Chapter 2

photosphere

2.1. Photosphere: The effective temperature, or black body temperature, of the Sun is 5777 K, which is the temperature of a black body of the same size that will yield the same total emissive power as that of the Sun. The visible surface of the Sun, the photosphere, is the layer below which the Sun becomes opaque to visible light.[45] Above the photosphere the visible sunlight is free to propagate into space and its energy escapes the Sun entirely. The change in opacity is due to the decreasing amount of H− ions, which absorb visible light easily.[45] Conversely, the visible light we see is produced as electrons react with hydrogen atoms to produce H− ions.[46][47]

The photosphere is actually tens to hundreds of kilometres thick, being slightly less opaque than air on Earth. Because the upper part of the photosphere is cooler than the lower part, an image of the Sun appears brighter in the center than on the edge or limb of the solar disk, in a phenomenon known as limb darkening.[45] Sunlight has approximately a black-body spectrum that indicates its temperature is about 6,000 K, interspersed with atomic absorption lines from the tenuous layers above the photosphere.

![Absorption lines of photosphere](image)

FIG 2A: Absorption lines of photosphere

The photosphere has a particle density of ~$10^{23}$ m$^{-3}$ (this is about 1% of the particle density of Earth's atmosphere at sea level).[42]

During early studies of the optical spectrum of the photosphere, some absorption lines were found that did not correspond to any chemical elements then known on Earth. In 1868, Norman Lockyer hypothesized that these absorption lines
were because of a new element which he dubbed "helium", after the Greek Sun god Helios. It was not until 25 years later that helium was isolated on Earth.

Sun is made up of different layers as discussed in chapter 1. Out of this photosphere is very important layer where lot of magnetic activity is observed.

2.2. Sunspots:
The magnetic activity of sun is manifested in form of sunspots. A sun spot consists of a central umbra surrounded by a penumbra. Through umbral tubes plasma drains down such that umbral tubes are cooler than its surroundings. Various sunspot models are proposed among which parker's model is famous. Compared to the surrounding photosphere sunspots are cool. Hence they look dark. The other features observed are evershed flow, wilson depression, umbral dots etc.

Individual sunspots only last for one to two weeks, but the number of sunspots follows an 11 year cycle. Sunspots are visible from Earth. Sunspots are classified into different types like A, B, C etc or α, β, γ, δ etc depending on their morphology.

FIG 2B: Sunspot group: credit: Royal Swedish Academy of Sciences

FIG 2C: Sunspot 1024, Coronado H-alpha filter
Magnetic fields are a little like rubber bands. They consist of continuous loops of lines of force that have both tension and pressure. Like rubber bands, magnetic fields can be strengthened by stretching them, twisting them, and folding them back on themselves. This stretching, twisting, and folding is done by the fluid flows within the Sun.

**Omega effect:**
At sunspot minimum, the solar magnetic field is relatively straight like lines of latitude. Because the equator rotates faster than the poles (differential rotation), as time goes on the field gets twisted. During the course of 11 years, the magnetic field so twisted and tangled that some of the field breaks through the Sun's surface causing sunspots.
FIG2F: Babcock model

The Babcock model says that the differential rotation of the Sun (the sun being a viscous fluid, the poles rotate at a slower rate than the equator) winds up the magnetic fields of its layers during a solar cycle. The magnetic fields will then eventually tangle up to such a degree that they will eventually cause a magnetic break down and the fields will have to struggle to reorganize themselves by bursting up from the surface layers of the Sun. This will cause magnetic north-South pair boundaries (bipolar spots) in the photosphere trapping gaseous material that will cool slightly. Thus, when we see sunspots, we are seeing these areas of magnetic field breakdown.

Sunspots are cross connected eruptions of the magnetic field lines, shown in red above. Sometimes they break, spewing tremendous amounts of gas and particles into space. Solar flares and coronal mass ejections (CME’s) are some examples of this process. Sometimes they snap back like rubber bands. The number of sunspots at solar maxima is a direct indicator of the activity level of the solar dynamo.

This illustration shows how magnetic fields are recycled to produce sunspots within the solar convection zone (the top 30% of the solar interior, shown in white, surrounding the radiative core, in orange). Because the sun rotates faster at the equator than the poles, the north-south (poloidal) magnetic field (a) gets twisted into an east-west (toroidal) field (b) (ie fig2G a &b). Pockets of enhanced toroidal field rise to the surface, twisting in the process, and emerge to create sunspots (fig2G c, upper right). Magnetic flux emerges and spreads outward as the spots decay. Panels (d) and (e) show the solar dynamo, the conveyor belt of plasma flow (yellow) carrying the surface magnetic flux toward the poles—reversing the polar field—and eventually downward and back toward the equator. New sunspots eventually form in the poloidal field (f), which is now reversed from that in (a). **Illustration by Mausumi Dikpati, NCAR.**
Solar rotation is able to vary with latitude because the Sun is composed of a gaseous plasma. The rate of rotation is observed to be fastest at the equator (latitude $\phi=0$ deg), and to decrease as latitude increases. The differential rotation rate is usually described by the equation:

$$\omega = A + B \sin^2(\phi) + C \sin^4(\phi)$$

where $\omega$ is the angular velocity in degrees per day, $\phi$ is the solar latitude and $A$, $B$, and $C$ are constants. The values of $A$, $B$, and $C$ differ depending on the techniques used to make the measurement, as well as the time period studied. A current set of accepted average values is:

- $A= 14.713 \text{ deg/day} (\pm 0.0491)$
- $B= -2.396 \text{ deg/day} (\pm 0.188)$
- $C= -1.787 \text{ deg/day} (\pm 0.253)$

2.3. Sidereal rotation:
At the equator the solar rotation period is 24.47 days. This is called the sidereal...
rotation period, and should not be confused with the synodic rotation period of 26.24 days, which is the time for a fixed feature on the Sun to rotate to the same apparent position as viewed from Earth. The synodic period is longer because the Sun must rotate for a sidereal period plus an extra amount due to the orbital motion of the Earth around the Sun. Note that astrophysical literature does not typically use the equatorial rotation period, but instead often uses the definition of a Carrington rotation: A synodic rotation period of 27.2753 days (or a sidereal period of 25.38 days). This chosen period roughly corresponds to rotation at a latitude of 26 deg, which is consistent with the typical latitude of sunspots and corresponding periodic solar activity. When the Sun is viewed from the “north” (above the Earth’s northern pole) solar rotation is counterclockwise. Sunspots viewed from Earth (its Northern hemisphere) appear to move from left to right across the face of the Sun.

2.4. Using sunspots to measure rotation
The rotation constants have been measured by measuring the motion of various features (“tracers”) on the solar surface. The first and most widely used tracers are sunspots. Though sunspots had been observed since ancient times, it was only when the telescope came into use that they were observed to turn with the Sun, and thus the period of the solar rotation could be defined. The English scholar Thomas Harriot was probably the first to observe sunspots telescopically as evidenced by a drawing in his notebook dated December 8, 1610, and the first published observations (June 1611) entitled “De Maculis in Sole Observatis, et Apparente earum cum Sole Conversione Narratio” (“Narration on Spots Observed on the Sun and their Apparent Rotation with the Sun”) were by Johannes Fabricius who had been systematically observing the spots for a few months and had noted also their movement across the solar disc. This can be considered the first observational evidence of the solar rotation. Christopher Scheiner (“Rosa Ursine sive solis”, book 4, part 2, 1630) was the first to measure the equatorial rotation rate of the Sun and noticed that the rotation at higher latitudes is slower, so he can be considered the discoverer of solar differential rotation.

Each measurement gives a slightly different answer, yielding the above standard deviations (shown as +/-). St. John (1918) was perhaps the first to summarise the published solar rotation rates, and concluded that the differences in series measured in different years can hardly be attributed to personal observation or to local disturbances on the Sun, and are probably due to time variations in the rate of rotation, and Hubrecht (1915) was the first one to find that the two solar hemispheres rotate differently.

Internal rotation in the Sun, showing differential rotation in the outer convective region and almost uniform rotation in the central radiative region. The transition between these regions is called the tachocline.

Until the advent of helioseismology, the study of wave oscillations in the Sun, very little was known about the internal rotation of the Sun. The differential profile of the surface was thought to extending into the solar inertia as rotating cylinders of constant angular momentum. Through helioseismology this is now known not to be the case and the rotation profile of the Sun has been found. On the surface the Sun rotates slowly at the poles and quickly at the equator. This profile extends on roughly radial lines through the solar convection zone to the interior.
At the tachocline the rotation abruptly changes to solid body rotation in the solar radiation zone [4]. Solar rotational period as determined by SOHO data for period 1998-1999 is depicted below.

**fig 2I:** sidereal rotation profile

**fig 2J:** differential rotation profile

**fig 2K:** rotation period profile

At the photospheric layer the 27.5 days branch appers 0 to 30° latitude while 28 day branch at 60° degree latitude. The non-branching at core level indicates that core rotates as a solid rotator. The branching starts at 0.45 fraction of solar radius.

**2.6 Carrington rotation number:**
Solar rotations are mentioned in terms a number called Carrington rotation number (CR).

The Carrington rotation of the Sun is a system for comparing locations on the Sun over a period of time, allowing the following of sunspot groups or reappearance of eruptions at a later time.
Because the Solar rotation is variable with latitude, depth and time, any such system is necessarily arbitrary and only makes comparison meaningful over moderate periods of time. Solar rotation is arbitrarily taken to be 27.2753 days for the purpose of Carrington rotations. Each rotation of the Sun under this scheme is given a unique number called the Carrington Rotation Number, starting from November 9, 1853. (The Bartels Rotation Number is a similar numbering scheme that uses a period of exactly 27 days and starts from February 8, 1832.) Richard Christopher Carrington determined the solar rotation rate from low latitude sunspots in the 1850s and arrived at 25.38 days for the sidereal rotation period. Sidereal rotation is measured relative to the stars, but because the Earth is orbiting the Sun, we see this period as 27.2753 days.

2.7. The Solar Dynamo: It is widely believed that the Sun’s magnetic field is generated by a magnetic dynamo within the Sun. The fact that the Sun’s magnetic field changes dramatically over the course of just a few years and the fact that it changes in a cyclical manner indicates that the magnetic field continue to be generated within the Sun. A successful model for the solar dynamo must explain several observations:

1) the 11-year period of the sunspot cycle,
2) the equator-ward drift of the active latitude as seen in the butterfly diagram
3) Hale’s polarity law and the 22-year magnetic cycle,
4) Joy’s law for the observed tilt of sunspot groups and,
5) the reversal of the polar magnetic fields near the time of cycle maximum can be seen in the magnetic butterfly diagram.

Magnetic fields are produced by electric currents. These currents are generated within the Sun by the flow of the Sun’s hot, ionized gases. We observe a variety of flows on the Sun’s surface and within its interior. Nearly all of these flows may contribute in one way or another to the production of the Sun’s magnetic field.

2.8. Surface Flows: The surface of the sun is in constant motion due to the presence of several velocity components. These components include: rotation, cellular convection, oscillations, and meridional flow. The largest velocity signal is that due to solar rotation with an equatorial velocity of 2000 m/s. Both the oscillations and the convective motions have amplitudes of about 300 m/s. The meridional flow is the weakest at only about 20 m/s.

Each of these components plays an important role in helping us understand the sun and how it produces its 11-year cycle of solar activity. Solar velocity data is available from the Global Oscillation Network Group (GONG) instruments.
and the **Michelson Doppler Imager** (MDI) on the SOHO Mission. Both of these investigations determine the flow velocities by measuring the Doppler shift of a spectral line formed by nickel atoms in the cooler layers of the solar atmosphere.

The GONG data presently consists of 1024 by 1024 pixel intensity images at three different spectral positions within the line with two different polarizations. These three images are processed to produce three *primary data images*. The sum of these raw images gives an intensity image which shows sunspots and limb darkening. The size of the change in intensity at the three spectral positions gives a modulation image that shows roughly where magnetic fields are located. The shift in the position of the spectral line with respect to its laboratory position gives a velocity image which is dominated by solar rotation and the cellular pattern of solar convection called supergranulation. GONG also produces magnetograms, images of the sun’s magnetic field using the two different polarizations.

The primary purpose of these GONG velocity images is to provide data for analyzing the oscillations of the sun. For studies of the nearly steady flows the oscillatory signal represents a source of noise and needs to be removed from the data. This is done by taking a *weighted average* of 17 velocity images taken at 1-minute intervals to produce an image of the nearly steady flows.

These time averaged images are then processed by an *image analysis program* (121 kb GIF image) that separates the signal into its various components: *Differential Rotation* (142 kb GIF image) - the rotation signal that includes a rapidly rotating equator and slowly rotating polar regions; *Meridional Flow* (82 kb GIF image) - a flow directed from the equator towards the poles; *Convective Blue Shift* (267 kb GIF image) - a velocity artifact due to the correlation of bright convective elements with rising motions; and the *Supergranulation* (26 kb GIF image) convection pattern.

The SOHO/MDI data consists of 1024 by 1024 pixel intensity images at four different spectral positions within the spectral line. This Higher resolution data provides excellent information on the cellular flows. Using the same image analysis program to separate the flow components provides a much clearer image of the supergranulation convection pattern.

This instrument also has a high-resolution mode with 3X magnification. This higher magnification reveals even finer details of the sun’s convective flow elements.

![FIG 2M: MDI super granule image](image-url)
2.9 Magnetic Butterfly diagram

In this "magnetic butterfly diagram," yellow regions are occupied by south-pointing magnetic fields; blue denotes north. At mid-latitudes the diagram is dominated by intense magnetic fields above sunspots. During the sunspot cycle, sunspots drift on average toward the equator, hence the butterfly wings. The uniform blue and yellow regions near the poles reveal the orientation of the Sun's underlying dipole magnetic field.

References: