UNIT 5  THE SUN

Structure

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5.1 INTRODUCTION

From Unit 4, you know that the principles of different branches of physics such as mechanics, thermodynamics and quantum mechanics are used in astronomy and astrophysics. In the present and subsequent Units, you will use these principles to investigate the behaviour and properties of the universe and its constituents.

On the cosmic scale, the Sun is just another star; there are bigger and brighter stars in the universe. The Sun is, however, very important to us because i) it is the nearest and the only star in our planetary system and ii) it provides almost all of our energy. Do you know that a slight variation in the energy received from the Sun can threaten life on the earth! Further, the Sun being the nearest star, we can study its structure, atmosphere, and other physical characteristics in greater detail. The information/data so obtained can be used to test the theories of stellar structure and evolution. In this way we can improve our theories and have a better understanding of other stars. In the present Unit, you will study about the Sun.

Due to the efforts of astronomers, today we have detailed information regarding the Sun. In Sec. 5.2, you will learn to arrive at the estimates of the basic solar parameters such as mass, radius and effective surface temperature. As far as we are concerned, all the visible radiation from the Sun comes from its surface layer called the photosphere. Above the photosphere is the atmosphere of the Sun consisting of two distinct layers namely the chromosphere and the corona. In Sec. 5.3, you will study the characteristic features of these layers. Interaction of the Sun’s magnetic field with highly mobile charged particles in it gives rise to a variety of observable events. These events, collectively known as solar activity, have been discussed in Sec. 5.4. The theoretical analysis of the interaction of magnetic field with conducting matter in motion is known as magnetohydrodynamics and it provides a basis to understand solar activity and related features of the Sun. Solar magnetohydrodynamics has been discussed in Sec. 5.5. In Sec. 5.6, you will learn, in brief, about helioseismology which provides valuable information about the Sun’s internal structure.

Objectives

After studying this unit, you should be able to:

• estimate values of the basic parameters of the Sun;
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- describe different layers of the Sun’s atmosphere;
- describe some of the observed features such as sunspot, prominence and solar flare associated with solar activity;
- explain the role of the Sun’s magnetic field in solar activity;
- derive the basic results of solar magnetohydrodynamics; and
- explain the seismology of the Sun.

5.2 SOLAR PARAMETERS

The basic parameters of the Sun are its mass \((M_\odot)\), radius \((R_\odot)\), luminosity \((L_\odot)\) and effective surface temperature \((T_{\text{eff}})\). In the following discussion, you will learn to estimate these parameters.

**Mass:** You know that the mean distance of the Sun from the Earth is \(1.5 \times 10^{11}\) m. It is called the mean solar distance, \(a\). In astronomy we measure mean distances in terms of \(a\) and it defines the Astronomical Unit (1 AU = mean solar distance). To obtain an expression for the mass of the Sun, we may use *Kepler’s third law* under the assumption that the mass of the planet can be neglected in comparison with the mass of the Sun. This assumption is valid for the Sun-Earth system and we can write:

\[
\frac{4\pi^2 a^3}{P^2} = GM_\odot
\]

where \(a, P, G\) and \(M_\odot\) are the mean solar distance, orbital period (~ 365 days) of the Earth, gravitational constant and mass of the Sun, respectively. With the values of the orbital period and the mean solar distance available at present, the value of \(GM_\odot\) is estimated to be \(132712438 \times 10^{12}\) m\(^3\)s\(^{-2}\). Since the laboratory measurements for \(G\) gives a value equal to \(6.672 \times 10^{-11}\) m\(^3\)kg\(^{-1}\)s\(^{-2}\), we obtain:

\[M_\odot \approx 2 \times 10^{30}\text{kg.}\]

This value is taken as the mass of the Sun as it exists today. In fact, solar mass decreases continuously since the Sun continuously emits radiation and particles which carry with them some mass. However, the total mass loss during the Sun’s estimated life time (~ \(10^{10}\) yrs) is found to be less than \(10^{27}\) kg. This value is much less than the error in measurement of the solar mass and is, therefore, negligible. This method can also be used to estimate the masses of the satellites/Moons of the planets in our solar system. How about solving an SAQ of this nature?

**SAQ 1**

One of the four Galilean satellites of the planet Jupiter is Io. Its orbital period is 1.77 days. The semi-major axis of its orbit is \(4.22 \times 10^{10}\) cm. Calculate the mass of Jupiter under the assumption that the Jupiter is too massive in comparison to Io.

**Radius:** The radius of the Sun can be estimated if we know the values of its angular diameter, \(\theta\) and the mean solar distance, \(a\) (Fig. 5.1). The angular diameter of the Sun is \(32^\prime\) and mean solar distance is \(1.5 \times 10^{11}\) m. Thus, with the help of Fig. 5.1, we obtain the value of the solar radius \(R_\odot\) as:

\[
R_\odot = \frac{1}{2} \left(1.5 \times 10^{11}\text{m}\right) \times (32 \times 2.9 \times 10^{-4}\text{rad})
\]

\[= 6.7 \times 10^8\text{m}.
\]
Astronomical observations indicate that the solar radius is not constant; rather, its value changes slowly. Over a period of \( \sim 10^9 \) years, the average change is about 2.4 cm per yr. Further, radius of the Earth is \( 6.4 \times 10^6 \) m. Thus, the Sun’s radius is almost 100 times larger than that of the Earth. To get an idea of the relative sizes of the Sun and the Earth, refer to Fig. 5.2.

**Luminosity:** The solar luminosity, \( L_{\odot} \), is defined as the total energy radiated by the Sun per unit time in the form of electromagnetic radiation. To estimate the value of luminosity of the Sun, let us imagine a sphere with the Sun at its centre (Fig. 5.3). The radius of this imaginary sphere is \( a \), the mean distance between the Sun and the Earth. Now, each unit area \( A \) of the sphere receives energy equal to \( S \), called the solar constant. Therefore, luminosity can be expressed as:

\[
L_{\odot} = 4\pi a^2 S
\]  

Fig.5.3: Imaginary sphere of radius \( a \) surrounding the Sun where \( a \) is its mean solar distance from the Earth
Since the solar radiation is absorbed in the Earth’s atmosphere, it is obvious that $S$ should be measured above the atmosphere. $S$ has now been measured accurately using satellites and its value is $1370 \text{ Wm}^{-2}$. Substituting the value of $S$ and the mean solar distance, $a = 1.5 \times 10^{11} \text{ m}$ in Eq. (5.2), we get:

$$L_{\odot} = 3.86 \times 10^{26} \text{ W}.$$  

**Temperature:** The temperature of the Sun at its surface and its interior regions are different. The surface temperature can be estimated using Stephan-Boltzmann law which you studied in our course on Thermodynamics and Statistical Mechanics (PHE-06). We leave this as an exercise for you in the form of an SAQ.

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**SAQ 2**

Assume that the Sun radiates like a black body at temperature $T$. Calculate $T$ using Stephan-Boltzmann law. Take Stephan constant $\sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$.

On solving SAQ 2, you would have found that the temperature of the Sun is 6000 K. This estimated temperature is called the **effective surface temperature** because it is the temperature of a black body whose surface emits the same flux as the Sun. This is the temperature of the surface layer of the Sun called the photosphere from which all the radiation is emitted.

To appreciate the validity of the approximation that the Sun radiates like a black body, refer to Fig. 5.4. It shows the observed solar radiation in the ultraviolet, visible and infrared regions of electromagnetic spectrum. Also plotted in this figure is the energy curve of a black body at 6000 K. In view of the similarity of the two curves, it is fair to assume that the Sun radiates like a black body at temperature 6000 K.

The Sun is a hot, bright gaseous ball and it does not have a well defined surface like the Earth. The visible surface of the Sun is called photosphere. Let us learn about it now.

### 5.3 SOLAR PHOTOSPHERE

The photosphere (Fig. 5.5) is the visible surface of the Sun. All the light received from the Sun, in fact, comes from the photosphere. You may ask: **Why do not we receive the radiation in the same form as generated in the interior of the Sun?** At the centre of the Sun, the energy is generated in the form of high energy photons called $\gamma$-rays. As these photons travel outwards, they collide with particles of matter and lose energy continuously. By the time these photons reach the surface – the photosphere – they are reduced to photons of visible region of electromagnetic spectrum. So, visible radiation is emitted from the photosphere.
The density of photosphere is 3400 times less than the density of the air we breathe. The thickness of the photosphere is about 500 km and the temperature at its base is \( \sim 6500 \) K. The temperature decreases upward and reaches a minimum value of \( \sim 4400 \) K at the top. This assumption is corroborated by the Sun’s absorption spectrum which indicates that the light we receive must be passing through a cool gas in which photons get absorbed.

The photosphere is not a quiet region (see Fig. 5.6). It shows a **granular structure**. If you look at Fig. 5.6a carefully, you can see that the photosphere consists of bright and irregularly shaped granules; each granule surrounded by dark edges. It has been found that these granules are very hot and their typical size is \( \sim 1500 \) km. The hot gas in the granules rises up with a speed of the order of \( 500 \) ms\(^{-1}\) and bursts apart by releasing energy. The cool material subsequently sinks downward along the dark edges or lanes between granules. The rising hot granules are seen only for a very short time (\( \sim 10 \) minutes) before they dissolve.

![Granular structure](image)

**Fig.5.6:** a) Photograph of the photosphere showing granular structure; and b) schematic diagram showing granules and their boundaries

The question is: **What causes granulation of the photosphere?** It is caused due to convection (a mode of energy transport by matter, about which you will study in Unit 8). The granulation can be visualised (Fig. 5.6b) as the top layer of a region where, due to convection, hot gas from below the photosphere moves upward. Thus, the centre of the granule is hotter and it emits more radiation and looks brighter in comparison to the edges which are relatively cooler and emit less radiation. Convection based explanation seems valid because the spectra of granules indicate that their centres are much hotter than the edges. **Further, the solar granulation provides observable evidence supporting the idea that there exists a convection zone below the photosphere.**

You may now like to know: **What is the chemical composition of the photosphere?** It consists of 79 percent hydrogen and the remaining 21 percent consists of nearly 60 other chemical elements. Interestingly, all the elements of the photosphere are known elements and their proportion in the earth is more or less the same as that in the photosphere. **This similarity in the chemical compositions of the photosphere and the earth is of utmost importance for understanding the formation of the solar system.**

Though the photographs of the Sun give the impression that it has a clear edge, such clear and distinct edge does not exist. Outside the apparent edge are the Sun’s outer layers, collectively known as the Sun’s atmosphere. These layers can be seen and probed and valuable information about their physical characteristics can be obtained. Let us learn about the various layers of the solar atmosphere.
5.4 SOLAR ATMOSPHERE

The Sun’s atmosphere is divided into two layers namely, the chromosphere and the corona. A schematic diagram of these layers is shown in Fig. 5.7.

5.4.1 Chromosphere

Chromosphere lies above the photosphere (Fig. 5.7) and extends up to ~ 2000 km. This layer of the solar atmosphere is normally not visible from the Earth because of its faintness. However, it can be seen during a solar eclipse. The name chromosphere is derived from the fact that a few seconds before and after a total solar eclipse, a bright, pink flash appears above the photosphere (Fig. 5.8). The spectrum obtained at that time is called a flash spectrum (Fig. 5.9).

The appearance of pink colour is due to the emission of the first Balmer line ($\text{H}_\alpha$) which occurs in the red region. The temperature, density and pressure in the chromosphere determine the intensities of various emission lines. In the chromosphere, the density decreases by a factor of $\sim 10^4$ from that of the photosphere.
while the temperature rises to ~ 25000 K within a short distance of ~ 2000 km. Therefore, the spectral lines that are not produced at relatively higher density and lower temperature of the photosphere are formed in the chromosphere as emission lines (see margin remarks).

At this point, it is logical to ask: **Why does the temperature in the chromosphere increase with height?** The clue to the answer of this question lies in observing the chromosphere just before the total solar eclipse. Hot gas, in the form of jets called **spicules**, is observed throughout the chromosphere (Fig. 5.10). These spicules extend upward in the chromosphere up to a height of ~ 10000 km and last for as long as 15 minutes. This implies that the lower part of the chromosphere is highly turbulent and the spicules transport energy and matter from the photosphere to the chromosphere. This causes heating of the chromosphere.

![Fig.5.10: Spicules in the Sun’s chromosphere](image)

Now, your next logical question could be: **What causes spicules?** The origin of spicules is not yet understood completely. However, it appears to be caused by the Sun’s magnetic field. Further, just above the chromosphere, there exists a **transition region** extending up to ~ 3000 km. In this region, the temperature rises sharply to ~ 10^6 K (Fig. 5.11). The transition region links the chromosphere with corona, the outermost part of the solar atmosphere.

![Fig.5.11: The variation of temperature and density in the Sun’s atmosphere with distance](image)
5.4.2 Corona

Corona, the outermost layer of the Sun’s atmosphere is named after the Greek word for Crown. Like the chromosphere, the corona can be observed only during total solar eclipse – when the Moon completely covers the solar disc (Fig. 5.12). You may wonder why we cannot see corona at normal times! The fact is that the density of matter in both the chromosphere and corona is very low (see Fig. 5.11). They emit very little light and, as a result, they are very faint. In the bright light of the photosphere, they are not visible.

Fig. 5.12: Two photographs of the solar corona

The spectrum of corona consists of bright lines superimposed on a continuous spectrum. When these lines were first discovered, they were thought to be due to a new element, coronium, not found on the earth. Later, it was realised that these lines were due to highly ionised atoms and not due to the so-called ‘new’ element coronium. Fig. 5.13 shows the temperature and height in the corona at which emission lines of various ionised elements are formed. You may note here that to excite the emission lines from highly ionised elements, say spectral line of SiX (read margin remarks), a temperature greater than $2 \times 10^7$ K is required. The observed emission lines of highly ionised atoms of iron, nickel, neon, calcium etc., in the spectrum of corona clearly indicate that the temperature prevailing in corona is very high (more than $10^6$ K). Now, before proceeding further, how about testing yourself?

**SAQ 3**

a) The temperature of chromosphere and corona is very, very high in comparison to that of the photosphere. Still, we observe that the photosphere is the brightest of the three. Why?

b) Calculate the temperature at which a particle will have sufficient energy to ionise a hydrogen atom.

Due to high temperature, electrons in the corona region have high energies. These electrons interact with ionised atoms and give rise to emission of X-rays. The coronal X-ray emission is much larger than that of the photosphere. Remember that the temperature of the photosphere is only 6000 K. So, it emits very little energy in the X-ray region. The Sun, as observed in X-rays is shown in Fig. 5.14 which clearly indicates the existence of very high (~ $10^6$ K or more) temperature in the corona.

You have already learnt that the temperature of the photosphere is lower than that of the chromosphere and as one goes further up in the corona, temperature rises to more than a million degree K. This gives rise to a very simple but important question: Despite being closer to solar interior, why is the photosphere far cooler than the corona? You know that the second law of thermodynamics precludes such a scenario.
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as heat cannot flow from a cooler region to a hotter region on its own. We also know that the radiation from the photosphere passes through corona almost freely because of its (corona’s) low density. Since hardly any absorption of radiation takes place in the corona, the existence of such high (~ million degree) temperature in the corona presents a paradoxical situation. Several mechanisms have been proposed to resolve the paradox. It is now generally believed that the magnetic field of the Sun might, in some way, be responsible for coronal heating. You will study the basics of this mechanism in Sec. 5.5 of this Unit. The observed overlapping of regions of intense X-ray emission and strong magnetic fields lend support to this idea.

Solar Wind

Unlike its visual appearance, the solar corona extends much beyond into the space. The outer layer of the solar atmosphere, in fact, continuously emits charged particles which fill the entire solar system. This emission is called the solar wind. It comprises streams of charged particles (mainly protons and electrons) and causes continuous loss of mass from the Sun. The phenomenon of solar wind was predicted much before its detection. Its characteristics can be investigated using rockets and satellites. For instance, the solar wind velocities range from 200-700 km s$^{-1}$ at the distance of the Earth from the Sun. The number density of the solar wind at this distance is $\sim 7$ particles per cm$^3$.

You may like to know: **What gives rise to the solar wind?** In view of the high temperature prevailing in the corona, the gas contained therein exerts tremendous pressure outward. In fact, the pressure is much higher than the inward pressure due to the Sun’s gravity. The gas, therefore, streams outward from the Sun and fills the interplanetary space. In 1962, Mariner II spacecraft detected the solar wind by its on-board instruments.

The electrically charged particles carried by the solar wind cannot cross the lines of force of the Earth’s magnetic field. These particles are deflected by the Earth’s magnetic field, spiral around the field lines and move back and forth between the magnetic poles of the Earth. As a result, two doughnut-shaped zones of highly energetic charged particles are created around the Earth and they are collectively called the **van Allen radiation belts**. These radiation belts are shown in Fig. 5.15.

Astronomers have observed a variety of short-lived events, collectively known as solar activity, occurring on or near the surface of the Sun. The root cause of all these

Fig.5.14: X-ray picture of the Sun

One of the manifestations of solar wind is observed in the shape of comets. You know that the tail of a comet points away from the Sun. It is because the solar wind sweeps along the material of the comet.

You know that when a charged particle passes through a magnetic field, it experiences a force which changes its direction of motion. The force experienced by a moving charged particle is known as Lorentz force.

As you know, satellites and space missions comprise very sophisticated integrated circuits, solar cells and other electronic gadgets. Therefore, care is taken to minimise the damaging effects of the radiation belts on the satellites and space missions.
activities is the existence of strong and localised magnetic field in the photosphere. Studies of these events/activities provide valuable information about the Sun and the nature of its magnetic field. You will now learn about some of these short-lived events.

5.5 SOLAR ACTIVITY

Sunspots

If you look at the photographs (Fig. 5.16) of the Sun, you see dark spots on its visible surface. These dark spots are called sunspots. Sunspots can be seen sometimes even with unaided eye at sunrise or sunset. (But you should not attempt to see the Sun with unaided eye as it may cause irreparable damage to your eyes because of its intense brightness.) Naked eye observations of sunspots date back to ~ 2000 years in China. It was in the seventeenth century that Galileo, using the telescope which he himself had fabricated, observed sunspots and found that these dark spots were in motion. This led him to suggest that the Sun was spinning in space. Galileo also observed that the sizes and shapes of the sunspots kept changing as they rotated with the Sun.

The sunspot temperature is ~ 4000 K. With such high temperature, you may wonder, why they appear dark! Sunspots appear darker because they are cooler than their surrounding areas in the photosphere that have an effective temperature of 6000 K. A typical white light picture of a large sunspot is shown in Fig. 5.17. Note that it consists of a dark central region, called umbra, surrounded by a less dark region, called penumbra. We do not see such details in the picture of smaller sunspots.

At this stage, a logical question is: Why is the temperature of the sunspots lower than their surroundings? It is due to the existence of strong magnetic fields in the sunspots. In the presence of a magnetic field, a spectral line emitted by an atom at a
single wavelength is split into three lines. This is called the **Zeeman Effect**. Such Zeeman splitting is observed in the spectrum of sunspots. Since the line separation, $\Delta \lambda$ is proportional to the applied magnetic field, a magnetic field up to ~ 3000 Gauss has been estimated in sunspots. Fig. 5.18 shows the mechanism of **Zeeman splitting** of a spectral line and the **Zeeman splitting** of a spectral line of a sunspot.

![Image of Zeeman splitting](image)

**Fig. 5.18**: Zeeman splitting of (a) a spectral line; and (b) a spectral line of the sunspot

The presence of strong magnetic fields in sunspots restrains the flow of hot material from layers below the photosphere. Therefore, within a sunspot, less heat comes up and they (sunspots) are cooler/darker than the surrounding region. Within a sunspot, the umbral magnetic field is quite intense ~ 3000 Gauss. It spreads like an umbrella and weakens in the penumbral region. The field strength in the penumbra is estimated to be ~ 1000 Gauss.

Sunspots can last for weeks. The question is: **How do these cooler regions survive for so long amidst the hotter regions?** This could happen due to the magnetic field. You know that magnetic field exerts pressure (equal to $B^2/2\mu$) across the lines of force. This pressure, along with the pressure of matter inside a sunspot balances the material pressure outside and the sunspots can exist in equilibrium.

**Sunspot Cycle**

The observed motion of the sunspots indicates that the Sun is spinning in space. In 1843, Heinrich Schwabe, a German who observed the sky for fun, discovered a periodic variation in the numbers of visible sunspots. He found an interval of 5.5 yrs between the time when maximum number of sunspots (**sunspot maxima**) were observed and the time when the minimum number of sunspots (**sunspot minima**) were observed. **Over the last two centuries, sunspot observations clearly suggest a periodic variation of about 11 years between two successive sunspot maxima** (Fig. 5.19a).

Another important observation pertaining to sunspot is that the sunspot zones migrate along solar latitude. It is observed that the first sunspot zone appears at latitude of ~ 35° in, say, the northern hemisphere and it migrates to lower latitudes. It lasts till it reaches a latitude of ~ 10°. The latitude migration of sunspot zones is shown in Fig. 5.19b. This is the famous **butterfly diagram** which shows a period of ~ 11 years between the successive occurrences of a sunspot at a given latitude. It is believed that the sunspot cycle is caused due to differential rotation of the Sun; it rotates faster at the equator compared to higher latitudes.
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Fig. 5.19: a) Sunspot cycle; and b) butterfly diagram which shows the migration of sunspots from higher to lower latitudes

Solar Prominences

Refer to Fig. 5.20 which depicts loop like structures surging up into the corona when the Sun is viewed along the edge of the solar disc. These structures are called prominences which are intimately connected with and formed due to the Sun’s magnetic field. The material in prominences comprises hot ionised gases trapped in magnetic fields associated with the active regions. Since these gases came from deeper layers of the solar atmosphere, they are cooler and therefore denser than the coronal gas. It is for this reason that prominences appear as bright structures. However, when viewed against the photosphere (solar disk), prominences appear as dark snake like objects, called filament.

Solar Flares

Yet another form of solar activity is called solar flare. Solar flares are sudden eruptive events which occur on the Sun (Fig. 5.21). Each event may involve energy in the
The range of $10^{22}$ to $10^{25}$ Joules. Usually the flares last anywhere between a few minutes to more than an hour. A large flare may have linear dimension as large as $10^5$ km and may be seen as a short-lived storm on the Sun. Such energetic eruptions are usually linked to sunspots because these quite often occur at the top of magnetic loops that have their feet in sunspots. Thus, the most likely places of occurrence of solar flare are the regions of closely packed sunspots. The tremendous amount of energy carried in solar flare is released in the form of X-rays, ultraviolet and visible radiation, high speed electrons and protons. You may ask: **What is the source of energy in solar flares?** This question can be answered on the basis of a model for solar flare shown in Fig. 5.22.
A Model of Solar Flare

All kinds of solar activities i.e., the sunspots, prominences, flares etc., are possibly linked to the release of stored magnetic energy. It is believed that the energetic solar eruptions are caused due to coming together and merging of magnetic fields in the active regions (the phenomenon is known as magnetic field reconnection) and thereby releasing the stored magnetic energy. To appreciate this phenomenon, magnetic lines of forces can be considered as stretched springs with certain amount of energy associated with each unit length. If the length of the lines of forces gets reduced by certain mechanism, energy is released. This is what happens when lines of force pointing in opposite directions meet and merge with each other (Fig. 5.22).

In order to fix these ideas, you should answer the following SAQ.

**SAQ 4**

a) What is the basis to conclude that the Sun is rotating in space?

b) What is the difference between spicules and solar prominences?

So far, you have studied about the photosphere, solar atmosphere and solar activity. You must have noted that the Sun’s magnetic field plays an important role in solar activity. Further, gaseous matter in the Sun is in the ionised form, that is, it is a conducting matter. We will now try to understand the nature of interaction between the Sun’s magnetic field and the conducting matter (fluid) in motion. This understanding is of utmost importance in astronomy because, everywhere in the universe, we find conducting matter moving in the presence of magnetic fields. The study of the motion of conducting fluid in the presence of magnetic field is called magnetohydrodynamics. Let us now turn to this subject.

### 5.6 BASICS OF SOLAR MAGNETOHYDRODYNAMICS

We begin our discussion of solar magnetohydrodynamics with Maxwell’s equations. You may recall from the physics course entitled Electric and Magnetic Phenomena (PHE-07) that three of the Maxwell’s equations can be written as:

\[ \nabla \cdot \mathbf{B} = 0, \quad (5.3) \]

\[ \nabla \times \mathbf{B} = \mu \mathbf{j}, \quad (5.4) \]

and

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (5.5) \]

where \( \mu, \mathbf{B}, \mathbf{E} \) and \( \mathbf{j} \) are the magnetic permeability of the medium, magnetic field intensity, electric field intensity and electric current density respectively. Note that in Eq. (5.4), we have not written the displacement current term. This is because, magneto-hydrodynamic phenomena in the Sun are usually slow whereas the displacement current gives rise to fast phenomena such as electromagnetic radiation.

Further, if the fluid (conducting matter) velocity is \( \mathbf{v} \) and its electrical conductivity is \( \sigma \), then Ohm’s law gives (see the margin remark):

\[ \mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (5.6) \]
where \((v \times B)\) term represents the electric field induced due to the motion of conducting fluid in the presence of magnetic field. Using Eqs. (5.3) to (5.6), you can readily obtain:

\[
\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \nabla^2 B
\]  

(5.7)

where \(\eta = (\mu \sigma)^{-1}\) is called the magnetic diffusivity. Its value is generally constant in solar conditions.

**SAQ 5**

Derive Eq. (5.7).

The first term on the right hand side of Eq. (5.7) gives the change in \(B\) due to the fluid motion. The second term represents the change in \(B\) due to conductivity \(\sigma\). It is generally called the Ohmic decay of the field. Note that for \(v = 0\), Eq. (5.7) reduces to:

\[
\frac{\partial B}{\partial t} = \eta \nabla^2 B
\]

(5.8)

Eq. (5.8) is the diffusion equation. It gives the rate at which magnetic field diffuses out due to conductivity. In the limit of infinite conductivity, we have \(\eta \to 0\), and Eq. (5.7) becomes

\[
\frac{\partial B}{\partial t} = \nabla \times (v \times B)
\]

(5.9)

Without going into the mathematical details, it is possible to understand the relative importance of the two terms on the right hand side of Eq. (5.7). To do so, let us obtain the orders of magnitude, of the values of the two terms. The order of magnitude of the first term is \(\frac{VB}{L}\), where \(V, B\) and \(L\) are the typical values of the fluid velocity, magnetic field and the dimension of the system. Similarly, the magnitude of the second term is \(\frac{\eta B}{L^2}\). The ratio of the two terms is called magnetic Reynold number, \(R_m\), and is given by:

\[
R_m = \frac{VL}{\eta}
\]

(5.10)

If \(R_m \gg 1\), the second term in Eq. (5.7), i.e. the diffusion term, is negligible. The condition \(R_m \gg 1\) is obtained in two situations: when the conductivity is very high because \(\eta\) appears in the denominator, and secondly when the dimension of the system, \(L\) is very large. In astrophysical systems, we have \(R_m \gg 1\) because of the second situation as their dimensions are very large. In any case, \(R_m \gg 1\) implies that there is no decay of the magnetic field as if the conductivity of the medium is infinite. Actually, the conductivity is finite, but the large dimensions ensure that \(R_m \gg 1\) and so there is no decay of the field.

If we drop the diffusion term in Eq. (5.7), the remaining equation (Eq. (5.9)), implies that the magnetic flux linked to a cross-section of the fluid remains unchanged as the fluid moves about. **In other words, the magnetic field is frozen in the fluid.** The idea of frozen field means that the magnetic flux is transported along with the material motion. We can show this formally in the following manner:
Let us consider a cross-sectional area \( A \) placed in a magnetic field \( \mathbf{B} \) (Fig. 5.23). The magnetic flux linked with area \( A \) may be written as:

\[
\Phi = \int_A \mathbf{B} \cdot d\mathbf{a}
\]  

(5.11)

where \( d\mathbf{a} \) is an element of area on the surface \( A \). Let \( l \) be the curve enclosing the area \( A \). Let us further assume that, in the time interval \( dt \) the area changes from \( A \) to \( A' \) as the fluid moves around. The magnetic flux \( \Phi' \) linked with \( A' \) may be different from \( \Phi \) because (i) magnetic field \( \mathbf{B} \) may have changed and/or (ii) some flux might have been exchanged through the surface of the volume generated between \( A \) and \( A' \). Now, the rate of change of magnetic field is \( \partial \mathbf{B}/\partial t \). The area of the curved surface surrounding the volume between \( A \) and \( A' \) is \( \mathbf{v} \times d\mathbf{l} \) where \( d\mathbf{l} \) is an element of length of the contour of \( A \). Therefore, the difference \( \Delta \Phi \) between fluxes through \( A' \) and \( A \) is given by:

\[
\Delta \Phi = \left( \int A' \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{a} + \int l' \mathbf{B} \cdot (\mathbf{v} \times d\mathbf{l}) \right) dt.
\]  

(5.12)

Further, using Stoke’s theorem, we can write the second term on the right hand side of Eq. (5.12) as:

\[
\int l' \mathbf{B} \cdot (\mathbf{v} \times d\mathbf{l}) = -\int A \nabla \times (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{a}
\]  

(5.13)

So, we can write the rate of change of flux (Eq. (5.12)) as:

\[
\frac{d\Phi}{dt} = \int A \left( \frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) \right) \cdot d\mathbf{a}
\]  

(5.14)

From Eq. (5.9), we have \( \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \). Thus, from Eq. (5.14), we find that the rate of change of magnetic flux is zero. It implies that \( \Phi \) remains constant. **We may, therefore, conclude that in astrophysical systems the lines of forces are completely attached or glued to the moving fluid when \( R_m >> 1 \).**

Now, let us pause for a moment and think about the significance of the above conclusion for solar activity. Recall that the active regions consisting of sunspots have strong magnetic fields and solar activities such as prominence and flare occur in these regions. The structures associated with solar prominences and solar flares are very similar to the magnetic lines of force. It is, therefore, believed that these activities are caused due to frozen magnetic lines of force in the conducting fluid.

You have learnt earlier in this unit that, in almost all the events associated with the Sun’s magnetic field, energy is also transported. **The energy transported by the magnetic field glued to the conducting matter is responsible for heating the chromosphere and corona. Would not you like to know how it happens?** To understand this process, we begin with the fact that an electric current exists in the solar atmosphere due to the drift of electrons with respect to ions carrying opposite charges. If a magnetic field \( \mathbf{B} \) is also present in the plasma, then a volume force, also called the **Lorentz force** (\( = \mathbf{j} \times \mathbf{B} \)), acts on the material. Since \( \mathbf{j} = \frac{1}{\mu} (\nabla \times \mathbf{B}) \) (from Eq. (5.4)) we may write the expression for Lorentz force as:
\[
\mathbf{j} \times \mathbf{B} = \frac{1}{\mu} \left( \nabla \times \mathbf{B} \right) \times \mathbf{B}
\]
\[
= \frac{1}{\mu} \left( \mathbf{B} \cdot \nabla \right) \mathbf{B} - \nabla \left( \frac{B^2}{2\mu} \right)
\]

(5.15)

The first term on the RHS of Eq. (5.15) denotes magnetic tension and the second term denotes the gradient of magnetic pressure. Therefore, in the presence of a magnetic field, a lateral pressure (due to the second term in Eq. (5.15)) acts on a conducting gas. To maintain equilibrium, the lateral pressure due to magnetic field is balanced by the gas pressure. The magnetic tension term is similar to the tension of a stretched string. When a stretched string is distorted, its tension provides the restoring force. Therefore, when the magnetic field lines (frozen in the conducting fluid) are disturbed we have a similar restoring force (due to the magnetic tension). Thus, a disturbance may propagate as a transverse wave along the magnetic field lines. Such waves are called \textbf{Alfven waves}. The speed of these waves is given by:

\[
v_m = \frac{B}{\sqrt{4\pi\rho}}.
\]

where \(\rho\) is the density of the plasma. Since Alfven waves propagate along the magnetic field lines, it is possible to transport energy outward along magnetic field lines which are threading the outer solar atmosphere. This energy is believed to be responsible for heating the chromosphere and corona.

**SAQ 6**

A pressure of \(10^3\) Pa (Pascal) prevails in the solar atmosphere. What should be the strength of the magnetic field required to balance such a pressure?

Now, before we close our discussion about the Sun, we will briefly discuss a new area of solar research called helioseismology.

### 5.7 HELIOSEISMOLOGY

In 1962, Leighton, Noyes and Simon noticed wiggling back and forth of some of the absorption lines in the solar spectrum with periods \(\sim 5\) min. They conjectured that the movement of the surface of the Sun is responsible for such observations.

Subsequently, careful observations of the solar surface confirmed the idea of waves rising up and down on the surface of the Sun (Fig. 5.24). Astronomers now use these waves to probe the solar interior much the same way as seismologists probe the earth’s interior using vibrations caused by an earthquake.

So far, millions of different vibrational modes also called \textit{acoustic modes} or \(p\)-modes have been observed on the Sun’s surface. All of them have different frequencies and surface patterns. Thus, the Sun appears to have a rhythmic surface motion similar to that of a beating heart. The observed rise and fall of the surface of the Sun is, in fact, due to superposition of many different acoustic modes. These modes are now believed to be driven by irregular motions in the convective envelope under the solar surface.

The name helioseismology derives from the fact that, in Greek, \textit{helios} means the Sun and the word \textit{seismos} is used for an earthquake.

As you know, seismology refers to the study of seismic waves moving inside the Earth. Their arrival at various points on the Earth’s surface enables us to find the point of origin of these waves. This way we are able to construct the internal structure of the Earth.
The combined effect, or the superposition of millions of these acoustic waves, results in the observed up and down motion of the photosphere with a period of the order of 5 minutes. The extent or size of a wave is called its horizontal wavelength. The relation between sizes and periods of waves, obtained theoretically, suggested that only specific combination of periods and sizes can resonate inside the Sun.

Fossat and Grec observed the solar oscillation from the South pole for around 120 hours. The analysis of this continuous record showed that the entire surface of the Sun is ringing like a bell with periods in the range of 5 minutes and the vibrations may last for days and weeks.

The natural frequencies of oscillations can be computed for any solar model. In view of the precision now possible for determining the frequencies, we may compare these with those computed for a given solar model. In case there is lack of agreement between the predicted and observed frequencies, the model is slightly modified to improve agreement. The improvement in the model brings it closer to reality. It has been found that the depth of the solar convection zone is at a radius of 71.3 percent of radius of the Sun. It has also been confirmed now that the proportion of helium in the Sun lies between 0.23 – 0.26. This is quite consistent with the value of 0.25 for helium believed to have been formed in the early phase of the universe after the big-bang.

Now, let us summarise what you have learnt in this unit.

### 5.8 SUMMARY

- The **mass**, **radius** and **effective surface temperature** of the Sun are $2 \times 10^{30}$ kg, $7 \times 10^8$ m and 6000 K, respectively.
- The Sun’s atmosphere comprises of the **photosphere**, **chromosphere** and **corona**.
- The **photosphere** is the visible surface of the Sun and all the radiation we receive from the Sun is emitted by this layer.
- The photosphere has a **granular structure** which is caused by convection of hot gas from below the photosphere.
- The **chromosphere**, which lies above the photosphere, extends up to ~ 2000 km and is normally not observable from the earth except during **total solar eclipse**. The temperature of the chromosphere is much higher than the photosphere.
- Relatively higher temperature of the chromosphere is perhaps caused due to **spicules** – jets of hot gas – which extend upward in the chromosphere.
• The outermost layer of the solar atmosphere, **corona** is also not visible at normal times due to its low material density. The temperature of the corona is of the order of $10^6\,\text{K}$, much more higher than that of the photosphere.

• The **sunspots** are the dark spots on the solar disk. They appear dark because they are cooler than their surrounding areas in the photosphere. The movement of **sunspots** indicate that the Sun is spinning in space.

• Solar **prominences** are the loop like structures surging up into the corona. They are caused due to the Sun’s magnetic field.

• Solar **flares** are sudden eruptive events involving energy in the range of $10^{22}$ to $10^{25}$ joules. The most likely places of occurrence of solar flares are the regions of closely placed sunspots and they are possible caused due to the release of stoned magnetic energy.

• The study of the motion of conducting matter in the presence of magnetic field is called **magnetohydrodynamics**.

• The **magnetic Reynold number** is given by
  \[ R_m = \frac{VL}{\eta} \]
  which indicates that for infinite conductivity (i.e. $\eta \to 0$), there is no decay of the magnetic field. In other words, magnetic field is frozen in the conducting matter in motion.

• Transportation of magnetic flux with conducting matter explains some of the solar activities like prominence and solar flare.

• **Helioseismology** has its origin in the observed wiggling back and forth of some of the absorption lines in the solar spectrum. The movement of the surface of the Sun, causing these back and forth motion of absorption lines, gives rise to waves on it. Investigation of the nature of these waves provides valuable information regarding the internal structure of the Sun.

### 5.9 TERMINAL QUESTIONS

**Spend 20 min.**

1. In a sunspot, magnetic diffusivity, linear dimension and velocity of conducting fluid respectively is $10^3\,\text{m}^2\text{s}^{-1}$, $10^4\,\text{km}$, and $10^3\,\text{ms}^{-1}$. Estimate the magnetic Reynold number, $R_m$. Is it possible to assume that the conductivity in the sunspot is virtually infinite?

2. The temperature inside a sunspot is 4000 K and that of its surface is 6000 K. Calculate the strength of the magnetic field inside the sunspot which will balance the pressure inside and outside.
   **[Hint:]** Remember that the magnetic pressure is $B^2/2\mu$ where $\mu$ is magnetic permeability of the medium and its value for the present case can be taken as $4\pi \times 10^{-7}\,\text{NA}^{-2}$.

3. The number density of particles (assume hydrogen) in the photosphere is $10^{20}$ particles per $\text{cm}^{-3}$ and the strength of the magnetic field of the Sun is 1 G. Calculate the velocity of the Alfven waves in the photosphere.
Self Assessment Questions (SAQs)

1. Since the mass of the planet Jupiter is very large compared to its satellite Io, we can use Kepler’s third law for Jupiter and Io system. Thus, we can write:

\[ \frac{4\pi^2 a^3}{P^2} = GM_J \]  

(i)

where \(M_J\) is the mass of Jupiter.

From the problem, we have

\[ a = 4.22 \times 10^{10} \text{ cm} = 4.22 \times 10^8 \text{ m} \]

\[ P = 1.77 \text{ days} = 1.77 \times 24 \times 60 \times 60 \text{ s} \]

\[ G = 6.672 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \]

Substituting these values in Eq. (i) above, we get

\[
M_J = \frac{4\pi^2 a^3}{GP^2} = \frac{4 \times (3.14)^2 \times (4.22 \times 10^8 \text{ m})^3}{(6.672 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}) \times (1.77 \times 24 \times 60 \times 60 \text{ s})^2} = 1.97 \times 10^{27} \text{ kg}
\]

2. According to the Stephan-Boltzmann law, the amount of energy radiated by a black-body per unit time per unit area at temperature \(T\) is given by

\[ E = \sigma \ T^4 \]  

(i)

where \(\sigma\) is Stephan constant.

The energy radiated by the Sun can also be expressed in terms of its luminosity \(L_\odot\) as

\[ E = \frac{L_\odot}{4\pi R^2} \]  

(ii)

where \(R\) is the radius of the Sun.

Comparing the above two expressions, we can write

\[ \frac{L_\odot}{4\pi R^2} = \sigma T^4 \]

Rearranging the terms and substituting the values of \(R = 6.7 \times 10^8\text{ m}\), \(\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}\) and \(L = 3.86 \times 10^{26}\text{ W}\), we get,

\[ T = \left( \frac{L_\odot}{4\pi R^2 \sigma} \right)^{1/4} \]
$$= \left( \frac{3.86 \times 10^{26} \text{ W}}{4 \times (3.14 \times (6.7 \times 10^8 \text{ m})^2 \times (5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4})} \right)^{1/4}$$

$$= \left( \frac{3.86 \times 10^2}{4 \times 3.14 \times (6.7)^2 \times 5.67} \times 10^{16} \text{ K}^4 \right)^{1/4}$$

$$= 0.5895 \times 10^4 \text{ K}$$

$$= 6000 \text{ K.}$$

3. a) It is because the density of matter in photosphere is much higher than the density of matter in chromosphere and corona.

b) We know that the ionisation energy of the hydrogen atom is 13.6 eV. Further, energy acquired by a particle at temperature $T$ is $k_B T$. If this energy is equal to the ionisation energy of the hydrogen atom, it will be ionised. Thus, we must have

$$k_B T = (13.6 \times 1.6 \times 10^{-19}) \text{ J}$$

$$T = \frac{(13.6 \times 1.6 \times 10^{-19} \text{ J})}{(1.38 \times 10^{-23} \text{ JK}^{-1})}$$

$$= 13.6 \times 10^4 \text{ K.}$$

4. a) Motion of sunspots.

b) Spicules are the jet like structures comprising hot gas and is observed throughout the chromosphere. Prominences look like structures surging up into the corona.

5. Ohm’s law can be written as:

$$\mathbf{J} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Taking curl of both sides, we get:

$$\nabla \times \mathbf{J} = \sigma (\nabla \times \mathbf{E} + \nabla \times (\mathbf{v} \times \mathbf{B}))$$

Using Eqs. (5.4) and Eq. (5.5) we can write:

$$\frac{1}{\sigma \mu} (\nabla \times \nabla \times \mathbf{B}) = -\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B})$$

$$\frac{1}{\sigma \mu} [\nabla (\nabla \cdot \mathbf{B}) - (\nabla \cdot \nabla) \mathbf{B}] = -\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B})$$

From Eq. (5.3), we have $\nabla \cdot \mathbf{B} = 0$. Thus, we get

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\sigma \mu} \nabla^2 \mathbf{B}$$
\[ \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \]

which is Eq. (5.7).

6. We know that the pressure generated by magnetic field \( \mathbf{B} \) is equal to \( B^2/2\mu \). Thus, for generating pressure equal to \( 10^3 \text{ Pa} \), we must have

\[
\frac{B^2}{2\mu} \approx 10^3 \text{ Pa}
\]

Substituting \( \mu = 4\pi \times 10^{-7} \text{ NA}^{-2} \) in the above expression, we get:

\[
B \approx 5 \times 10^{-2} \text{T} = 5 \times 10^2 \text{ G}.
\]

Terminal Questions

1. The magnetic Reynold number is given by (Eq. (5.10)):

\[
R_m = \frac{VL}{\eta}
\]

Substituting the values of \( V \), \( L \) and \( \eta \) from the problem, we get

\[
R_m = \frac{(10^3 \text{ m/s}) \times (10^7 \text{ m})}{10^3 \text{ m}^2 \text{s}^{-1}} = 10^7
\]

Yes, conductivity can be taken to be virtually infinite because \( R_m \gg 1 \).

2. On the basis of the equation of state for the sunspot and using the fact that magnetic pressure is equal to \( B^2/2\mu \), we can write:

\[
\frac{B^2}{2\mu} = Nk_B (T_2 - T_1)
\]

where \( N \) is number density. Since \( \mu = 4\pi \times 10^{-7} \text{ NA}^{-2} \), \( T_2 = 6000 \text{ K} \) and \( T_1 = 4000 \text{ K} \), we can write:

\[
B^2 = 2 \times (4\pi \times 10^{-7} \text{ NA}^{-2}) \times (10^{23} \text{ m}^{-3}) \times (1.38 \times 10^{-23} \text{ J K}^{-1}) \times (2000 \text{ K})
\]

\[
B = 0.08 \text{T} = 800 \text{ G}
\]

3. Velocity of Alfven waves is given by

\[
v_m = \frac{B}{\sqrt{4\pi \rho}}
\]

where \( \rho \) is density. Substituting the values of \( B \) and \( \rho \), we get:

\[
v_m = \frac{1 \text{ G}}{\sqrt{4\pi \times (10^{20} \times 1.6 \times 10^{-24} \text{ g cm}^{-3})}}
\]

\[
\approx 25 \text{ cm s}^{-1}.
\]