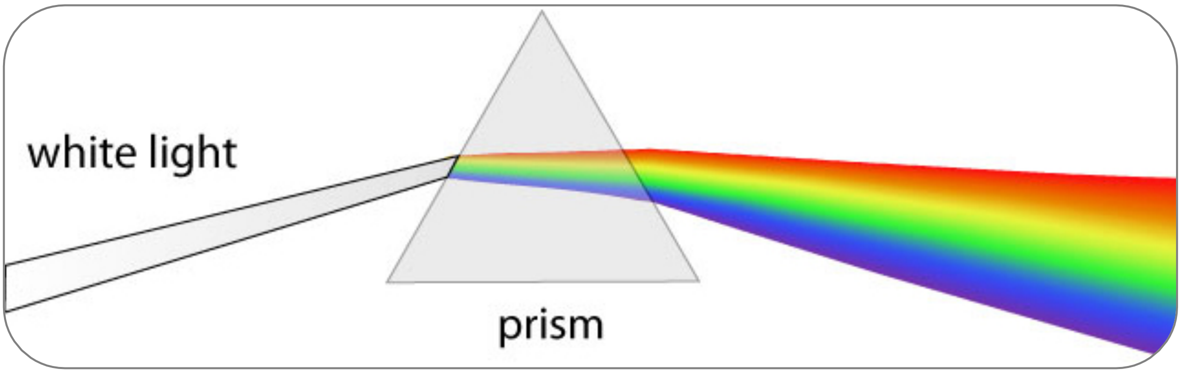


Figure 1: *White light passing through a prism creates a rainbow. (Credit: physics.stackexchange.com)*

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.

Light as waves

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.

Properties of waves

A wave (Figure 2) is a periodic perturbation from an *undisturbed or rest state* that is transmitted in space. The maximum deviation from this undisturbed state is called the *amplitude* of the wave, and is a measure of the intensity of the perturbation; the top of the wave is called a *crest* and the lowest state, a *trough*.

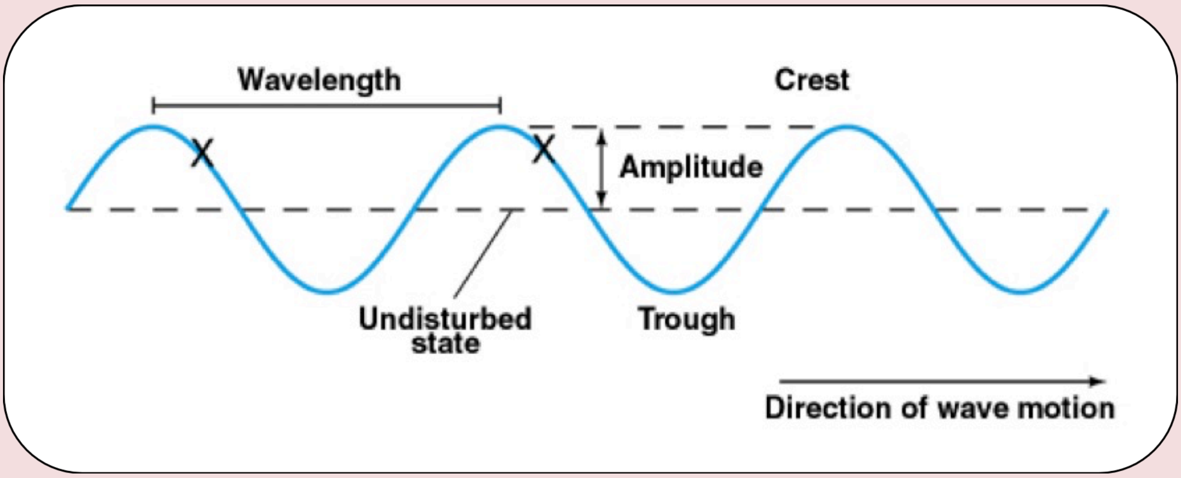


Figure 2: *Properties of a wave. (Credit: Pearson Prentice Hall)*

Waves are characterised by their size, measured as the distance between two equal states; this distance is called the *wavelength,* λ. The colours of visible light are the way our eyes perceive the different wavelengths.

The time it takes for the perturbation to move one wavelength –in other words, to repeat itself–, is called the *period* of the wave, *P*. Wavelength and period are related through the *speed* of the wave, *c*, because speed is defined as space travelled per unit time:

$$c = \frac{\lambda}{P} \tag{1}$$

The number of complete cycles –the number of times the wave repeats itself– in one second is called the *frequency* of the wave, ν. Thus, the frequency is the inverse of the period, and is also related to the wavelength through the wave speed:

$$\upsilon = \frac{1}{P} = \frac{c}{\lambda} \tag{2}$$

It is important to note that *the speed of light waves does not depend on the frequency, wavelength or period, but only on the medium the wave is traveling through*. However, contrary to other waves like sound or water waves, electromagnetic waves (light) do not actually require a medium to be transmitted through: they can travel through the vacuum. If light travels through a vacuum, it has the maximum possible speed –and this speed is the same for all frequencies of light.

Figure 3 summarises the properties of the electromagnetic spectrum:

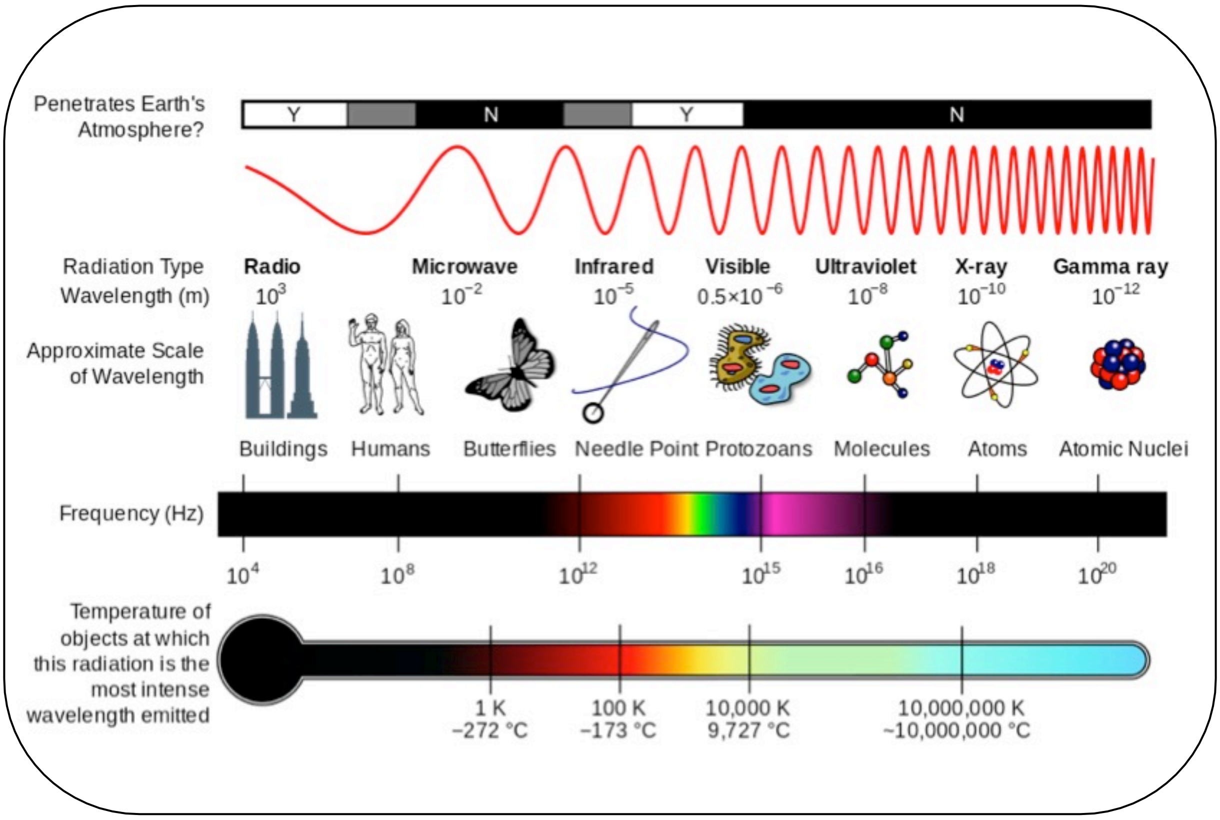


Figure 3: *Properties of the electromagnetic spectrum. (Credit: Wikimedia Commons)*

The colours of stars

The amount of light of a given colour (or wavelength) that is emitted by a body depends on its temperature. And since all macroscopic bodies have a temperature above absolute zero, all of them emit light, at all times and in all wavelengths. The reason is that they are made of microscopic, electrically charged particles that are constantly in random motion; and Physics shows that a charged particle in motion emits electromagnetic radiation.

Thus, even if you cannot see it with your eyes, everything around you is emitting light: stars and light bulbs of course, but also your table and chair, your cat, even ice cubes, even *you*. However, for most everyday objects, the amount of light emitted in the visible range is very low; we see most of the things around us thanks to the light they reflect, not to the light they emit.

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!

Blackbody radiation

The emission of light from many macroscopic objects, including stars and other astronomical bodies, can be approximately described by a so-called *blackbody curve*. A blackbody is an ideal object that absorbs all radiation falling upon it, in all frequencies, and that is able to re-emit the same amount of energy it absorbs. If we plot the amount of energy radiated by a blackbody as a function of wavelength (or frequency), we get a characteristic distribution that depends solely on the temperature of the object.

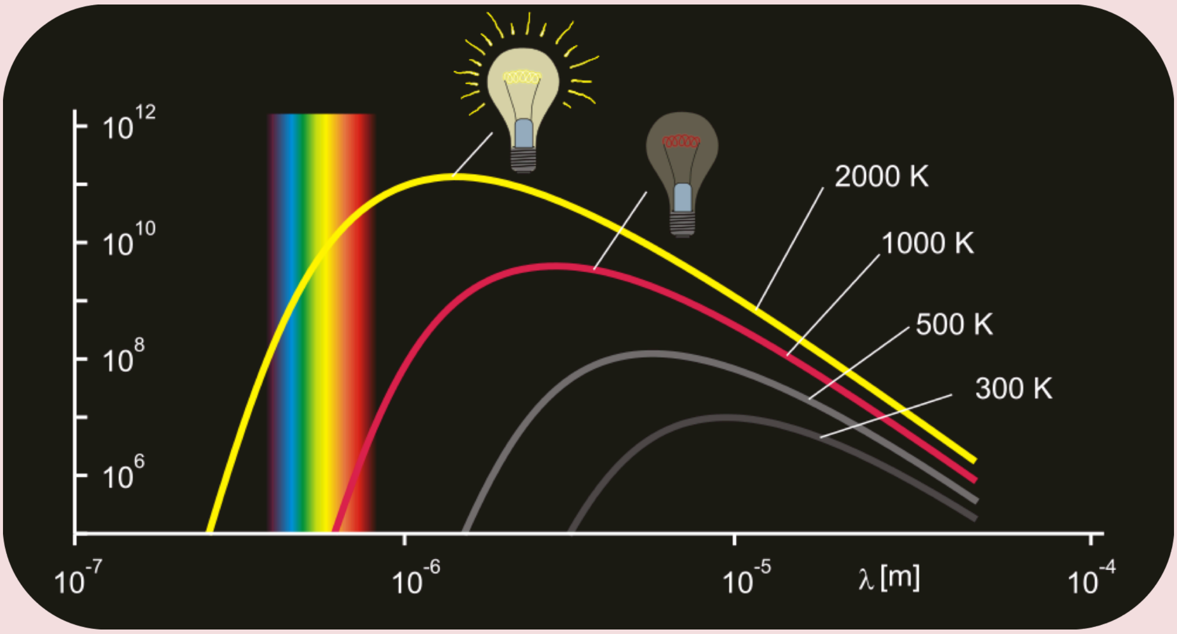


Figure 4: *Blackbody curves of different temperatures. (Credit: Wikimedia Commons)*

As seen in Figure 4, the blackbody curve has a peak at a given wavelength (or frequency), and this peak gets higher as the body's temperature increases, meaning that the area below the curve also gets bigger. This means that the amount of energy radiated by the object also increases; and the opposite: as temperature decreases, the energy output from the blackbody decreases. This behaviour is known as *Stefan-Boltzmann's Law*, and it goes mathematically like this:

$$E = \sigma T^4 \tag{3}$$

The quantity σ, known as *Boltzmann's constant*, has the value:

$$\sigma = 5.6704 \cdot 10^{-8}\ \mathrm{W{\cdot}m^{-2} \cdot K^{-4}}$$

In plain words, Stefan-Boltzmann's Law is telling us that *the hotter the object, the more energy it radiates*.

Also the position of the curve peak depends on the blackbody's temperature. If the temperature increases, the peak shifts toward shorter ('bluer') wavelengths (higher frequencies), while it will shift toward longer ('redder') wavelengths (lower frequencies) as the temperature decreases. The mathematical relation between the peak wavelength λ_{max} and the blackbody's temperature *T*, known as *Wien's Law*, is the following:

$$\lambda_{max} = \frac{b}{T} \qquad (4)$$

where the constant of proportionality *b* is called *Wien's displacement constant*, and its value is:

$$b = 2.8978 \cdot 10^{-3}\ \text{m·K}$$

The position of the peak is related to the colour of the blackbody: If the curve peaks in the blue or violet end of the visible spectrum, the object will look blue to our eyes; if it peaks in the red end, it will look red. If it peaks in-between, the amount of light emitted by the blackbody in all visible colours is relatively high, and so our eyes will perceive a mixture of all those colours; that is why we don't see any green stars!

Hence, what Wien's Law is telling us is: *The hotter the star, the bluer it is.*

If the blackbody curve peaks outside the visible range of the electromagnetic spectrum, the colour we see will depend on the amount of light emitted in each frequency (or wavelength) of the visible spectrum: A blackbody radiating most in the ultraviolet will still emit a lot of energy in the violet and blue, and thus those objects will be a deep blue colour to our eyes. On the other hand, a blackbody peaking in the infrared will emit very little in the visible range, and hence we will see it black.

Figure 5 shows the (approximated) colours of stars of different temperatures.

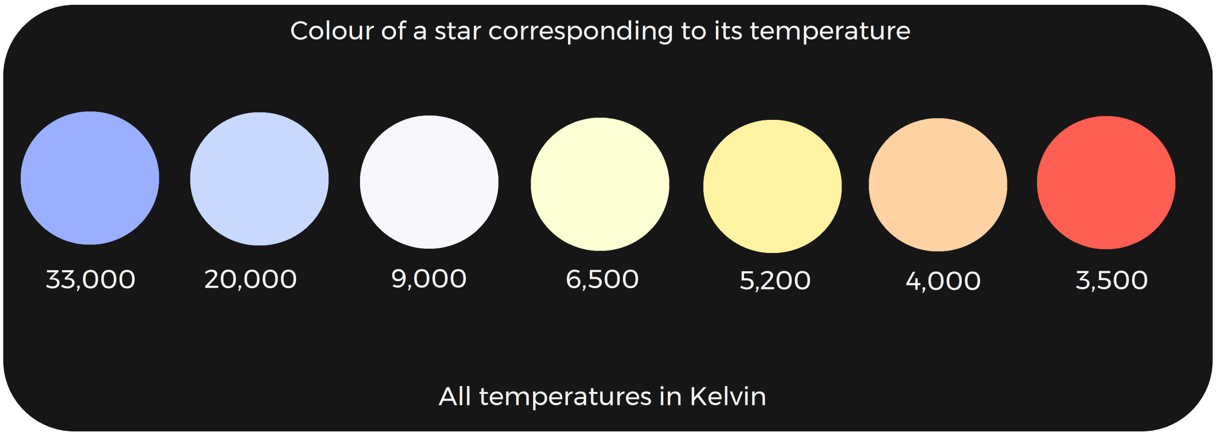


Figure 5: *Colours of stars of different temperatures. (Credit: Quora)*

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 6 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.

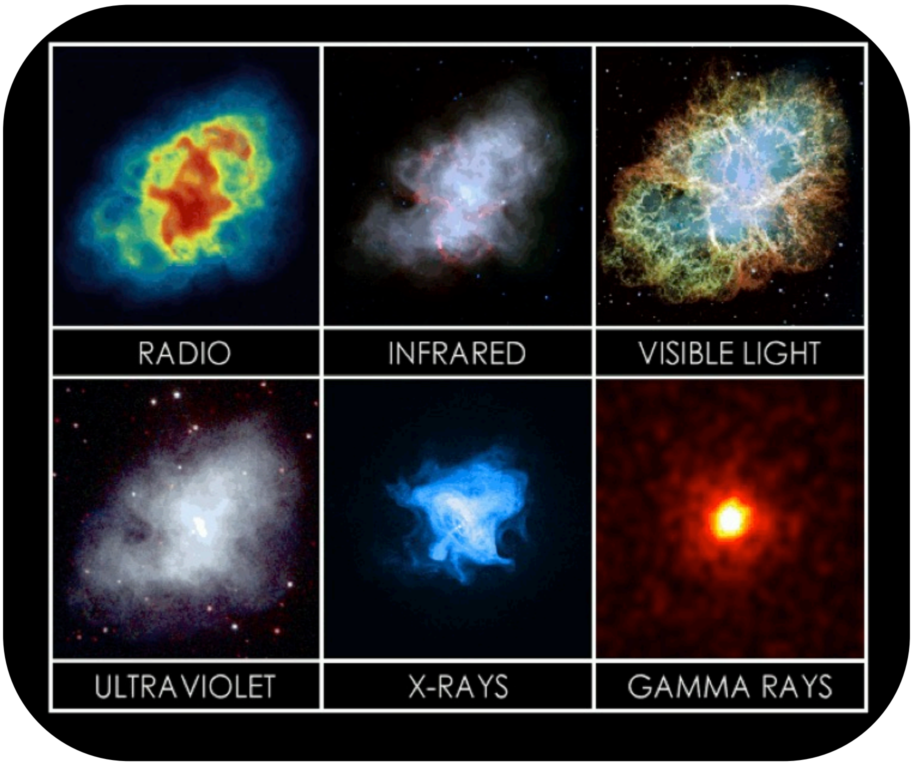


Figure 6: *The Crab Nebula observed across the electromagnetic spectrum. (Credits: NASA/ESA/NRAO)*

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 (see Figure 3). For this reason, telescopes observing the universe in invisible colours (except part of the radio and infrared) must be placed in space. Figure 7 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!*

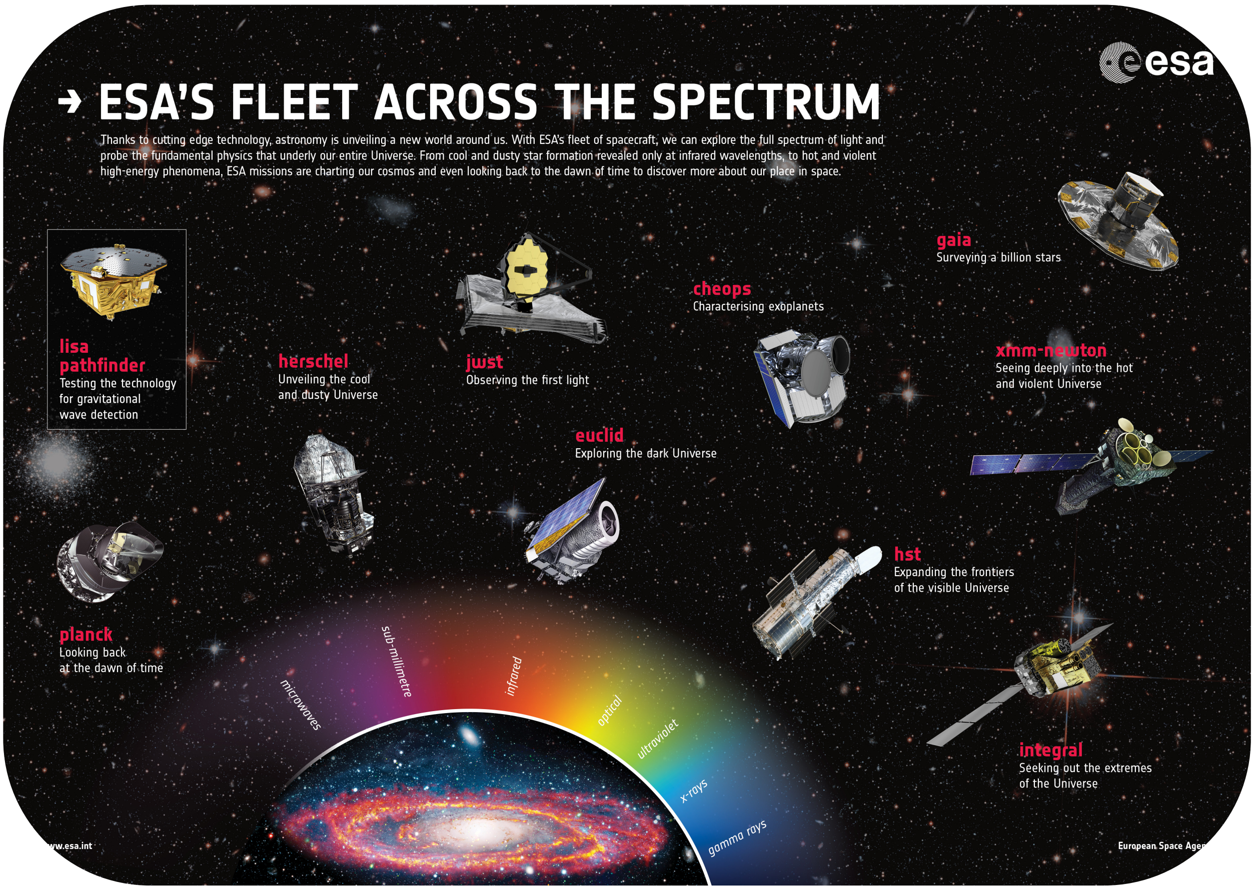


Figure 7: *ESA's fleet of telescopes across the electromagnetic spectrum. The sub-millimetre range corresponds to the shortest radio waves. (Credit: ESA)*