Chapter 1

An introduction of the Sun and its magnetic activity

The Sun, our host star, is the primary source of energy that sustains every living organism on the planet Earth, that we call home. Before the technological revolution of the 19th and 20th centuries, our relationship with our star has been that much simple and straightforward. The Sun could be considered as one of the billions of main-sequence stars, with properties that are pretty much ordinary (and boring!). However, a few events and discoveries changed our perspective regarding our host star and its impact on us forever.

The invention of the telescope by Galileo Galilei in the beginning of 17th century commenced the era of systematic observation of the sunspots, the dark patches on the solar surface. Since then, It took astronomers two more centuries of observations to understand that, there is a cyclic pattern in the appearance of the sunspots, with a period of 11 years, which was first mentioned by Heinrich Schwabe in 1844 (Schwabe, 1844), and is now called the 'Schwabe Cycle' or more commonly known as the 'Solar Cycle'. In 1859, while observing a sunspot closely using a telescope, Carrington witnessed a bright flash just above the spot (now known as the Carrington event, Carrington (1859)). A few days later reports of the malfunction in the telegraph lines came from different parts of the World.

This event later made it clear that the true nature of the sunspots was yet to be unraveled. In 1908, Hale discovered that the light from the sunspots, when looked closely, show strong splitting in its components (Hale, 1908), a phenomenon that closely resembles the newly discovered Zeeman Effect (Zeeman, 1896). This discovery led to the understanding of the sunspots as the concentrated seats of magnetic fields.

Since then there has been enormous growth in the study of the Sun's magnetic field over the past century, which led humankind to understand the nature and variability of the Sun's magnetic field in great detail. With the rapid increase of the dependence of our society on different technologies, we now understand that our star, which gives us enough resources to sustain on this planet, can also take away all our technological advances and can throw us back to the stone age with a magnetic whip! The magnetic disturbances and energetic particles that come along with it from the Sun causes a plethora of phenomena on Earth and in near-Earth space at multiple levels, which ranges from the occurrences of the beautiful aurora in the polar regions to the shortened lifetime or even malfunction of the satellites, disturbances in the radio communication and GPS navigation systems, hazardous impact on astronauts' health in space and the failures of power grids and telecommunication networks on the ground to say the least which can make today's life on earth incredibly difficult (Gopalswamy, 2022).

The malfunctions of the telegraph lines after the Carrington event (Cliver and Dietrich, 2013) are now understood beyond any doubt to have been occured due to the solar flare, originated from the sunspot observed by Carrington. This event, was so extreme, if repeated in today's technology-packed time, can hit the global economy with multiple years of power outage and trillions of dollars of bills in restoring the technical capacities (Fry, 2012). In recent times, on March 13th, 1989, Canada's city of Quebec witnessed power grid failure due to a solar storm that had hit the Earth, which costed millions of dollars to repair (Boteler, 2019). More recently, on February 4, 2022, a constellation of

SapceX's Starlink project, containing nearly 40 satellites malfunctioned due to enhanced atmospheric drag caused by a solar storm (Baruah et al., 2024; Dang et al., 2022).

Other than the intriguing Physics behind the Sun's magnetic fields (which makes it a much more interesting astrophysical object to study than it was thought to be!), it is the urgency to gain enough understanding regarding the origin and evolution of the fields to make good enough prediction about the solar cycles and the energetic events to safeguard our assets in space and on the ground what makes the field of Solar Physics and Space Weather so important in today's time, which is the goal of this thesis as well!

1.1 The Sun: Its many layers

The Sun, situated at a distance of 150 Mkm from Earth, at 5 billion years of age is currently going through its midlife. In terms of its overall properties, The Sun is a pretty ordinary main sequence star of spectral type G2V. What makes it unique to us is its proximity to the Earth, which gives us an opportunity to observe it in great detail and makes it our go-to cosmic laboratory to study the behavior of large-scale astrophysical plasma and its interaction with the magnetic field. The Sun has a mass ($M_{\odot}$) of 1.99×10^{30} kg and its radius ($R_{\odot}$) is around 6.96×10^{5} km. The overall structure of the Sun can be divided into two broad categories, namely the (a) internal structure and the (b) external structure. Here I discuss some details of these two structures in brief.

1.1.1 The Internal structure

The Sun, just like many other stars is a massive ball of enormous amount of plasma held together in a spherical structure under its own gravity. Its mass is mostly made up of Hydrogen ($\sim 90\%$) and Helium ($\sim 10\%$) along with Carbon, Nitrogen, and Oxygen present in very small amounts ($\sim 0.1\%$). Being an optically opaque object, the interior

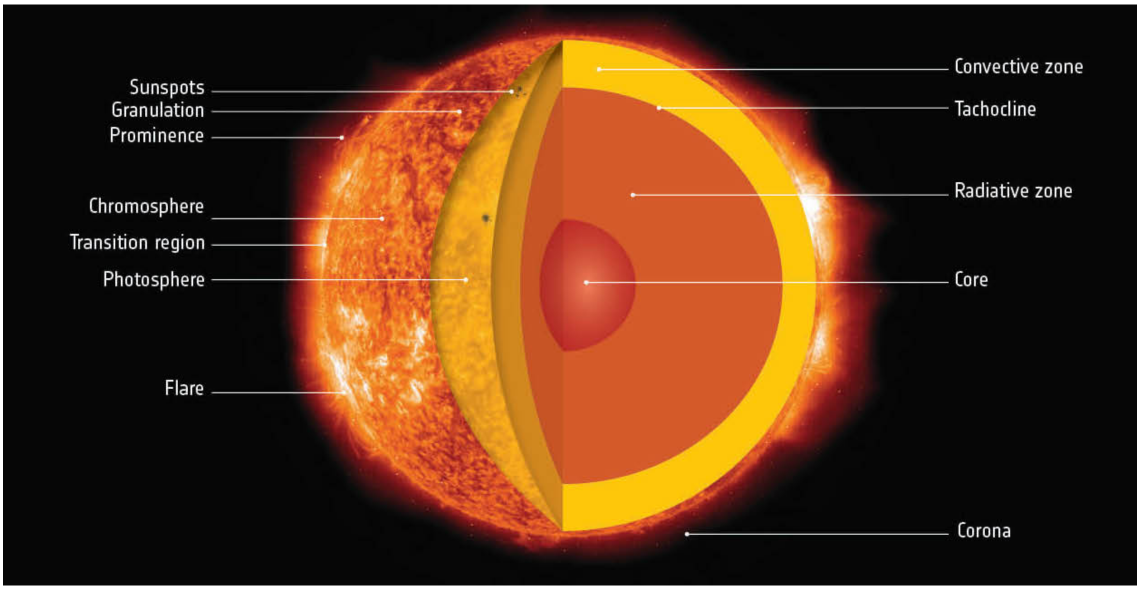

Fig. 1.1 The different layers of the Sun's internal and external structure. Image Credit: ©ESA.

of the Sun is shielded from outside observers. However, the models of stellar structure, when applied to Sun, reveal several layers of its inner structure. Here brief details of these structures are mentioned:

- **The Core:** The innermost 20% $(0-0.2R_{\odot})$ of the Sun's structure is the solar core, the powerhouse of the Sun. Inside the core, the estimated temperature goes up to 15 MK at the center of the Sun. The high pressure and temperature makes the condition favorable for nuclear fusion reaction where H nuclei (or, basically a proton) get converted to He by proton-proton chain reaction as follows:

$$4H^1 \longrightarrow He^4 + 2e^+ + 2\nu + 2\gamma \tag{1.1}$$

  It is the energy produced in the form of the two γ photons ($\sim$ 26.2 Mev), which gets radiated (although damped by the radiative zone) out of the Sun and makes the Earth habitable. The temperature gradient produced by this energy provides stability to the structure of the Sun supporting it against its own gravitational pull.

- **Radiative Zone:** The layer just out of the core is the radiative zone, extending from $0.2R_\odot$ to $0.7R_\odot$. Owing to the high density of this layer, the gamma photons produced in the core due to nuclear fusion goes through a phase of repeated absorption and re-emission, like a random-walk process. It takes the photos around 10000 years to eventually escape the radiative zone and come out of the Sun. The two neutrinos on the other hand owing to their very tiny collisional cross-section, escape this layer unimpeded.

- **The Tachocline:** This is a very thin layer sandwiched between the radiative zone and the convection zone. As we go out of the radiative zone towards the convection zone, the rotation profile of the Sun gets converted from that of a solid body to a differential profile, dependent on the radial and latitudinal coordinates. This rapid change (or a large gradient) in the rotation profile facilitates the generation of a large-scale toroidal magnetic field (more on this in the following sections) inside this layer which is important from the solar dynamo perspective.

- **Convection Zone:** The layer that extends from the tachocline to the solar surface ($\sim 0.7R_\odot - R_\odot$) is known as the convection zone. Due to the reduced density of the plasma material and a strong temperature gradient, the convection sets in. The hot and buoyant plasma blobs move toward the solar surface and lose temperature, and the cold heavier blobs come down toward the bottom of the convection zone. This vigorous convective motion and the differential rotation profile make this layer suitable for the dynamo action, the primary physical process behind several features of solar magnetism.

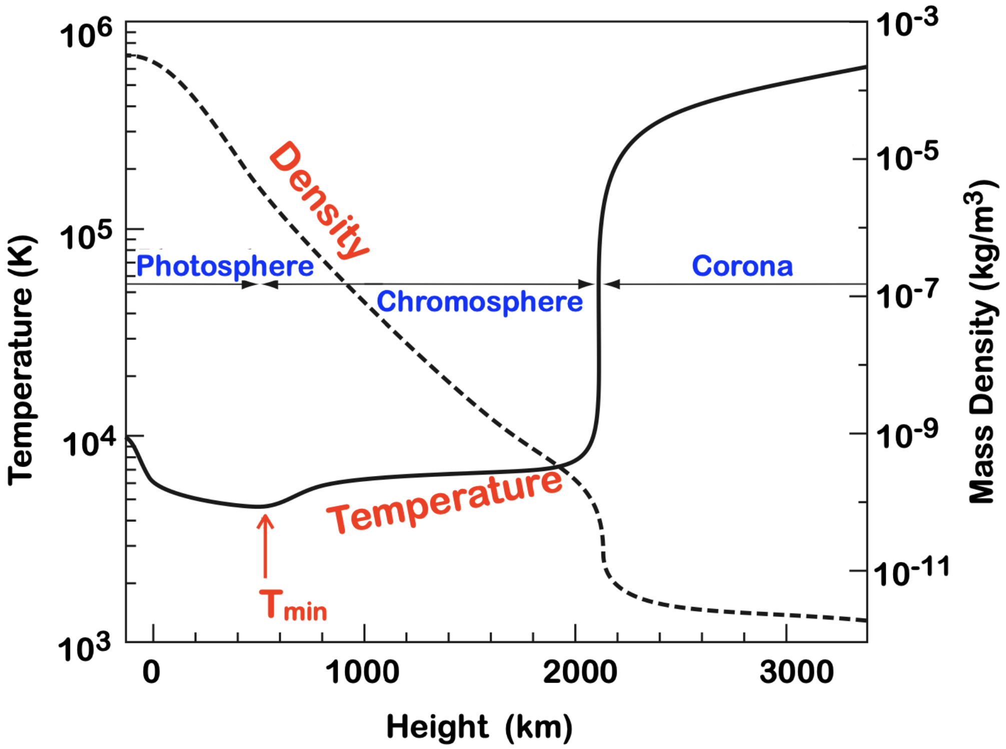

Fig. 1.2 The average temperature and density variation in the quite Sun regions with the height from the solar surface (Joshi, 2021; Lang, 2001; Priest, 2014) . Image Credit: Joshi (2021).

1.1.2 The External structure: The Solar Atmosphere

With the advent of multi-wavelength spectroscopic techniques and innovations in space-based satellite imaging capabilities, it has been possible to study the outer and optically thin Atmospheric layers of the Sun in great detail. These helped in segregating the external structure of the Sun, namely the ‘Solar Atmosphere’ into four major regions based on the temperature and density profiles and compositions of these layers. In Figure 1.2, the variation of the temperature and density profiles averaged over the quiet Sun regions is shown, where the different layers of the solar atmosphere are marked. These layers are briefly discussed below:

- **Photosphere:** This is the layer we get to see when we directly look at the Sun. The name of the layer itself suggests it as the layer of light. The Photosphere works as a boundary or the surface of the Sun marking a divide between the internal and the external regions. The temperature of this layer is around 5700 K. As we go above this layer, the density in the upper layers decreases gradually, however, the variation in temperature shows dramatic trends.

- **Chromosphere:** The layer extending up to a few thousands of kilometers above the photosphere and that appears in bright red color during the full solar eclipse is known as the Chromosphere, or as the ‘layer of color’. From the minimum temperature (T_{min} in Figure 1.2) region of the photosphere, the temperature steadily rises through the chromosphere, upto 20000 K, whereas the density shows a steady fall.

- **Transition Region:** It is a thin layer extending upto 100 km just above the Chromosphere. In this region, the temperature shows a rapid rise, from a few thousand Kelvin to a million Kelvin and the electron density shows a rapid fall within a very short interval.

- **The Solar Corona:** The outermost layer of the Sun is the solar corona, named after its crown-like structure as appeared during a full solar eclipse. This layer extends from just above the transition region to well into the heliosphere, up to 30-50 $R_{\odot}$. The temperature in the Corona shows variations from 1 million to 10 million K, whereas the density exhibits a steady decrease. The existence of mysteriously high temperatures in the Corona as compared to the photosphere is one of the puzzling problems in modern-day science and is known as the ‘Coronal heating problem’.

1.2 The Sunspots: The protagonist of the story

The darker spots on the bright surface of the Sun are known to humankind for centuries now, from a time much before the invention of the telescopes. Their earliest possible records are found in the literature of medieval Chinese civilization. In many parts of the world, their occasional sightings have been treated as omens from the heavens carrying certain astrological messages, mostly regarding the fate of the contemporary civilization or the Kingdom (Choudhuri, 2015). These dark spots on the solar surface are now called sunspots. It is only after a significant improvement of the then telescope by Galileo Galilei, the sunspots have been systematically observed, recorded, and studied by astronomers. For the last four centuries, the sunspots have been one of the central aspects of study in not just Solar Physics, but also in Astronomy and Astrophysics. By taking repeated observations of the sunspots over several days, Galileo inferred that the gradual longitudinal shift in the position of the sunspots is due to the rotation of the Sun. Later, the data from the sunspot observations has been extensively used to map the latitude-dependent profile of the Sun's differential rotation (see Jha et al. (2021) for one such recent example). The first presence of magnetic field outside the Earth was found in the sunspots by Hale (Hale, 1908), as already mentioned earlier. The study of their origin and evolution has revealed several fascinating aspects of the interaction between the large-scale magnetic field and plasma medium. Here, I mention some of their basic features, from what we know so far!

1.2.1 What they are: The basic properties

In short, sunspots are darker patches on the solar surface that consist of a strong magnetic field and are cooler than their surroundings. They come in various shapes, and structures ranging from the simple single-spot structure to complicated ones consisting of multiple spots, and their sizes range from a few hundred μHem to a few thousand μHem (Solanki, 2003). The sunspot area follows a log-normal distribution, showing the abundance of

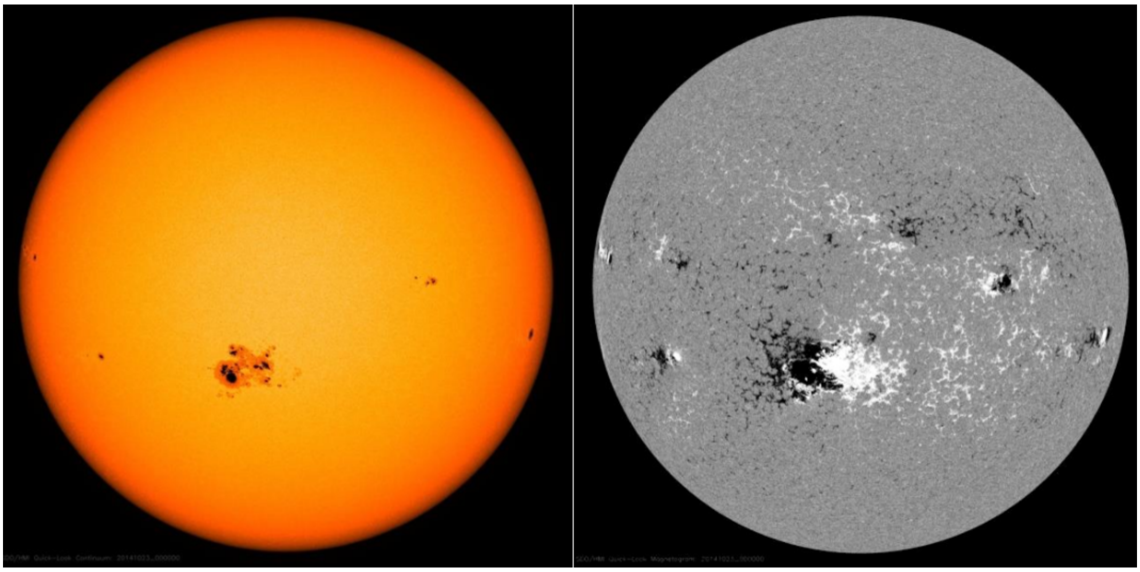

Fig. 1.3 In left: A typical white-light full disk image of the Sun with a few sunspots. On right: The magnetogram image of the Sun showing the corresponding magnetic activity (wavelength: 617.3 nm). Image Credit: NASA: SDO/HMI (23/10/2014).

the smaller sunspots over the bigger ones (Baumann and Solanki, 2005). The lifetime of the sunspots varies in a wide range as well, with the short-lived sunspots vanishing in a few hours to the long-lived ones sustaining for even more than a month on the solar disk. The sunspots are generally observed to emerge in the mid-to-low latitudes on the solar surface. The magnetic fields of the sunspots are the primary driver of their evolution and make them such a fascinating object to study. The strength of the magnetic field inside the sunspots can be as high as up to 3000 G (Solanki, 2003) which is significantly stronger than the background field on the solar surface ($\sim$ 10 G), or the magnetic field in Earth's magnetosphere ($\sim$ 1 G). The presence of strong magnetic field inside the sunspots suppresses the convection (the efficient process of heat transfer in the Sun's convection zone) in the local region, making the heat transfer from the inside of the Sun to that region of solar surface inefficient, as a result, the regions consisting the sunspots are cooler (3000 – 4000 K) than the surrounding solar surface (5770 K) which makes it appear to be darker than the surrounding in the white light image of the solar photosphere (Biermann, 1941). The left panel of Figure 1.3 shows a group of sunspots as seen in the white-light image.

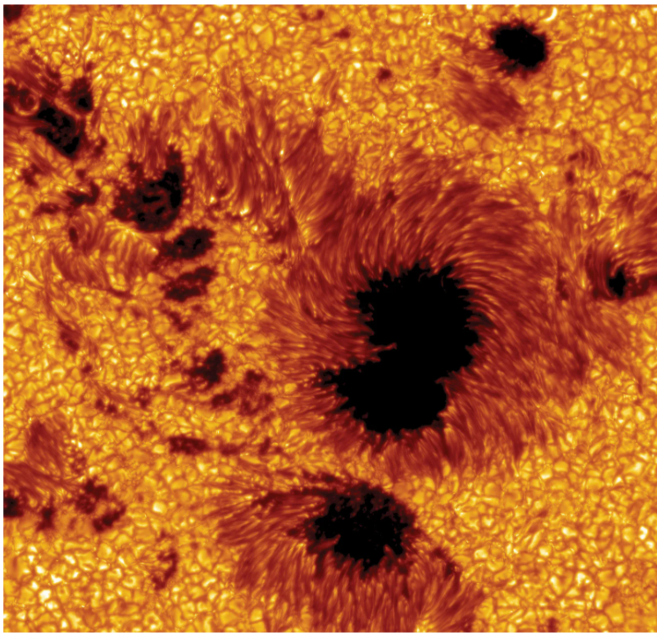

Fig. 1.4 A zoomed-in view of a group of sunspots as observed by the Swedish Solar Telescope. The inner darker region is the umbra whereas the lighter outer region is the penumbra of the sunspot. Image Credit: The Royal Swedish Academy of Sciences/The Institute for Solar Physics.

The basic two-part structure of the sunspots consists of the inner darker region named the umbra and the less dark outer region named the penumbra. The penumbral regions consist of filamentary structures that exhibit inflows and outflows of plasma (Borrero and Ichimoto, 2011; Wang and Zirin, 1992). The Figure 1.4 provides a closer look at a group of sunspots revealing finer details of its appearance.

1.2.2 The Bipolar Magnetic Regions: They have a life of their own

Very often the sunspots appear as a pair of two opposite polarity patches which are referred as the ‘Bipolar Magnetic Regions’ or ‘BMRs’. The right panel of Figure 1.3 is a magnetographic image (or a magnetogram) of the solar disc shown in white light in the left panel. The magnetogram reveals the magnetic features of the solar surface which consists of many such BMRs in the places of the sunspots. For the understanding of the evolution of solar cycles and the study of the solar dynamo, these BMRs and their properties play a crucial role which will be extensively discussed in various chapters of this thesis.

The polarities of the BMRs generally exhibit a systematic pattern in their magnetic field orientation (with some exceptions) and in their position on the solar surface. The polarity situated at a higher longitude, towards the direction of the Sun's rotation, is known as the leading polarity whereas, the one situated at the lower longitude is known as the trailing polarity. The line joining the centers of these two polarities is generally not parallel to the equator of the sun, but is tilted with respect to the equator. This tilt statistically follows a trend known as 'Joy's Law' (Hale et al., 1919), which says, the tilt of a BMR situated at a higher latitude is more than that of a BMR at a lower latitude. For a particular solar cycle, the polarities of the leading and trailing spots of a BMR flip from one hemisphere to the other, i.e. if in the northern hemisphere, the leading spot has the positive polarity (shown in white in Figure 1.3), then the trailing spot would have negative polarity (shown in black), on the other hand, in the southern hemisphere, the polarities of the leading and trailing spots would be negative and positive respectively. Also, the orientation of the magnetic polarities among the leading and trailing spots changes signs for each subsequent cycle. This interesting phenomenon is known as 'Hale's polarity rule' after its discoverer (Hale et al., 1919).

1.2.3 The formation of the sunspots: The rise of the buoyant flux tubes

How do the sunspots form? This has been one of the central questions in Solar Physics for a very very long time. Careful observations of the structure and magnetic orientation of the BMRs and their theoretical explanation provide crucial insights regarding the birth of sunspots. In 1955, Parker came out with a possible mechanism for the birth of the Sunspots (Parker, 1955b). It turns out, the key ingredient for the theoretical understanding of the formation and emergence of sunspots is the millennia-old concept of buoyancy, discovered by Archimedes, but with a twist in it. Inside the Sun's convection zone, strands of toroidal magnetic fields are present which are oriented in the azimuthal direction. As the magnetic field lines have tension along them, they suppress the convection in those regions as it leads to imparting twist in the field lines. The interplay between the magnetic tension and the convection makes the magnetic field lines to form very strong and highly concentrated bundles of field lines known as flux tubes, where the convection is inhibited to a large extent. The magnetic field lines carry a pressure associated with them and as a result, when a flux tube comes into thermal equilibrium with its surrounding inside the convection zone, the plasma material inside the flux tube exhibits less pressure than the surrounding plasma materials outside the flux tube. Hence, the density of the plasma inside the flux tube is lesser than the outside medium. As a result, the flux tube becomes buoyant (magnetic buoyancy) and starts rising through the convection zone ultimately piercing out of the solar surface and giving birth to a pair of sunspots. The opposite magnetic polarities of the BMRs are formed in the regions where the flux tubes emerge through the solar surface (see Choudhuri (1998, 2010); Parker (1955b) for the detailed mathematics behind the physics of the birth of sunspots). During the rise of a flux tube through the convection zone, the action of Coriolis force (due to the rotation of the Sun) is believed to impart a tilt to the orientation of the flux tube with respect to the solar equator producing the tilt of the BMR. (D'Silva and Choudhuri, 1993; Fan et al., 1994)

1.3 The Solar Cycles: Spans from decadal to millennial time scales

In the 17th and 18th centuries, sunspots were observed and studied using telescopes in different places of the world, especially in Europe, mostly by some individuals or groups of amateur astronomers. There was a lack of synergy between these groups which led to discontinuities in the sunspot observation records. It took a great deal of effort for astronomers in the 19th century to collect these records from different groups and create a continuous series of sunspot observations. Through a careful study of these records, in 1844, Heinrich Schwabe came out with his findings that the appearance of the sunspots on the solar surface goes up and down in a cyclic manner with a period of about 11 years (Schwabe, 1844). This cycle is now famously known as the '11-year Solar Cycle' (Hathaway, 2015). The modern-day counting of the solar cycle was started in 1755 which marked the minimum of solar cycle 1, currently in 2023, we are going through the rising phase of the solar cycle 25. I will discuss more on the various properties of solar cycles in the following sections, now we shall take a look at how solar activity is measured.

1.3.1 Measuring the solar activity: Different proxies

The sunspots on the solar surface appear in various shapes and sizes and often they come in complicated group-like structures consisting of several spots within it. As a result, the records of sunspots were very much dependent on the bias of the observers, and to have a homogenous record to be regarded by the whole solar physics community around the world, a formula was needed to simplify the process of sunspot observations. While working in the Bern observatory in Switzerland, Rudolf Wolf came out with a formula for counting the number of sunspots (R) on the solar surface which is of the following form:

$$R = K(10G + N) \tag{1.2}$$

where K is a correction factor, G is the number of sunspot groups present on the solar surface and N is the number of isolated sunspots situated outside the groups. R is now regarded as the 'Wolf Sunspot Number' or 'International Sunspot Number' (ISN). At present time, ISN is one of the primary proxies to measure the solar magnetic activity or the strength (and many other properties) of a solar cycle (Clette et al., 2014).

Other than the sunspot number, the area of the solar surface covered by the sunspots (in the millionth of hemisphere, μHem), i.e. the total area of sunspots present on the solar surface is also an important proxy for the solar activity (Mandal et al., 2020).

A major drawback of the sunspot number or sunspot area series for measuring solar activity is that they are available for a limited period of time, only for the last few centuries. As a result, it is not possible to study the long-term evolution of solar activity to find out how the Sun's magnetic field has behaved over the previous millennia using these proxies. This drawback inspired astronomers to find out other means of measuring solar activity in the past beyond the available sunspot data series. Eugene Parker in 1965 advocated that the cosmic ray particles, that are continuously showered on the Earth from every direction, get deflected by the magnetic field of the solar wind, the constant stream of particles leaving the solar atmosphere. Hence, the amount of cosmogenic radioactive isotopes (like C^{14} or Be^{10}) that are created on Earth's environment by the impact of cosmic rays on the atmosphere should be anti-correlated with solar magnetic activity (Parker, 1965). These radioisotopes with half-lives of several millennia get deposited on the layers of ice in glaciers of polar regions and in the rings of trees. This enabled the dating and the measurements of quantities of these isotopes deposited in the glacial layers over the last 12 millennia spanning over the entire Holocene, giving a reliable proxy for the very long-term measurements (see Usoskin (2017), for a detailed discussion on these proxies). In the following sections, we will discuss the findings regarding the trend of solar activity inferred from these proxies in some more detail.

Apart from the above-mentioned proxies, there are some other methods to infer the solar activity like the use of 10.7 cm radio flux data which shows a good correlation with the ISN (Tapping, 2013). On the other hand, the Total Solar Irradiance (TSI), which is

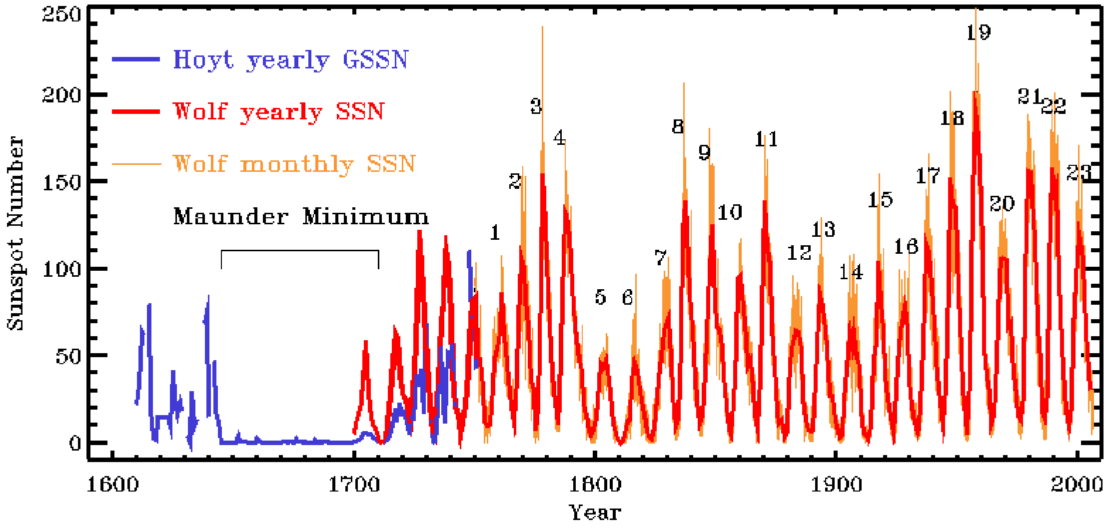

Fig. 1.5 The solar cycles from the last four centuries as observed in terms of sunspot numbers (ISN Version 2.0). Image Credit: Paul Charbonneau, Wikimedia.(https://commons.wikimedia.org/wiki/File:Solar_cycle.gif)

measured by calculating the total flux from the Sun, over all the wavelengths per unit area also shows a good correlation with the ISN data (Fröhlich, 2013). However, the data related to these proxies are limited to only the last few cycles, as their measurements were not possible before the advancements in ground and space-based telescopic instrumentations of the 20th century.

1.3.2 Properties of the 11-year solar cycle: The enigmatic features

The Figure 1.5 shows the ISN (or Wolf SSN) plotted against time for the last four centuries. It does not take a sharp look to notice the cyclic patterns in the evolution of the number of sunspots. Although the cyclic patterns are quite regular for the last three centuries, the individual cycles possess properties that are dramatically different from one another. A closer look at the data reveals that the strength of the cycles varies in a wide range where the peak of the strongest cycle (Cycle-19) is more than 4 times higher in strength than the weakest cycle (Cycle-5)! This wide range of variation in strength from one cycle to another makes it very difficult to predict the strength of an upcoming cycle (Petrovay, 2020). The lengths of these cycles vary within a range of 9 to 13 years, with the average period being nearly 11 years. The shape of an individual cycle is similar to an asymmetric Gaussian function, that is, the rising phase of the cycle is shorter than the decline phase. There exists an anti-correlation between the strength and the length of the solar cycle, i.e. the period of weaker cycles is longer than the stronger ones (Hathaway, 2015).

One of the crucial properties of the solar cycles is that the stronger cycles tend to rise from their minimum to maximum in less time with a higher rise rate than the weaker ones. This rule is known as the famous Waldmeier Effect after M. Waldmeier first pointed this out in 1935 (Hathaway and Wilson, 2004; Karak and Choudhuri, 2011; Waldmeier, 1935). This effect has provided important insights regarding the evolution of the solar magnetic fields and has been useful in assessing the strength of a cycle well in advance. In 1955, Waldmeier pointed out something more fascinating regarding the solar cycles, he found irrespective of their strength, all the solar cycles decline in the same way with similar statistical properties (Waldmeier, 1955). In very recent times, this aspect of the solar cycle has been studied extensively with better observational data and theoretical simulations (Biswas et al., 2022; Cameron and Schüssler, 2016; Talafha et al., 2022b).

At the beginning of the solar cycle, the sunspots start appearing in the mid-to-high solar latitudes (between $35\circ - 45^{\circ}$), as the cycle progresses, the sunspots keep on appearing towards the lower latitudes, with the activity band migrating towards the equator. When the latitudes of sunspot emergences throughout the solar cycle is plotted against time, it produces a beautiful pattern resembling the wings of a butterfly, hence the time-latitude plot of the sunspots is called the ‘Butterfly Diagram’ (See Hathaway (2015) for further discussions).

In the Figure 1.5, one intriguing feature of solar activity is that, during the 2nd half of the 17th century, the sunspots were rarely observed. Other than some occasional sightings of isolated groups of sunspots, the cyclic nature of the solar activity was largely absent in this time. This phase of unusually low magnetic activity of the Sun is known as the ‘Maunder Minimum’ (Eddy, 1976). What is more interesting is that extreme weather conditions like unusual and severe winters were observed in many parts of the world during this period which makes one wonder whether magnetic activity has been a key driver of the weather and climate conditions of Earth in the preindustrial era!

1.3.3 Long-term trend of the solar activity: Looking beyond the decadal scale

The cosmogenic isotopes deposited over the millennia in the ice cores of glaciers in the polar regions or in tree trunks provide the amount of modulation of the galactic cosmic rays due to the solar magnetic activity before the beginning of the direct measurements of solar activity. The initial efforts for quantitative reconstruction of solar activity over a millennial time scale using this approach came from Solanki (2003); Usoskin et al. (2003). However, the technological advancement in recent times and the use of different cosmogenic isotopes helped the reconstruction extend to a large part of the Holocene, the recent period of stable and warm climate spanning over the last 12 millennia (Wu et al., 2018). The Figure 1.6 presents the reconstructed solar activity during the last 9 millennia.

Although the 10-year temporal resolution of the reconstructed data limits its scope to identify individual solar cycles, it provides a plethora of new information regarding long-term solar activity. For most of the last 9 millennia, the magnetic activity of the Sun has been within a moderate window as shown in the Figure 1.6 by blue and red dashed lines. However, the activity has shown a significant amount of variations and the theoretical explanation of this modulation of solar activity has provided important insights into the nature of the internal working of the Sun’s magnetic field. It has now been understood that the mysterious period of the ‘Maunder Minimum’ during the 17th century was not

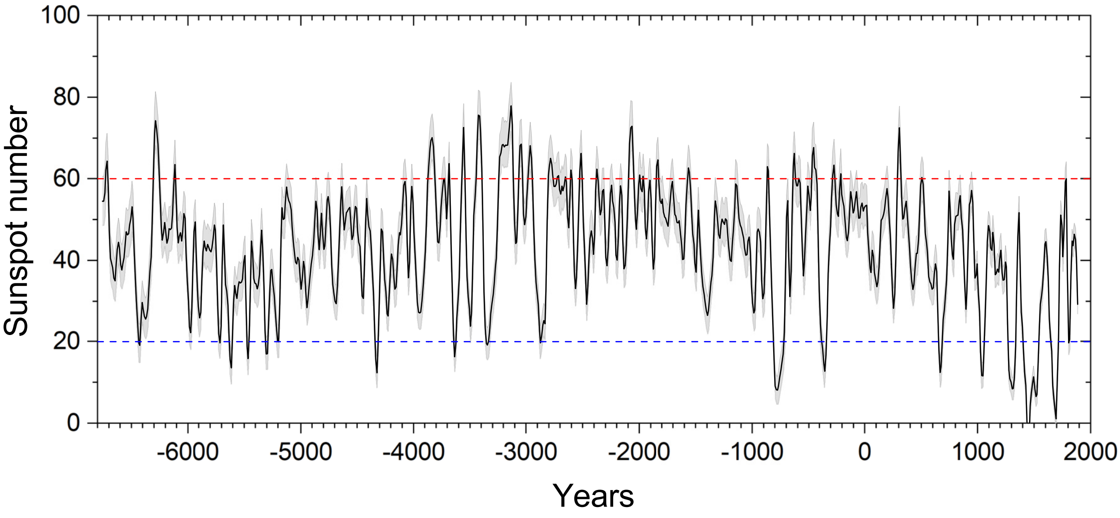

Fig. 1.6 The multi-proxy reconstructed solar activity in terms of decadal-scale sunspot numbers over the last 9 millennia. The grey shading indicates the 1σ uncertainties (Wu et al., 2018). The red and the blue lines show the thresholds for the grand maxima and grand minima respectively. Image Credit: Biswas et al. (2023b).

a one-of-a-kind phenomenon for the Sun, in fact, in the past, there have been many such periods where the magnetic activity has been extremely low (below the blue dashed line), as if the Sun had gone to sleep! On the other hand, there have been multiple occasions, where the activity has been extremely high (above the red dashed line). These periods are now generally called the 'Grand Minima' and 'Grand Maxima' periods respectively.

Further analysis of the modulation in solar activity in the reconstructed data hints towards the fact that there are multiple other 'cycles' present with periods that are much higher than the known cycle period of 11 years. Although these so-called 'cycles' are far from being perfect clock ticks, with a period that is not strict to a value but varies within a range, they play an important role in the long-term variabilities of solar magnetism. These periodicities are found with the help of power spectrum analysis of the reconstructed data, which shows prominent peaks around these period values as shown in Figure 1.7. The first one is called as the Gleissberg cycle with a century-scale periodicity within the range of 60-140 years. The next prominent peak indicates the Suess/de Vries cycle with a period range of 200-210 years. The millennia-scale cyclicality, although the statistical

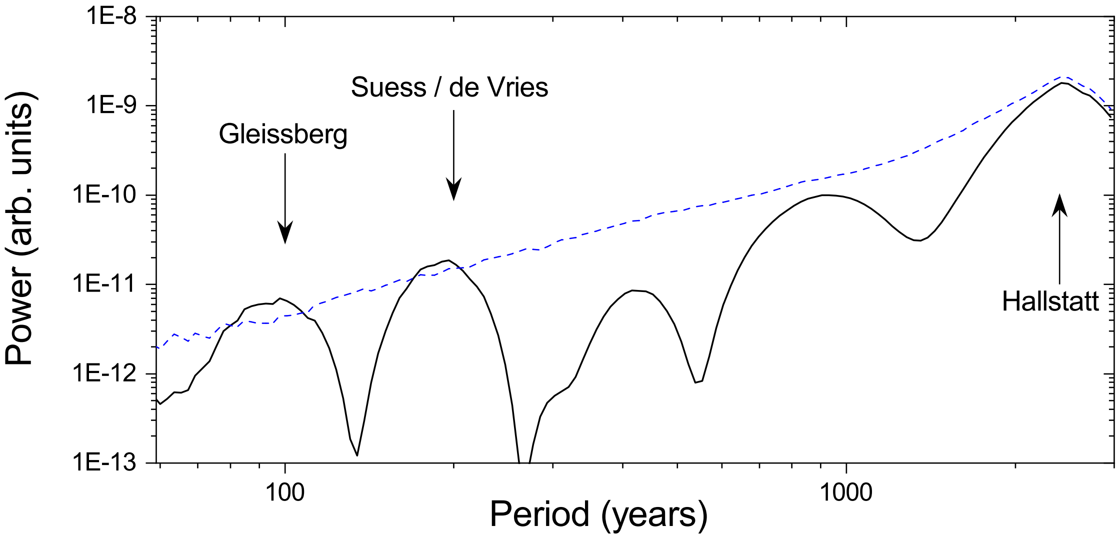

Fig. 1.7 Power spectrum analysis of the reconstructed Solar activity. The blue line shows the 90% confidence level. Image Credit: Biswas et al. (2023b).

significance of which is questionable, is known as the Eddy cycle. Finally, the one with the very long period of 2000-2400 years is called the Hallstatt cycle. However, due to the long period, its existence can not be robustly established with the 9000 years of reconstructed data. See Biswas et al. (2023b); Karak (2023) for detailed discussions on the long-term modulation of the solar activity and their modeling aspects.

The fascinating magnetic activity of the Sun, in the form of both the long-term modulations and short-term intricacies, has become a central piece of modern-day Astrophysics, and theoretical explanations to many of the observed phenomena have given a significant boost to our understanding of the heavenly bodies and how the magnetic field interacts with the highly conductive medium that the plasma is. However, there still remains a plethora of open-ended questions that seek explanations from the available or yet-to-be-discovered theories. In the following section, I discuss the current theoretical understanding of the Sun's large scale magnetic field and its evolution.

1.4 The Solar Dynamo: Magnetohydrodynamics in action

The large-scale magnetic field of the Sun is generally divided into two components, namely the Poloidal, and the Toroidal component. Imagining a spherical coordinate system situated at the center of the Sun, the azimuthal or the ϕ component of the magnetic field is considered as the toroidal field on the other hand, the poloidal field consists of both the radial (r) and the co-latitudinal (θ) component. The solar cycles are nothing but manifestations of the cyclic oscillations of strength between these two components of the magnetic field. At the minimum of a solar cycle, the orientation of the magnetic field is largely poloidal in nature, on the other hand, during the maximum, the toroidal component dominates the global magnetic field. This can be clearly seen in Figure 1.8. The polarity of the magnetic field in the polar region of a certain hemisphere alters in each consecutive cycle minima. As this poloidal field becomes the source for the following cycle's toroidal field, hence the regular orientation of polarities of the leading and following sunspots of the BMRs in a certain hemisphere alters in each consecutive cycle. Considering the polarity reversals, the magnetic cycle has a period of about 22 years, which is called the 'Hale Cycle'.

The physical mechanism behind the cyclic variation of these components is known as the 'Solar Dynamo' mechanism that takes place throughout the convection zone of the Sun. The dynamo action is the process that facilitates the conversion of the poloidal field into the toroidal field and the conversion of the toroidal field back into the poloidal field in the time scale of about 11 years, completing one solar cycle. The process continues over and over again with some occasional hiccups during the grand minima, where the regular cycles are generally not observed.

The theoretical study of the solar dynamo at its current stage, generally revolves around building sufficient numerical models using the available theories and their associated equations. The task of making a numerical model that can explain all the observational

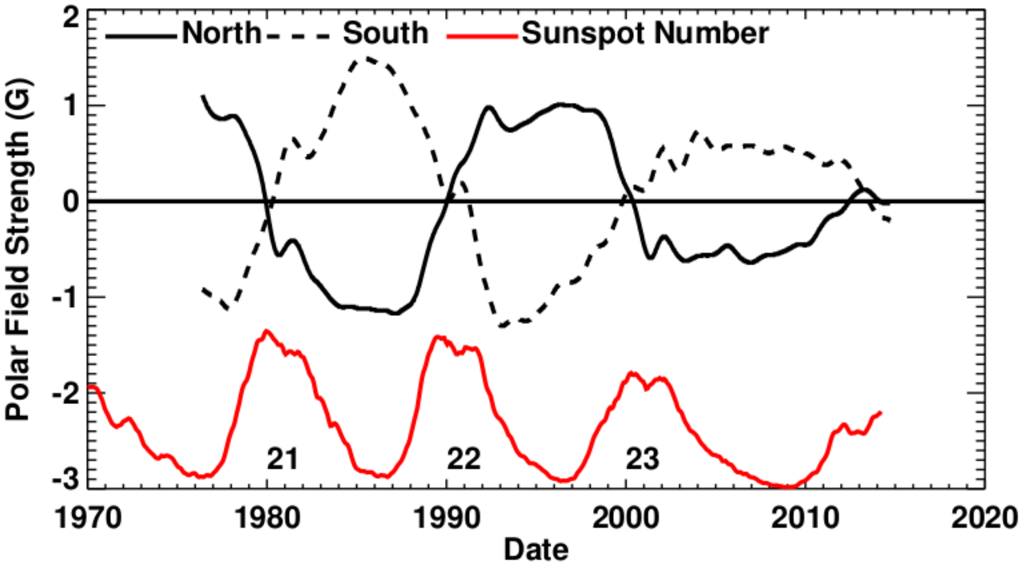

Fig. 1.8 The evolution of the poloidal (top panel, measured through the polar field strength) and toroidal (bottom panel, measured by the sunspot number) field strength of the Sun's magnetic field. There exists a phase lag between these two components. The poloidal component peaks near the sunspot minima whereas the toroidal component peaks during the cycle maxima. Image Credit: Hathaway (2015).

aspects of solar magnetism is daunting and severely limited by the currently available computational power and algorithms as well. Here a list of key observational factors that any numerical model of the solar dynamo must reproduce is presented:

- There must be an oscillation of the strength of the magnetic field components over a period of about 11 years.
- There has to be a $\pi/2$ phase difference between the poloidal and toroidal components
- The orientation of the magnetic field should be antisymmetric about the equator.
- The magnetic field polarities should change every 11 years.
- There should be migration of the toroidal component towards the equator and the migration of the diffused poloidal field towards the polar regions.

- Last but not at all the least, the model must successfully produce the characteristics of the long-term solar activity including the large fluctuations in cycle strength and grand minima.

Apart from these basic features, there are some more intricacies that a robust dynamo model must be able to simulate. It has been observed that the magnetic activity of the Sun are not totally symmetric in the two hemispheres. There exists a significant asymmetry between the North and South hemispheres in terms of sunspot number and sunspot area measurements along with other indices of the solar magnetic activity (Chowdhury et al., 2013; Das et al., 2022; Ravindra and Javaraiah, 2015). This asymmetry of sunspot properties eventually leads to the asymmetry in the reversal and buildup of the polar field. In Chapter 5, the observational aspect of the differences in polar field reversal timing between North and South hemisphere has been discussed in detail.

Before we jump into the theoretical aspects of the solar dynamo, here is a brief discussion on some fundamentals of Magnetohydrodynamics (MHD) and the associated equations, which make the dynamo action sustainable inside the solar convection zone.

1.4.1 The MHD equations: Frozen magnetic fields move with the plasma

Magnetohydrodynamics (MHD) is a branch of Physics that studies the evolution of magnetic fields in a highly conductive and dynamic fluid medium. To begin with the study of solar dynamo using the MHD theories assuming the solar plasma is an incompressible fluid, we need the following two fundamental equations dictating the evolution of the magnetic field and the flow of the medium.

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B} - \lambda \vec{\nabla} \times \vec{B}) \tag{1.3}$$

$$\rho \frac{d\vec{v}}{dt} = -\vec{\nabla} p + \rho \vec{g} + \frac{(\vec{\nabla} \times \vec{B})}{\mu_0} \times \vec{B} - 2\rho(\vec{\Omega} \times \vec{v}) + 2\vec{\nabla}.(\nu \rho \vec{S}) \tag{1.4}$$

The Equation (1.3) is known as the ‘Induction equation’ which can be easily derived by combining the Ohm’s law with the Maxwell’s equations. The induction equation gives the time evolution of magnetic field $\vec{B}$ under the action of the flow of the medium ($\vec{v}$) and diffusion (λ). The term $\lambda = \frac{1}{(\mu_0 \sigma)}$, is the magnetic diffusion under Ohmic dissipation. The ratio of the two terms on the right-hand side of the induction equation is known as the ‘Magnetic Reynolds Number’ (R_m) which is of the form, $R_m = \frac{VL}{\lambda} = \frac{L^2}{(\lambda \tau)}$, where, L and τ are the typical length and time scales. For astrophysical systems, the velocity and length scales usually have high values and on the other hand, the diffusion term λ has a small value owing to the highly conductive nature of the plasma medium. Hence, for large-scale astrophysical systems, $R_m >> 1$. It can be easily shown that, in the systems with large values of R_m, the advective term of the induction equation dominates over the diffusion term and the induction equation can be written in the following form:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) \tag{1.5}$$

With a few more mathematical operations on Equation (1.5), one can infer that the equation simply means that the magnetic field in a highly conductive medium with high R_m simply moves with the plasma material without exhibiting significant decay with time, as if the magnetic fields are ‘Frozen’ inside the plasma. This celebrated theory was first proposed by Hannes Alfven and is called ‘Alfevn’s Flux Freezing Theorem’- the central mechanism for the dynamo action (Alfvén, 1942; Alfven, 1950). For an elaborate and mathematical discussion of MHD please see Choudhuri (1998, 2010). The Equation (1.4) is the MHD version of the celebrated Navier-Stokes equation of fluid dynamics, with the volume force term of the right-hand side having the magnetic force included in it. It gives the evolution of the velocity field of the medium. To get the complete solution of the solar dynamo, these two coupled equations (along with the energy equation, mass continuity equation and equation of state) need to be numerically solved simultaneously. It is an extremely challenging task to reproduce the regular features of solar magnetism due to the small viscosity and magnetic diffusivity. The resolution of these solutions in 3 dimensions is also limited because of the limitation in the computational power. Please refer to Charbonneau (2020) for a detailed and comprehensive review on the topic of numerical modeling of the solar dynamo. Here in the next section, we briefly discuss a few approaches often used to simplify the solution of the dynamo equations.

1.4.2 Mean-Field Dynamo Theory: Separating the fluctuations from the mean

The first successful theory for the solar dynamo was proposed by Gene Parker in 1955 (Parker, 1955a). According to his turbulent dynamo theory, the poloidal component is stretched in the azimuthal direction due to the shear induced by the differential rotation by virtue of the flux freezing phenomenon. This shear of the poloidal field is most efficient at the bottom of the convection zone, where a strong toroidal field gets produced. The convection zone is highly turbulent due to vigorous flows of plasma and the continuous upward motion of hot plasma is followed by the downward motion of relatively cold plasma. Parker argued that the blobs of hot plasma rising from the bottom of the convection zone containing the frozen toroidal field in them would be acted upon by the Coriolis force of the rotating Sun which would produce twists in these plasma blobs. As a result, the orientation of the magnetic fields frozen inside these twisted blobs will have a significant poloidal component. The diffusion of numerous such twisted turbulent eddies would eventually produce the poloidal field of the Sun. As the direction of the Coriolis force is in the opposite directions in both hemispheres and the direction of the toroidal field is also in the opposite direction in both hemispheres, these two causes the large-scale poloidal field to have the observed structure resembling a similarity with the field of a bar magnet having opposite polarities in both the poles.

This intuitive idea of Parker was later put in a mathematical framework by Steenbeck, Raedler, and Kraus in 1966 using the 'Mean-Field Approximation' approach (Steenbeck et al., 1966). As the length and time scales of the Sun's large-scale magnetic field is much larger than that of the turbulent eddies, in the mean-field approach, the velocity and magnetic fields can be written as a sum of the mean or average of the quantities and the fluctuations in the quantities as shown here:

$$\vec{v} = <\vec{v}> + \vec{v}'; \vec{B} = <\vec{B}> + \vec{B}' \tag{1.6}$$

with $<\vec{v}'> = <\vec{B}'> = 0$. Once we put these values in the induction equation as shown in Equation (1.3), with some mathematical simplification and after taking the average, we reach to the following equation:

$$\frac{\partial <\vec{B}>}{\partial t} = \vec{\nabla} \times (<\vec{v}> \times <\vec{B}> + \varepsilon - \lambda \vec{\nabla} \times <\vec{B}>) \tag{1.7}$$

where $\varepsilon = <\vec{v}' \times \vec{B}'>$ which is called the mean turbulent electromotive force (or mean-field emf). This is the celebrated mean-field dynamo equation. For the case of homogeneous and isotropic turbulent medium, ignoring the higher order terms, the mean-field emf can be written as:

$$\varepsilon = \alpha \vec{B} - \beta \vec{\nabla} \times \vec{B} \tag{1.8}$$

where α and β are the alpha effect and turbulent diffusion. Putting this form of ε into the Equation (1.7) and dropping the average sign (as we will discuss in terms of mean fields only) we reach to the following equation:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B} + \alpha \vec{B} - \eta \vec{\nabla} \times \vec{B}) \tag{1.9}$$

where $\eta (= \lambda + \beta)$ is the total diffusivity (magnetic and turbulent) of the system.

1.4.3 The Kinematic and Axisymmetric approximations

The Equation (1.9) is the mean-field induction equation that needs to be solved to study the solar dynamo problem. To make the dynamo solutions simpler, yet reasonably accurate, often the kinematic and axisymmetric approximations are adopted. The main idea of the kinematic approach is that the velocity field is given, so there is no need to solve the Equation (1.4) to produce the velocity field. In recent times, the ingenious technique of Helioseismology has given us the velocity profiles inside the Sun's convection zone with reasonable accuracy (Basu, 2016; Gizon and Birch, 2005). Here, let us take a slight discourse from the dynamo equations to learn a little about the velocity components in the Sun which will be important in the upcoming discussions. In most of the dynamo simulations using the kinematic approach the time-independent velocity field in the Sun's convection zone can generally be divided into two parts:

$$\vec{v}(r,\theta,\phi) = \vec{v_m}(r,\theta) + v_\phi(r,\theta)\hat{\phi} = v_r\hat{r} + v_\theta\hat{\theta} + r\sin(\theta)\Omega(r,\theta)\hat{\phi} \tag{1.10}$$

where, $\vec{v_m}(r,\theta) (= v_r\hat{r} + v_\theta\hat{\theta})$ is the meridional circulation and $\Omega(r,\theta)$ is the angular velocity. The measurement of the meridional circulation in the upper half of the convection zone ($\sim$ 20 m/s) is provided by Helioseismology, and in the bottom half of the convection zone ($\sim$ 1 m/s), the meridional circulation has been calculated based on mass conservation arguments for several years in the past. In very recent times, Helioseismology has also provided signatures of the meridional flow in the deep layers of the convection zone (Chen and Zhao, 2017; Gizon et al., 2020). The meridional circulation is towards the poles near the solar surface, and towards the equator near the bottom of the convection zone. The interesting fact about the Sun's angular velocity is that it is highly dependent on the latitude and the radial depth. The equator of the Sun rotates much faster than the poles. Hence, it is called the 'Differential Rotation' of the Sun (Beck, 2000; Stix, 1989).

From the perspective of observations, the global magnetic fields (like the global dipole moment or the general structure of the solar corona) and the large-scale flows of the Sun are generally symmetric with respect to the rotation axis of the Sun, i.e. mostly independent of the azimuthal (ϕ) coordinate. Hence, to reduce the complexity of numerical modeling, instead of solving the dynamo equations in all three dimensions, historically there has been a practice among the dynamo modelers to take the average value of quantities along the azimuthal direction (ϕ) and solve the dynamo equations only on the meridional ($r-\theta$) plane. In this method, the magnetic field is written in the following form:

$$\vec{B}(r,\theta,\phi) = \vec{B_p} + \vec{B_t} = \vec{\nabla} \times [A(r,\theta,\phi)\hat{\phi}] + B(r,\theta,\phi)\hat{\phi} \tag{1.11}$$

where, $\vec{B_p}$, and $\vec{B_t}$ are the poloidal and toroidal components, and $A(r,\theta,\phi)$ is the azimuthal component of the vector potential. This approach of considering the magnetic configuration symmetric along the rotational axis is known as the 'Axisymmetric approximation'. In what follows, I discuss the development of dynamo theory in the kinematic-axisymmetric regime with some of the recent developments in the kinematic 3D dynamo simulations.

By putting the velocity and magnetic fields from the Equation (1.10) and Equation (1.11) respectively into the Equation (1.9), and adopting the axisymmetric approximation, we can obtain the following two coupled equations for the evolution of the poloidal and toroidal component of the magnetic fields respectively:

$$\frac{\partial A}{\partial t} + \frac{1}{s}(\vec{v_m}.\vec{\nabla})(sA) = \eta_p \left(\nabla^2 - \frac{1}{s^2}\right) A + \alpha B \tag{1.12}$$

$$\frac{\partial B}{\partial t}+\frac{1}{r}\left[\frac{\partial(rv_rB)}{\partial r}+\frac{\partial(v_\theta B)}{\partial\theta}\right]=\eta_t\left(\nabla^2-\frac{1}{s^2}\right)B+s(\vec{B_p}.\vec{\nabla})\Omega+\frac{1}{r}\frac{d\eta_t}{dr}\frac{\partial(rB)}{\partial r} \quad (1.13)$$

Here, $s = r\sin(\theta)$. The last term in the right-hand side of Equation (1.12) is the mean-field source term for the poloidal field, where α represents the helical turbulent effect on the rising flux tubes for the generation of twisted eddies, it is called the 'Helical-α Effect'. The second term in the right-hand side of Equation (1.13) represents the shearing of the poloidal magnetic field (B_p) by the action of the differential rotation (Ω) which is the primary source of the toroidal field. The dynamo action described by the aforementioned equations is known as the so-called $\alpha\Omega$ dynamo. Here I note that the source term for the toroidal field due to the mean-field alpha effect in the Equation (1.13) has been ignored here as its contribution is much smaller than the contribution of the differential rotation in the production of toroidal field. For many years now, these two equations have been the foundation for the numerical studies of the solar dynamo (Charbonneau, 2010, 2020; Chatterjee et al., 2004; Dikpati and Charbonneau, 1999). In the mean-field regime of turbulent helical-α effect, the dynamo entirely works inside the bulk of the convection zone. The most remarkable aspect of these equations is that they provide a travelling wave solution mimicking the latitudinal migration of the toroidal field towards the solar equator as seen in observation.

Although the mean-field turbulent dynamo theory was successful in explaining many of the observational aspects of solar magnetism and provided important insights into the evolution of solar activity, by the end of the 20th century numerical simulations and solar observations were making it more and more evident that, the turbulent dynamo theory may not be the best suited one for explaining all the intricacies of the solar dynamo and the theoreticians had to look for some alternate mechanism that can withstand the new found details of the solar magnetism (Choudhuri, 2015; D'Silva and Choudhuri, 1993;

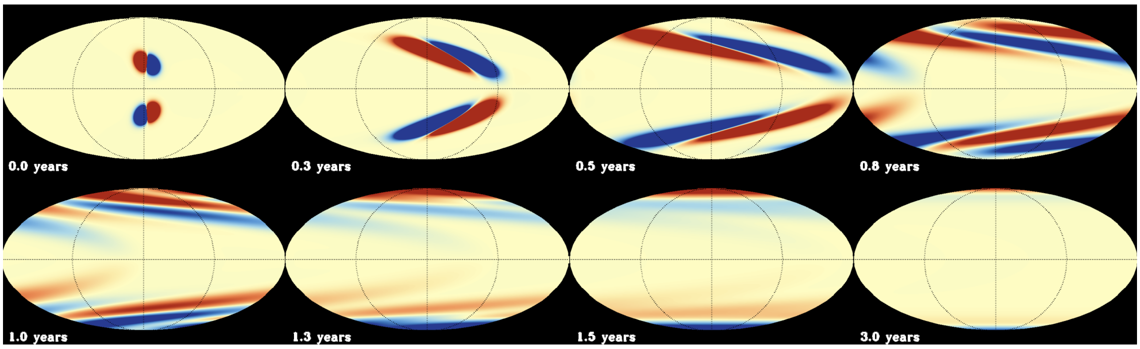

Fig. 1.9 The build-up of the polar field through the Babcock-Leighton process using 3D kinematic dynamo simulation by Karak and Miesch (2017). Image Credit: Karak (2023)

Wang et al., 1991). In this context came the Babcock-Leighton dynamo theory of the solar dynamo which we are going to take a look at in the next section.

1.4.4 Babcock-Leighton Mechanism: Flux Transport Dynamo

The Babcock-Leighton (B-L) mechanism as the name suggests was first proposed by Babcock (1961b) and Leighton (1969). In this mechanism, the poloidal field is produced by the diffused weak field resulting from the decaying BMRs. Due to the tilts of the BMRs (following Joy's law) with respect to the equator, the two polarities evolve in slightly different latitudes. This leads to the polarity of the leading spots (generally situated at lower latitude nearer to the equator) crossing the equator and getting canceled with the opposite polarity of the leading spot from the BMRs on other hemisphere. On the other hand, the trailing spots, situated at a higher latitude comparatively nearer to the pole, gets advected towards the pole which in turn cancels the polar field of the previous cycle and builds the polar field for the following cycle. This mechanism doesn't need to be highly efficient to be effective, as the total flux of the peak polar field near the polar region is of the order of the flux content of a single BMR ($\sim 10^{22} Mx$).

This idea of B-L mechanism was however overshadowed for decades by the initial success of the turbulent dynamo theory and due to the lack of observational evidence.

However, thin flux tube simulations (D'Silva and Choudhuri, 1993) later showed that the strength of toroidal flux tubes is much higher for the helical-α effect to be efficient enough to generate the observed strength of the polar field. Also, time-latitude maps of long-term magnetogram observations shows signatures of magnetic fields from trailing polarities rushing from lower latitudes toward the poles, which can be explained by the B-L mechanism (Wang et al., 1991). In this context, the Surface Flux Transport (SFT) model is worth mentioning. The SFT model describes the evolution of the surface radial field on the solar surface from the dying BMRs, which is the essence of the Babcock-Leighton framework. The success of SFT models in explaining the build-up of the polar field and in reproducing the observational features for the evolution of the surface magnetic field over multiple cycles led to more consensus toward the effectiveness of the B-L mechanism (Baumann et al., 2004; Cameron et al., 2010a; Jiang et al., 2014b; Yeates et al., 2023). These events facilitated the adoption of the B-L mechanisms as an alternative to the helical-α effect for the production of the poloidal field in the solar dynamo. Many of the recent dynamo models have been created using the B-L mechanism, which are called the Babcock-Leighton type flux transport dynamo models. Other than the SFT model or the 2D axisymmetric kinematic dynamo models, recently the B-L process has also been captured in 3D dynamo models as well. The Figure 1.9 shows the manifestation of the B-L mechanism in 3D dynamo simulations performed by Karak and Miesch (2017). The mechanism for the production of toroidal fields in these B-L dynamo models is the same as the turbulent dynamo theory, the shearing of poloidal fields by the differential rotation produces the toroidal field.

Although the B-L type dynamo models are derived from the same set of Equation (1.12) and Equation (1.13) similar to the turbulent dynamo models, the treatment of the source term (αB) for the poloidal field is entirely different in these two models. In the turbulent dynamo, the helical-α effect takes place in the bulk of the convection zone and is mathe-

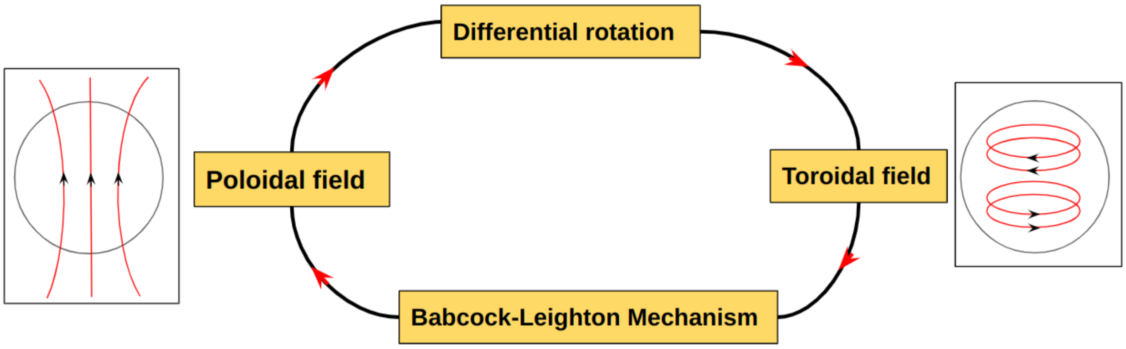

Fig. 1.10 A pictorial description of the basic idea behind the Babcock-Leighton solar dynamo model.

matically describable from the mean-field approximation as discussed earlier. On the other hand, the B-L α source term is introduced in an ad-hoc manner which has a non-zero value only near the solar surface. The B-L α source term is basically introduced in the models to mimic the observationally established trend of the BMR tilts following Joy's law.

There came another difficulty in incorporating the B-L mechanism in the solar dynamo perspective. We already mentioned that the turbulent mean-field dynamo solution gave the dynamo wave solution explaining the equatorward migration of the toroidal field throughout the cycle. For the dynamo wave to be equatorward, the Parker-Yoshimura (Parker, 1955a; Yoshimura, 1975) sign rule demands $\alpha\frac{\partial\Omega}{\partial r} < 0$ in the northern hemisphere. But, the observation shows $\frac{\partial\Omega}{\partial r} > 0$ in the low latitudes, where the sunspots emerge, on the other hand, the observations of BMR tilts also show $\alpha > 0$ in the same region in the northern hemisphere. Hence, the Parker-Yoshimura sign rule gives poleward migration of the dynamo wave. This problem has been resolved by introducing an equatorward meridional flow at the bottom of the convection zone. Recent observations through helioseismology show signatures of significant return flow of meridional circulation towards the equator deep inside the convection zone (Chen and Zhao, 2017; Gizon et al., 2020). A sufficiently strong meridional flow can overturn the sign rule and make the toroidal field transported toward the equator. The dynamo models which use this kind of meridional flow profile are known as the 'Flux Transport Dynamo' models (Chatterjee et al., 2004; Choudhuri et al., 1995; Dikpati and Charbonneau, 1999; Durney, 1995; Nandy and Choudhuri, 2002).

Despite several initial criticisms, the Babcock-Leighton type Flux Transport Dynamo models and the SFT simulations have successfully produced most of the observational aspects of the solar cycles and are currently the most accepted theory for the solar dynamo (Charbonneau, 2010, 2020; Karak et al., 2014). Throughout my thesis, I have extensively used these models to understand the nature of the solar dynamo. Here, I present a brief summary of the solar dynamo in the B-L framework. The Figure 1.10 provides a pictorial presentation of the main components involved in the Babcock-Leighton type solar dynamo. During a solar minimum, the poloidal field attains its peak strength which gradually gets converted into the toroidal field by the action of the solar differential rotation. The sunspots get formed from the toroidal flux tubes and the solar activity increases with time. The equatorward meridional flow transports the toroidal belts towards the equator with time, making the sunspots to emerge closer and closer to the equator as the cycle progresses. During the maximum, the strength of the poloidal field gets diminished and the reversal in its polarity is observed. During this time, the orientation of the large-scale solar magnetic field is dominated by the toroidal component. This process of the toroidal field getting generated from the poloidal field is fairly linear and predictable, which enables the prediction of the strength of the upcoming solar cycle from the peak strength of the polar field during the cycle minimum (Bhowmik and Nandy, 2018; Cameron and Schüssler, 2015; Choudhuri et al., 2007a; Kitchatinov and Olemskoy, 2011; Kumar et al., 2021, 2022; Petrovay, 2020; Schatten et al., 1978b). Now, the sunspots or more generally the BMRs once emerged through the solar surface undergo decay majorly due to diffusion and inter-polarity flux cancellation and get dispersed over time. Due to the tilt of the BMRs, the remnant radial components of the magnetic field from the sunspot at the higher latitude get carried toward the polar regions by the poleward meridional flow on the solar surface. This mechanism of the poloidal field getting rebuilt from the toroidal field via the decay of sunspots is the essence of the Babcock-Leighton mechanism. However, the nonlinearities and the stochastic nature of the BMR properties mainly the tilt, flux content, and the rate of their emergence make the contribution of each individual BMR to the polar field build-up vary widely making this process highly unpredictable limiting the scope of long-term multi-cycle forecasts in solar activity. I will discuss on these aspects elaborately throughout the following chapters of this thesis.

1.4.5 Global MHD simulation of solar dynamo: The final frontier

It would be an incomplete discussion about solar dynamo simulations without mentioning the global MHD convective dynamo simulations, the holy grail of the solar dynamo modelers. Although the mean-field dynamo model or the Babcock-Leighton type flux transport dynamo model are derived from the above mentioned MHD equations and supported by some observations, they are reliant on several assumptions and approximations. Especially the kinematic assumption, that requires the velocity fields to be specified has been a daunting task modelers for several years. On the other hand, in the full MHD simulations, in addition to the Equation (1.3), and Equation (1.4), one needs to solve the continuity equations for the mass and energy of the of the plasma medium. I refer the readers to Brun and Browning (2017); Charbonneau (2020); Käpylä et al. (2023); Karak (2023) for some excellent discussions on the topic of the MHD dynamo simulations. One of the most important advantages of the global MHD convective simulations are that, the velocity fields are determined by solving the Navier-Stokes equations of Equation (1.4) rather than relying on assumptions. The stochastic as well as nonlinear nature of the solar dynamo are also captured in these models by default whereas in the mean-field approach they are introduced in the equations to replicate the observations.

In the last decade there have been some significant developments in the field of global MHD simulations. Several groups achieved breakthrough in producing many of the long term features of the solar cycles in their simulations. Passos and Charbonneau (2014) produced 40 regular cycles with an average period of 40 years. These cycles show modulation in the cycle strength along with the pattern of the Gnevyshev-Ohl rule. Augustson et al. (2015) used the 3D MHD ASH code to produce grand minima like long term features of the solar cycles along with other features consistent with observations. Käpylä et al. (2016) used the Pencil code for a 3D MHD simulation setup to produce features like regular polarity reversals and equatorward migration of toroidal field.

However, the major drawback is that the simulation of global MHD dynamo models are extremely challenging due to the complicated nature of the equations. These simulations also require enormous computational resources to run for longer durations. As a result long term global MHD convective simulations are rare. On the other hand despite the shortcomings and criticisms, the Babcock-Leighton type kinematic models have been fairly successful in replicating many observed features of the solar cycles as well as in studying the long term variabilities. These models are relatively easier to simulate and require much lesser computational resources than global MHD simulations. As already discussed earlier, the major reasons behind the growing success and acceptance of kinematic dynamo models are that the flow profiles are now known from helioseismology, there are also no large variations in these flows in the solar convection zone, and there are observational support for the B-L mechanism and the nonlinearities involved in the process. These topics are discussed further in more detail in the following chapters.

1.5 Space Weather: The Sun-Earth connection

In the earlier sections we took a look at the Sun as a distant star and discussed the intricacies of its long term magnetic activity and how to simulate the same using different theories and models. In this section, we look at the impact of the solar magnetic field on the near-Earth space environment. Since the dawn of the space-age it has been known that the space is not an empty place as thought earlier, but it has presence of magnetic fields and charged particles. The environmental conditions of the near-Earth space changes with time as well, a phenomenon now known as space weather. The Sun is the primary driver of the of the space weather in the solar system making the space weather conditions vary in synch with the phases of the solar cycles. The constant stream of charged particles that escape from Sun’s gravity due to thermodynamic instability and gets spread in the solar system produce a steady flow around Earth as well which are termed as the "Solar Wind". Other than that, the coronal mass ejections (CMEs) which are the sudden ejection of large amount of plasma materials and magnetic fields from the solar atmospheres as well as the solar flares which are the sudden enhancement in the electromagnetic radiation from the Sun are among primary causes for the severe changes in space weather conditions (Schrijver et al., 2015; Temmer, 2021).

The impact of space weather and the solar wind on the earth’s magnetic field and on the upper atmosphere are generally mild in most cases, due to the shielding effect of the Earth’s own magnetosphere. However the growing space explorations and the use of sensitive space-borne equipments make us vulnerable to the even mild variabilities of space weather. On the other hand the severe changes in the space weather conditions have hazardous consequences for even ground based technologies, especially for power grids causing large scale long term power outages. The Figure 1.11 gives an overview of the many ways in which the space weather and solar energetic events impact our modern technology-reliant civilization.

The impact of these individual energetic events generally have a time window ranging from a few hours to a few days. However, it has been found that the occurrences of the CMEs and solar flares exhibit a distinct pattern with short periods of a few months where

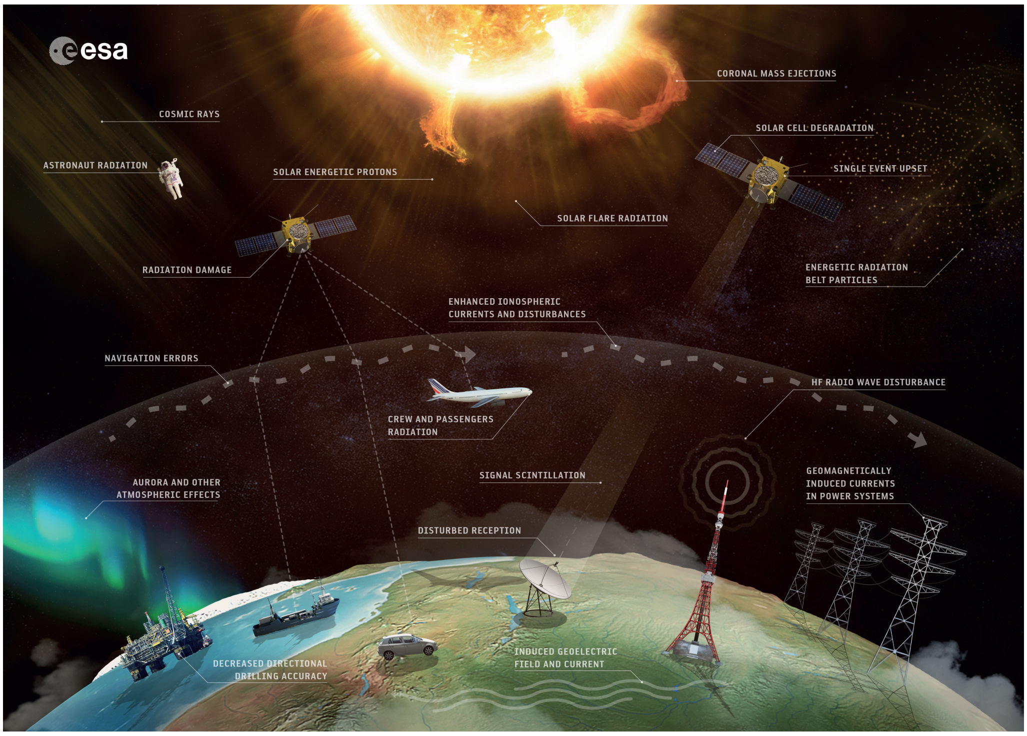

Fig. 1.11 An illustration of the impact of space weather on modern technology-reliant human civilization. Image Credit: ©ESA.

the activity is significantly high which is then followed by quieter intervals with less frequent energetic events. These type of quasi-periodic phenomena are now termed as the "seasons" of space weather. These "seasons" like periods are observed in every phases of the solar cycles with different levels of frequency in the occurrences of the energetic events. Dikpati et al. (2017) argued that the seasons are originated due to the dynamics of the tachocline shear-layer of the Sun which produces nonlinear oscillations that changes energy periodically between magnetic field, differential rotation and Rossby waves.

Over the last two decades there has been sincere efforts to understand the variations in the space weather with a major focus on forecast of short and medium term space weather conditions. A reliable long term forecast spanning over a few years can help in planning and scheduling space mission timelines, estimating operational lifetime of satellites and so on. In this context prediction of strength and timing of an upcoming solar cycle gives a general idea regarding the space weather conditions for the upcoming few years, as it is coupled with the solar magnetic activity (Bhowmik et al., 2023; Petrovay, 2020). In the Chapter 4, a new method for an early prediction of solar cycle strength is discussed in detail. For medium term assessment of space weather spanning over the upcoming few months, forecast of the ‘seasons’ can be a promising aspect. On the other hand, the very short term forecasts with a time window of a few hours to a few days can be much more demanding as it requires detailed real time information regarding the evolution of the energetic events like the CMEs (Riley et al., 2018; Vourlidas et al., 2019). However, this is the most crucial aspect of space weather forecast as reliable short term forecasts with an adequate time window can be of great help in safe-guarding the space and ground-based technologies and in preparing for disaster management efforts. In this aspect data driven simulations along with Machine Learning and Artificial Intelligence can be utilized using the data accumulated over the previous years by the solar and space weather observatories. In Chapter 6, I elaborate on the efforts made to forecast the timing and impact of CMEs on near-Earth space weather using using artificial intelligence.

1.6 Outline of the thesis

The rest of the thesis is organised into 6 further chapters each dealing with some of the unique features of solar activity and space weather. The chapters are organised in such a way that the regions of the Sun that are of concern in each of the chapters follow an outward order from the solar interior in Chapter 2 to the space weather and geomagnetic storms in Chapter 6. In Chapter 2 we explore the role of nonlinear toroidal flux loss from the solar interior due to the rise of toroidal flux tube during the formation of sunspots leading to the observed pattern of similar decline of all the solar cycles. In Chapter 3 we identify crucial nonlinear and stochastic processes in the solar dynamo that drive the wide variability in the long-term trends of solar cycles. Chapter 4 extensively explores the robustness of the polar field rise rate as a reliable precursor for the prediction of the peak strength of an upcoming solar cycle much earlier than the cycle minima, effectively extending the window for the solar cycle prediction by a few years. The polar field reversal time is a crucial landmark in the evolution of the solar cycle and for the prediction of an upcoming cycle's strength, however, it has been observed that the reversal timing exhibited variations in the past cycles. In Chapter 5 we utilise surface flux transport simulations to understand the role of anomalous and stochastic properties of BMRs behind the variation of polar field reversal timing in different cycles. Chapter 6 deals with forecasts of short-term space weather events with a time window of about a few days using a trained Artificial Neural Network from the knowledge of initial properties of CMEs extracted from the forward modeling technique. Finally, In Chapter 7 the key findings of the thesis are summarized in brief.