

natural processes that support life on Earth. In this chapter, we will explore how stars emit energy (luminosity), how we use tools like standard candles and redshift to measure cosmic distances, and how radiation laws help in estimating the temperature and size of stars. We will also learn how Earth's climate system functions through complex interactions among air, water, ice, land, and life, and how these elements respond to solar energy, wind, and ocean circulation.

21.1 LUMINOSITY OF A STAR

Luminosity is the total amount of energy emitted by a star per unit time in the form of electromagnetic radiations. It is a fundamental property that defines the intrinsic brightness of a star. Luminosity is represented by the symbol L and is measured in watts, indicating the total power of radiation emitted by a star. Luminosity of a star primarily depends on its radius and surface temperature. Larger stars have more surface area to emit radiations and therefore, tend to be more luminous. Similarly, for stars of equal size, the one with the higher surface temperature will radiate more energy and hence, exhibits greater luminosity. The luminosity of a star can be represented as the product of its surface area ($A = 4\pi r^2$) and radiant intensity ($I = \sigma T^4$);

$$L = 4\pi r^2 \sigma T^4 \dots\dots\dots (21.1)$$

Equation (21.1) is called Stefan-Boltzmann law. It states that;

The total output power of a star is proportional to the product of its surface area and the fourth power of its temperature.

where σ is Stefan-Boltzmann constant. Its value is $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$. T is the surface temperature and r is the radius of the star.

Example 21.1 The luminosity of a star is given as $2.5 \times 10^{26} \text{ W}$, and its surface temperature is 6000 K. Estimate the radius of the star.

Solution Luminosity of the star $L = 2.5 \times 10^{26} \text{ W}$
 Surface temperature of the star $T = 6000 \text{ K}$
 Radius of the star $r = ?$

Using Stefan-Boltzmann law; $L = 4\pi r^2 \sigma T^4$

$$\text{or } r = \sqrt{\frac{L}{4\pi\sigma T^4}} = \sqrt{\frac{2.5 \times 10^{26} \text{ W}}{4 \times 3.14 \times 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \times (6000 \text{ K})^4}}$$

$$r = 5.2 \times 10^8 \text{ m}$$

Tidbit!



The Sun shines with an immense luminosity of about 4×10^{26} watts that is equivalent to billions of nuclear explosions happening every second.

Do you know?

Stefan-Boltzmann's law helps astronomers estimate the size and brightness of stars just by knowing their temperature.

Brain Teaser

If a star becomes twice as hot, how many times more energy will it radiate?

21.2 RADIANT FLUX INTENSITY

Radiant flux intensity is the amount of electromagnetic energy per unit area per unit time emitted from a star that reaches the Earth's surface.

It is a small fraction of the total value of luminosity. In other words, radiant flux intensity is the luminosity per unit area measured on the surface of Earth. Radiant flux intensity from a star at a distance d is expressed as:

$$\text{Radiant flux intensity } F = \frac{L}{4\pi r^2} \dots\dots\dots (21.2)$$

where L is the luminosity and $4\pi r^2$ is the surface area of star. As the luminosity of a star remains constant, therefore, radiant flux intensity follows inverse square law with distance as demonstrated in Fig. 21.1. According to this law, when the distance from centre of a star is doubled (from r to $2r$), intensity of the radiant flux reduces to one-fourth of its original value. Similarly, increasing the distance to three times its initial length ($3r$), decreases the flux by a factor of nine, and this pattern continues accordingly.

Fig. 21.1: Schematic illustration of the inverse-square law for radiant flux intensity

Tidbit!

If Earth were twice as far from the Sun, the sunlight reaching it would be only one-fourth as intense. Such low energy might have made the evolution of life impossible.

Brain Teaser

Two stars appear equally bright in the night sky. However, one is 10 times farther away than the other. Which star is more luminous, and by how much?

Example 21.2

The luminosity of a star is 4.50×10^{26} W. It is located at a distance of 1.40×10^{11} m from a planet. Calculate the radiant flux intensity of the star at the surface of that planet.

Solution

Luminosity of the star $L = 4.50 \times 10^{26}$ W
Distance between Earth and the star $r = 1.40 \times 10^{11}$ m
Radiant flux intensity $F = ?$

Using the formula;

$$F = \frac{L}{4\pi r^2} = \frac{4.50 \times 10^{26} \text{ W}}{4 \times 3.14 (1.40 \times 10^{11} \text{ m})^2}$$

$$F = 1.83 \times 10^3 \text{ W m}^{-2}$$

Do you know?

The idea of standard candles dates back to the 1910s, when Henrietta Swan Leavitt discovered that Cepheid variable stars pulse in a predictable way. Her work laid the foundation for measuring cosmic distances and the scale of the universe. Without standard candles, we would not even know how big the universe is.

21.3 STANDARD CANDLES

In astronomy, measuring the distances to stars and galaxies is essential for understanding the structure and expansion of the universe.

The standard candles are astronomical objects with known intrinsic brightness that serve as vital tools for measuring cosmic distances.

By comparing how bright a standard candle appears from the Earth (apparent magnitude) to how bright it actually is, astronomers can calculate its distance using the inverse-square law of light. Examples of standard candles are Cepheid variable stars and Type Ia supernovae, both of which have predictable luminosities that make them reliable distance indicators.

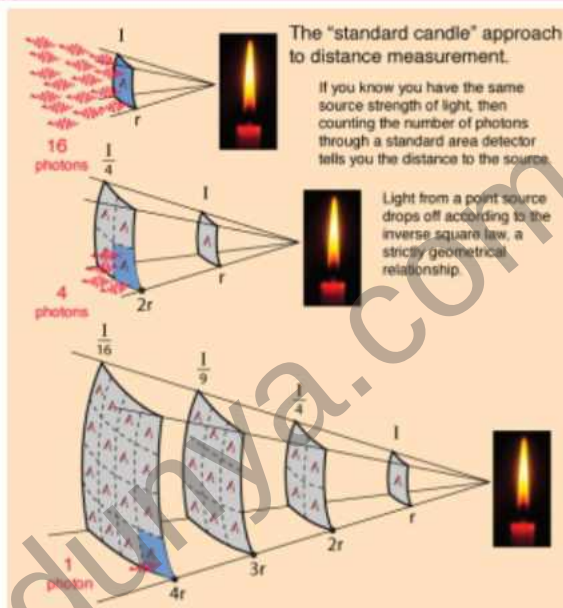


Fig. 21.2:

21.4 BLACKBODY RADIATION

When an object is heated, it starts to glow and releases energy in the form of radiation. This radiation depends only on the temperature of the object, not on its material or shape. As the temperature increases, the colour of the object changes from dull red to bright yellow and then to white, indicating that the radiation is shifting from longer wavelengths (infrared) to shorter ones (ultraviolet). However, real objects do not absorb or emit all the radiation completely, which makes it difficult to study their behaviour accurately. To understand this better, scientists consider an ideal object, called a blackbody.

A blackbody is one that absorbs all the radiations falling on it and also emits radiations at all wavelengths perfectly.

In real life, a good example of a blackbody is a hollow cavity with a small hole and blackened inner walls as shown in Fig. 21.3. The inner walls of the cavity are coated with black carbon soot to help them absorb radiation effectively and reflect it internally.

Brain Teaser

Two stars appear equally bright in the sky. One is a standard candle whose true brightness is well known. The other is not. If the standard candle is farther away, what can you say about the true brightness of the second star?

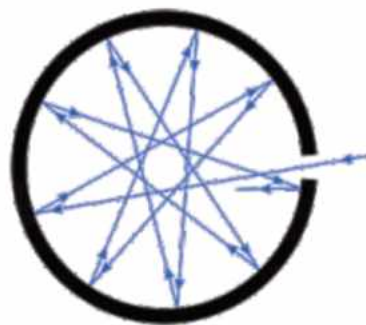


Fig. 21.3: Perfect or an ideal blackbody

When radiation enters through the small hole, it bounces around inside and gets trapped. If the cavity is heated to a high enough temperature, it starts to emit radiation of all wavelengths. This is known as blackbody radiation. The pattern of this radiation depends only on the temperature of the blackbody. As the temperature increases, the energy it gives off also increases. When we plot the intensity of this radiation against its wavelength (Fig. 21.4), we find that the peak of the curve shifts to shorter wavelengths with rising temperature. This means hotter blackbodies emit more energy at shorter wavelengths.

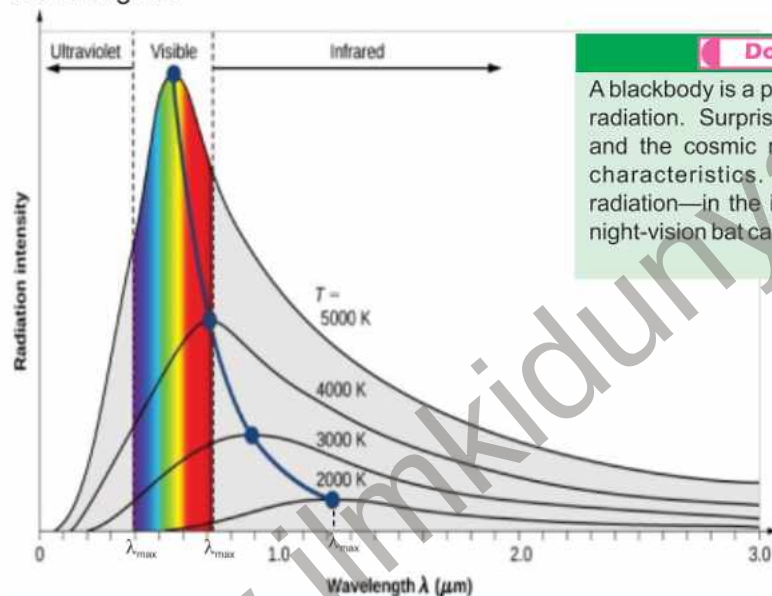


Fig. 21.4: Blackbody radiation spectra

Do you know?

A blackbody is a perfect absorber and emitter of radiation. Surprisingly, both microwave oven and the cosmic microwave exhibit blackbody characteristics. Even we emit blackbody radiation—in the infrared range—which is why night-vision bat can detect us in the dark!

Brain Teaser

Two objects are heated to different temperatures. One glows red-hot, and the other glows white-hot. Which one is hotter, and why?

Stars as Black Body Radiators

Stars such as Sun behave like blackbody radiator. They generate and emit their own energy due to nuclear fusion and this energy spreads into space in the form of electromagnetic radiation. The radiation emitted by a star covers a wide range of wavelengths and forms a continuous spectrum without any gaps. This spectrum is similar to a blackbody spectrum. By studying the spectrum, scientists can estimate the surface temperature of the star accurately. As each star has its own spectrum, so its surface temperature is also different.

Wien's Displacement Law

Wien's Displacement law describes the relationship between the surface temperature T of a blackbody and the wavelength λ_{max} at which it emits radiation most intensely. According to this law;

Tidbit!

The moment you switch on your mobile phone, your location can be tracked immediately by global positioning system.

The wavelength corresponding to the radiation of maximum intensity emitted by a blackbody is inversely proportional to its surface temperature.

i.e.,

$$\lambda_{\max} \propto \frac{1}{T}$$

or $\lambda_{\max} T = b \dots\dots\dots (21.3)$

where b is a constant called Wien's constant whose value is 2.9×10^{-3} mK. This law demonstrates that, as the temperature of a blackbody increases, the maximum wavelength of its emitted radiation shifts towards shorter values. In simple words, hotter objects emit radiation with shorter wavelengths (appearing blue or violet), while cooler objects emit radiation with longer wavelengths (appearing red or infrared). This shift explains the change in colour of heated objects and helps to determine the temperature of stars and other radiating bodies.

Example 21.3 The surface temperature of a star is 6000 K, and its peak wavelength of emitted radiation is 480 nm. Another star has a peak wavelength of 320 nm. Calculate the surface temperature of this second star.

Solution Surface temperature a star-1 $T_1 = 5800$ K

Wavelength at peak intensity of star-1 $\lambda_{\max 1} = 480$ nm

Wavelength at peak intensity of star-2 $\lambda_{\max 2} = 320$ nm

Surface temperature of star-2 $T_2 = ?$

Using the relationship for Wien's displacement law;

$$\lambda_{\max} T = b$$

$$\text{i.e., } \lambda_{\max 1} T_1 = \lambda_{\max 2} T_2 \quad \text{or} \quad T_2 = \frac{\lambda_{\max 1} T_1}{\lambda_{\max 2}}$$

$$T_2 = \frac{480 \times 10^{-9} \text{ m} \times 6000 \text{ K}}{320 \times 10^{-9} \text{ m}} = 9000 \text{ K}$$

So, the surface temperature of star-2 is 9000 K

Brain Teaser

If a star's peak wavelength is shorter, what does that tell us about its temperature?

Tidbit!

Every star has its own light signature by studying the emission and absorption spectra, scientists can determine what elements a star is made of.

21.5 RADIUS OF A STAR

The radius of a star can be calculated using Wien's displacement law and the Stefan-Boltzmann law. For this purpose, the surface temperature T of a star is first determined using Wien's displacement law. The Luminosity of a star can be calculated using the radiant flux intensity and then Stefan-Boltzmann law is used to determine the radius of star.

21.6 EMISSION AND ABSORPTION SPECTRA FROM DIFFERENT STARS

Stars emit a continuous spectrum of light because of their extremely hot, dense surfaces that behave like near-perfect blackbodies. As this light passes through the cooler outer atmosphere of a star, atoms in the gaseous layers absorb specific wavelengths corresponding to electronic transitions between energy levels. This creates dark lines in the continuous spectrum where specific colours of light have been

absorbed. It is known as the absorption spectrum. Although the absorbed energy is re-emitted at the same wavelengths, the emitted photons are scattered in various directions making them unlikely to reach observers on Earth. Therefore, we detect a characteristic absorption spectrum with distinct missing wavelengths. In emission and absorption spectra from distant stars and galaxies, the lines in the spectra show an increase in wavelength from their known laboratory values (Fig. 21.5). This phenomenon is called redshift which occurs due to stretching of photons when they travel through the universe.

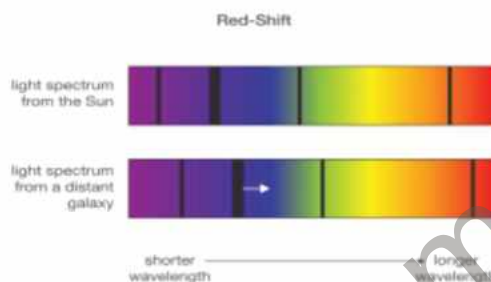


Fig. 21.5: Light spectra from Sun and distant galaxies, showing a redshift in wavelength

21.7 COSMIC REDSHIFT: EVIDENCE FOR AN EXPANDING UNIVERSE

Cosmic redshift refers to the effect in which light coming from distant galaxies across the universe is stretched toward the red end of the spectrum. This happens because the universe is expanding, causing galaxies to move away from us. As a result, the wavelength of light emitted by the galaxies increases. The greater the distance of a galaxy, the larger its redshift, i.e., it is moving away faster. By studying cosmic redshift, scientists can measure how fast the universe is expanding.

The observed change in the wavelength of light is directly related to the relative velocity between the source and the observer.

$$Z = \frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$$

$$\text{or } Z = \frac{\Delta\ell}{\ell} \gg \frac{\Delta f}{f} \gg \frac{v}{c} \dots\dots\dots (21.4)$$

When the observed change in wavelength $\Delta\lambda$ is positive, it indicates a redshift (Z). This illustrates that the celestial object is moving away from Earth. On the other hand, a negative $\Delta\lambda$, represents a blue shift, showing that the object is approaching the Earth. Astronomers study the changes in the colour of light from stars and galaxies to understand how fast and in which direction they are moving. The light from faraway galaxies appears more red than expected (redshift phenomenon). This happens because space itself is stretching as the universe expands, which also stretches the light waves and makes their wavelengths longer. The redshift pattern is observed in all directions which indicates the expansion of the universe. It is not just that galaxies are moving apart through space, rather, the space between them is increasing. These findings strongly support the Big Bang theory, which suggests that the universe originated from an extremely hot and dense state and is growing ever since. The relationship between redshift and distance enables scientists to determine the size of

the universe and how it has changed over time.

21.8 HUBBLE'S LAW

Edwin Hubble established the foundation for modern cosmology by demonstrating that galaxies are moving away from the Earth, and their velocity increases with distance. In other words, the farther a galaxy is, the faster it appears to be moving away. This observation led to Hubble's law, which states that:

The recession velocity v of a galaxy is directly proportional to its distance d from the Earth.

Therefore $v \propto d$

or $v = H_0 d \dots\dots\dots (21.5)$

Here v is the recession velocity and d is the distance. H_0 is called Hubble's constant and its value is $2.3 \times 10^{-18} \text{ s}^{-1}$.

Fig. 21.6 illustrates graphical representation of Hubble's law, revealing a direct and linear relationship between the redshift of galaxies and their distance from Earth. As the distance increases, the recession velocity also increases, providing a strong evidence for an expanding universe. The slope of this linear trend corresponds to the Hubble constant (H_0), which quantifies the rate of cosmic expansion.

All the galaxies in the universe are moving away from each other. An observer in another galaxy will observe the same effect. This is happening because space itself is stretching. An inflated-balloon model is often considered by scientists to explain the Big Bang expansion, as shown in Fig. 21.7. The dots which are marked on the surface of a balloon represent the galaxies, and the skin of balloon represents four dimensional space-time. As the balloon is inflated, every dot "sees" the other dots moving away. This is similar to how galaxies move apart in space. This model helps us to understand two main ideas. First, no matter where we are in the universe, we would see galaxies moving away

Do you know?

Before Hubble's discovery, most scientists thought the universe was static. Hubble's law turned that idea on its head, suggesting the universe had a beginning, leading to the Big Bang theory.

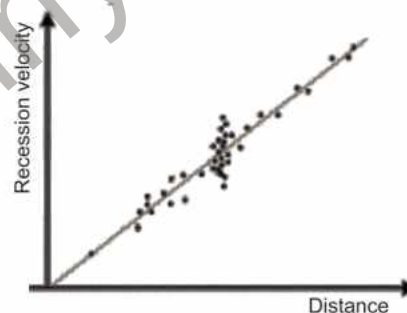


Fig. 21.6: Graphical representation of Hubble's law

Brain Teaser

A galaxy is moving away from us very fast. According to Hubble's Law, what does that tell us about its distance?

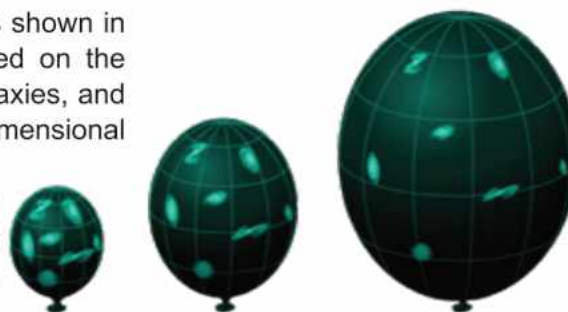


Fig. 21.7: Analogy of the expanding universe: dots move apart as the balloon inflates

from us. This means the expansion is happening everywhere, and there is no special centre. Earth is not at the centre of the universe. The universe is expanding now, we can conceptually reverse time. Doing so implies:

- (i) in the past, galaxies were closer together.
- (ii) going further back, all matter was compressed into a very small, dense, and hot state.

This idea forms the basis of the Big Bang Theory, which proposes that the universe began from an initial singularity about 13.8 billion years ago and has been expanding ever since. Hubble's law provides strong observational evidence that the universe is not static but expanding, which is one of the key pillars supporting the Big Bang model.

An approximate timeline for the evolution and expansion of the universe from the Big Bang till present is presented in Fig. 21.8.

Steps of Satellite Remote Sensing

Satellite remote sensing is a powerful technology that uses sensors aboard orbiting spacecraft to monitor and analyze Earth's environment from space. It enables scientists to track phenomena such as deforestation, climate change, ocean temperatures, and atmospheric composition. Unlike ground-based methods, it offers wide geographic coverage and repeated observations over time, making long-term environmental monitoring possible.

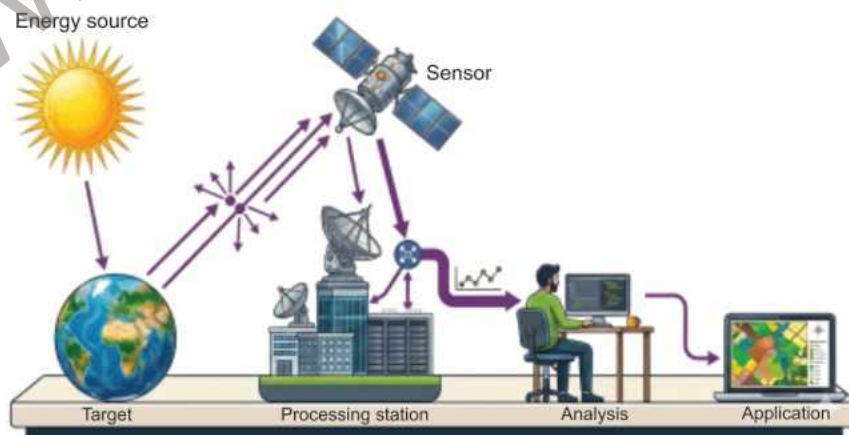


Fig. 21.9: The remote sensing process

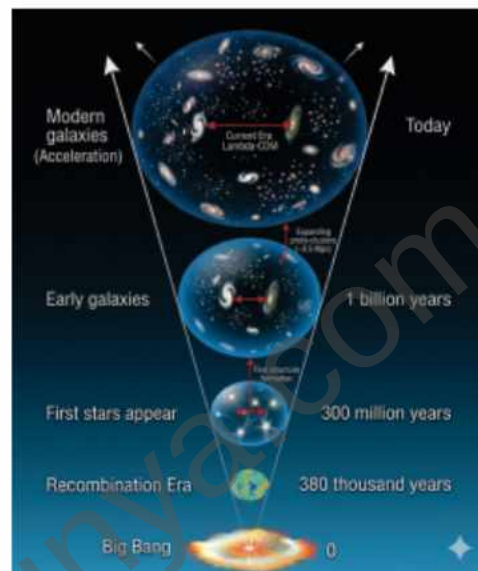


Fig. 21.8: Approximate timeline of the universe's evolution from the Big Bang to present

21.10 OCEAN CURRENTS AND WIND PATTERNS

Ocean currents and wind patterns play an important role in regulating Earth's climate and weather systems. Ocean currents are generated due to large-scale movement of the seawater. The seawater circulates in two main ways: i.e., across the surface and between the deeper layers. Surface currents are mostly caused by wind, pushing water across the ocean's top layer. The vertical circulation of water is called thermohaline circulation. This is driven by differences in water temperature and salinity, which affect its density. The rotation of the Earth also shapes ocean movement, creating large circular current systems known as gyres. These spin clockwise in the northern hemisphere and anticlockwise in the southern hemisphere. The currents move warm water from the equator toward the poles and bring cold water back, helping in regulating the climate of the planet.

Gyres patterns on the surface of an ocean are shown in Fig. 21.11. Wind patterns are created due to an uneven heating of the Earth's surface. This causes warm air to rise and cooler air to move in, forming distinct wind belts like trade winds, westerlies, and polar easterlies. These winds not only move surface ocean water but also influence the direction and strength of ocean currents. Together, wind patterns and ocean currents help distribute heat and energy across the planet, affecting climate zones and weather patterns.

Tidbit!

The trade winds that helped ancient sailors navigate are caused by Earth's rotation and solar heating. Ocean currents can change global weather patterns causing floods in one region and droughts in another.

Brain Teaser

A storm system is observed rotating clockwise in the southern hemisphere. If an identical system were observed in the northern hemisphere, which direction would it rotate, and why?

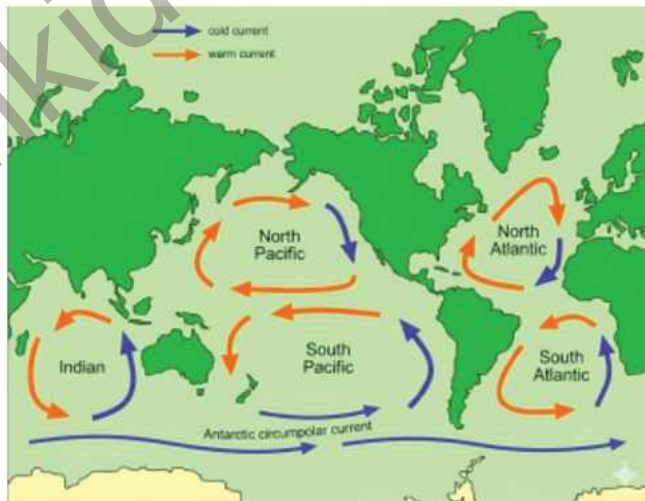


Fig. 21.11: Gyres patterns on the ocean surface

21.11 GLOBAL CLIMATE AND ENERGY TRANSFER FROM THE SUN

Energy received from the Sun plays an important role in producing changes in the global climate. Here, we will briefly describe how energy received from the Sun is distributed on Earth and how uneven heating of Earth between equator and poles can produce atmospheric changes.

1. Earth's Energy Budget

The Earth's energy budget refers to the balance between the solar energy absorbed by the Earth and the energy it radiates back into space.

It is a measure of how much solar energy is received at the Earth and how much of that energy is lost to space through reflection and emission. When the Earth is colder, more ice and snow cover the surface. Ice and snow are bright and reflect a large amount of sunlight back into space, which makes the Earth even cooler. But when the Earth gets warmer, ice and snow start to melt. This exposes darker surfaces like land and oceans, which absorb more sunlight and reflect less. As a result, the Earth becomes warmer. This balance of incoming and outgoing energy is known as the Earth's energy budget which plays an important role in keeping Earth's temperature steady. A schematic diagram illustrating Earth's energy budget is shown in Fig. 21.12. The figure depicts how sunlight reaches the Earth's surface and atmosphere. The energy coming in from the Sun is balanced by the energy going out from Earth in the form of infrared (heat) radiation. When this balance is maintained, the temperature of Earth remains constant over time. However, greenhouse gases trap infrared radiations, preventing it from escaping into space. As a result, the Earth is warming up, a problem known as global warming.

Do you know?

The Earth only absorbs about 70% of the Sun's energy the rest is reflected back into space by clouds, ice, and desert surfaces. A 1% imbalance in this budget can lead to major global temperature shifts.

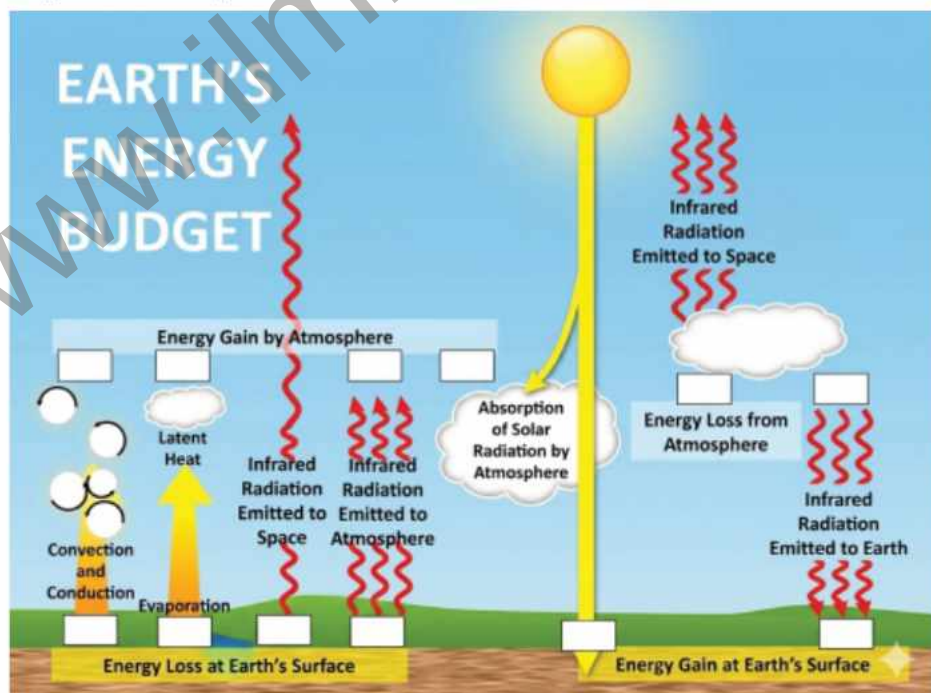


Fig. 21.12: Schematic diagram illustrating Earth's energy budget