Solar Phyiscs

Learners' Space Astronomy

Contents

Introduction

Welcome to the fascinating world of solar astrophysics! In this module, we will embark on a journey to explore the most important and captivating star in our solar system—the Sun. As a 4.5-billion-year-old celestial body, the Sun holds a pivotal role in sustaining life on our home planet, Earth.

Enveloped in scorching temperatures and comprised mainly of hydrogen and helium, the Sun's immense mass and gravity bind the entire solar system together. Its colossal volume could accommodate a staggering 1.3 million Earths within its boundaries, demonstrating the sheer magnitude of this radiant sphere.

At the heart of the Sun lies its core, where temperatures reach an astonishing 27 million degrees Fahrenheit (15 million degrees Celsius). Within this fiery crucible, nuclear fusion reactions take place, converting hydrogen into helium and releasing an unfathomable amount of energy. It is this energy, predominantly in the form of light, ultraviolet, and infrared radiation, that serves as the primary source of sustenance for life on Earth.

The Sun, classified as a G-type main-sequence star or yellow dwarf, came into existence approximately 4.6 billion years ago through the gravitational collapse of matter within a vast molecular cloud. Through the process of nuclear fusion, the Sun continuously fuses around 600 million tons of hydrogen into helium every second, unleashing tremendous amounts of energy. This energy takes thousands of years to traverse the Sun's core before finally escaping as light and heat, shaping the nature of space within our solar system.

To unravel the secrets of this celestial behemoth, various space agencies, including NASA, maintain an extensive fleet of spacecraft dedicated to studying the Sun's atmosphere, surface, and even its core. Vessels such as the Parker Solar Probe, Solar Orbiter, and the Solar Dynamics Observatory tirelessly observe and analyse the Sun, providing us with invaluable insights into its complex dynamics.

Moreover, the Sun's profound influence on Earth has been recognized since ancient times. From early civilizations revering the Sun as a deity to the creation of solar calendars, our understanding of time and seasons owes much to the Sun's synodic rotation and its gravitational pull on our planet. Throughout this solar astrophysics module, we will delve into the remarkable phenomena occurring within the Sun, its evolving life cycle, and the profound impact it has on the delicate balance of our solar system. Get ready to explore the captivating realm of the Sun and unravel the mysteries of our extraordinary star.

Some really good links to watch before we start the module:

- https://www.youtube.com/watch?v=2HoTK_Gqi2Q
- https://www.youtube.com/watch?v=b22HKFMIfWo
- https://www.youtube.com/watch?v=bD0SpfHy__o

1.1 Some common data about the Sun

Radius	$\sim 7 \cdot 10^8$ m $\left(R_\oplus = 6.4 \cdot 10^6 m\right)$
Mass	$\sim 2 \cdot 10^{30}$ kg $\left(M_\oplus = 6 \cdot 10^{24} kg\right)$
Earth-Sun Distance	$\sim 1.5 \cdot 10^{11}$ m$(1AU)$; $\approx 214 R_{Sun}$
Effective Temperature	$\sim$ 5800 K
Luminosity	$\sim 4 \cdot 10^{26}$W
Solar Constant	$\sim 1.36 \cdot 10^3\ W/m^2$
Age of the Sun	$\sim 5 \cdot 10^9 yr$

Solar Structure

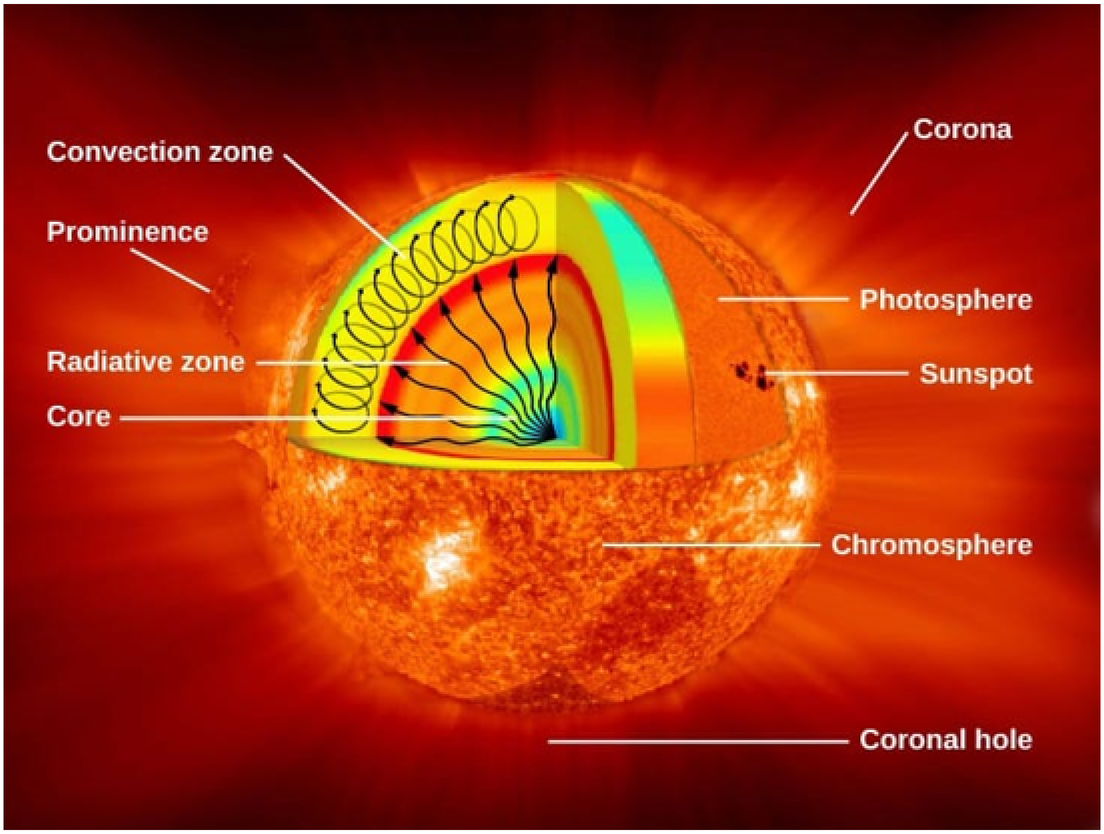

Figure 2.1: Solar Structure

The Sun, a G2 star, is approximately five billion years old, making it a middle-aged star. Its core is the site of nuclear reactions that produce energy for the Sun. In this part of the module, we shall explore the internal structure of the Sun, from the core to the outer layers, and discuss the phenomenon of sunspots and their relationship to the solar cycle.

Inside the core of the Sun, nuclear reactions take place, which are the source of all the energy the Sun emits. The temperature at the core is about 15 million Kelvin, where protons and electrons combine to form helium atoms, releasing gamma rays in the process. These high-energy gamma rays then travel through the radiation zone, which is the region where energy is transported mainly by radiation.

The radiative zone of the sun is the thickest layer, extending up to 0.45 solar radii. Within this region, thermal radiation is the primary mechanism for transferring energy from the core to about 0.7 solar radii. As one moves away from the core, the temperature gradually decreases from around 7 million to 2 million kelvins. This temperature gradient is insufficient to drive convection due to its lower value compared to the adiabatic lapse rate. Consequently, energy transfer in this zone occurs through radiation rather than thermal convection. Hydrogen and helium ions emit photons, but these photons are quickly reabsorbed by other ions after traveling a short distance. The density in this region decreases significantly, dropping by a factor of a hundred, from 20,000 kg/m^3 to 200 kg/m^3, between 0.25 solar radii and the upper boundary of the radiative zone at 0.7 radii.

It takes an astonishingly long time for the photons to diffuse their way across the radiation zone, approximately a few hundred thousand years. This means that even if the nuclear reactions were to cease, it would take a significant amount of time for us to notice, as the photons would continue to reach us. As the gamma-ray photons travel, they lose energy and their frequency decreases, eventually reaching the top of the radiative zone as ultraviolet rays.

Tachocline: The radiative zone and the convective zone of the sun are divided by a transition layer known as the tachocline. This region experiences a significant change in rotation characteristics, shifting from the uniform rotation of the radiative zone to the differential rotation of the convection zone. As a result, there is a substantial shear between the two zones, causing successive horizontal layers to slide past each other. It is currently hypothesized, as per the Solar dynamo theory, that the Sun's magnetic field is generated by a magnetic dynamo located within this tachocline layer.

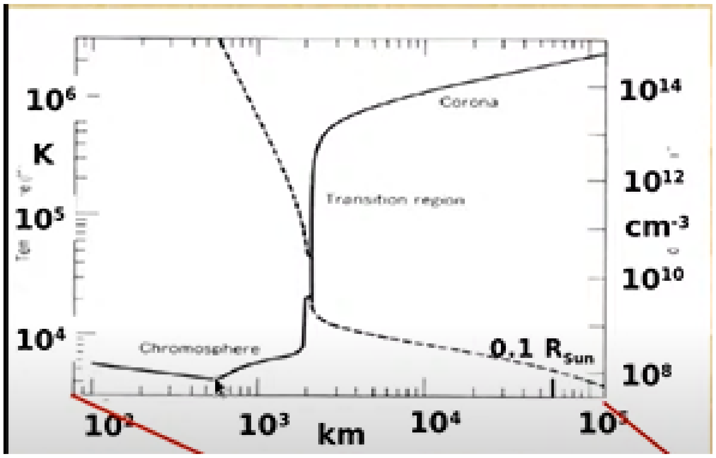

Figure 2.2: The Corona region is filled with very high temperature electrons. The above graph is a model (close to what we believe is the reality). So, the surface of the sun is at around 5800K. (x-axis is distance in a logarithmic scale)

Beyond the visible surface of the Sun, there is a region called the corona. The corona is filled with very hot plasma, reaching temperatures of about a million Kelvin. This region is full of electrons that reflect solar light, making the magnetic field lines visible. The distribution of electrons in the corona follows the distribution of the magnetic field, indicating that the energy of the magnetic field is sufficient to control the dynamics of the electrons.

Sunspots are observed on the surface of the Sun and are regions of relatively cooler temperatures compared to their surroundings. They appear as dark regions, indicating lower temperatures. Sunspots are associated with intense magnetic fields that inhibit the convective motion, preventing the hot plasma from rising to the surface. The presence of these magnetic fields influences the temperature distribution in sunspots.

The number of sunspots on the Sun follows a cyclic variation known as the sunspot cycle. The sunspot cycle has an average period of about 11 years, during which the number of sunspots increases and decreases. The sunspot cycle is the longest observed astronomical time series and has been recorded since before the invention of telescopes.

Sunspots exhibit variations in size, shape, and position on the Sun. They appear and disappear suddenly, with lifetimes ranging from a few days to a couple of months. Sunspots tend to appear at higher latitudes at the start of a new solar cycle and migrate closer to the equator as the cycle progresses. The concentration of sunspots is primarily in the equatorial region, and few sunspots appear at latitudes above ±30 or 35 degrees.

The solar cycle is not only observed in the visible range but also manifests itself across the entire electromagnetic spectrum, including x-rays and extreme ultraviolet light. Bright patches in x-ray and extreme ultraviolet images correspond to active regions or sunspots on the Sun.

Overall, studying sunspots and the solar cycle provides valuable insights into the dynamics of the Sun's magnetic field and its influence on solar activity and space weather.

Chapter Summary

- The Core and Radiation Zone:
    - The core of the Sun is where nuclear reactions occur, resulting in the fusion of protons to form helium atoms.
    - The temperature in the core is about 15 million Kelvin, and gamma rays are produced during these reactions.
    - Gamma rays slowly diffuse through the radiation zone, which is primarily responsible for transporting energy through radiation.
    - It takes an incredibly long time, ranging from a hundred thousand to a few hundred thousand years, for the energy in the form of photons to reach the surface.

- The Convection Zone:
    - Beyond the radiation zone lies the convective zone, where energy transport occurs mainly through convection.
    - The convective zone consists of large convective cells, super granules, and smaller granules that bring hot plasma from the deeper layers to the surface.
    - The surface of the Sun marks the transition from the convective zone to the outer layers.
- The Corona and Magnetic Fields:
    - The corona, the region above the Sun's visible surface, is filled with extremely hot plasma and is responsible for the emission of light.
    - The corona contains electrons that reflect solar light, making the apparent magnetic field lines visible.
    - The distribution of electrons follows the magnetic field structures, indicating that the magnetic field controls the electron dynamics.
    - The corona exhibits high temperatures, reaching up to a million Kelvin, and low densities due to the energy stored in the magnetic fields.
- Sunspots and Solar Cycle:
    - Sunspots are regions of relatively cooler temperatures compared to their surroundings on the Sun's surface.
    - The magnetic field inhibits convection in sunspot regions, resulting in lower temperatures.
    - Sunspots appear dark in visible light due to their lower temperatures.
    - Active regions or sunspots are associated with bright patches in extreme ultraviolet and X-ray observations.
    - The number of sunspots observed on the Sun follows a cyclic variation known as the solar cycle, with an average period of approximately 11 years.
    - Sunspots appear at higher latitudes at the beginning of the solar cycle and migrate towards the equator as the cycle progresses.

Solar Cycle

The number of sunspots on the sun follows a sort of cyclic variation. This is also, probably, one of the longest observed astronomical series from Earth. The Valleys and peaks are not all the same sized. Some peaks are much lower, some valleys are broader than others, some minimas drop to zeroes, some don't. There are a lot of variations in the observations. The average time difference between two peaks is around 11 years. The individual cycles can vary in length, ranging from around 9 to 14 years. The average time difference between two peaks is around 11 years. This number is called as sunspot cycle. While, the graph above shows it as a relatively smooth curve, the curve is rather jagged when we watch it more closely.

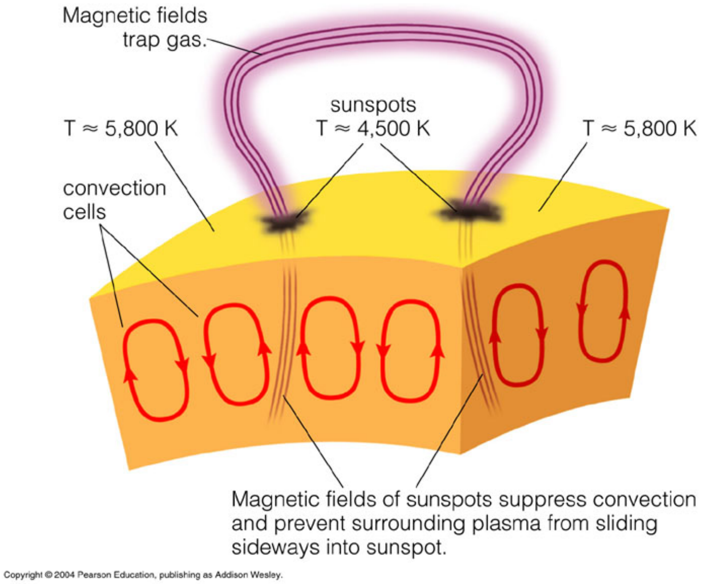

Figure 3.1: How Sunspots work

Thus, the sunspots appear and disappear very suddenly. Apart from this too, we have found that the sunspots appear more at certain areas more. The sunspots appear to follow a certain trend in where they appear. (This was first observed by Richard Carrington). At the start of a new sun cycle, these spots appear at a rather high latitude. These sunspots move towards the equator where the cycle ends.

The Carrington Cycle consists of two main phases—the Solar Maximum and the Solar Minimum.

- **Solar Maximum:** During this phase, solar activity is at its highest, and the Sun experiences the maximum number of sunspots. Solar flares and coronal mass ejections (CMEs) are more frequent during this period. Solar Maximum is the most active phase of the solar cycle.
- **Solar Minimum:** In contrast, the Solar Minimum represents the period of lowest solar activity. Sunspot numbers decrease significantly, and solar flares and CMEs become less frequent. The Solar Minimum is the least active phase of the solar cycle.

The Carrington Cycle is often represented graphically as the sunspot butterfly diagram. This diagram shows how sunspots emerge at higher latitudes and gradually migrate towards the solar equator during each cycle. As the cycle progresses, new sunspots with opposite magnetic polarity appear, leading to the reversal of the Sun's overall magnetic field.

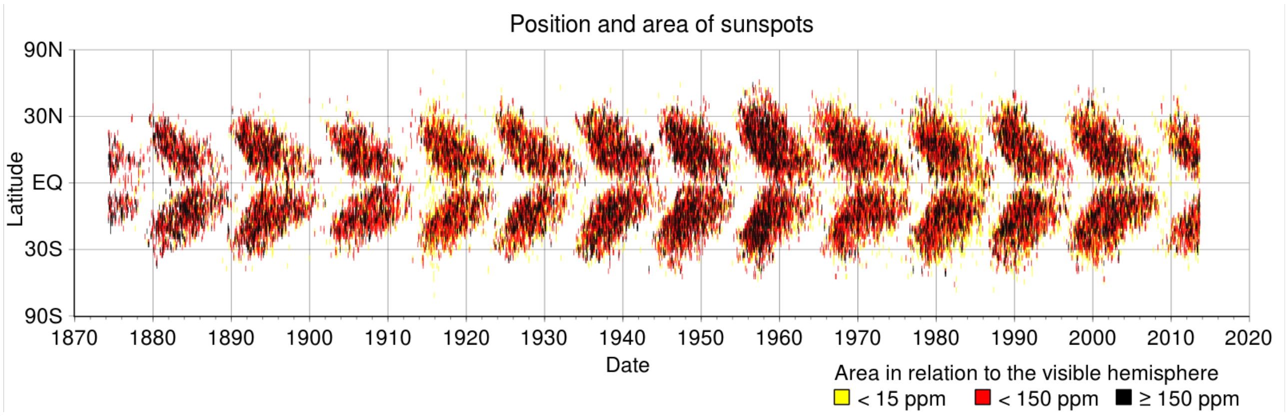

Figure 3.2: Butterfly depiction of Carrington Cycle

Solar activity during the Carrington Cycle has significant implications for space weather. Solar flares and CMEs can cause disturbances in the Sun's magnetic field, leading to geomagnetic storms on Earth. These space weather events can affect satellite communications, power grids, and other technological systems. While the overall pattern of the Carrington Cycle is well-established, the precise timing and intensity of each cycle's Solar Maximum and Minimum are challenging to predict accurately. Scientists use various observational and modelling techniques to forecast solar activity, but there are still uncertainties involved in predicting specific solar events.

Solar Dynamo

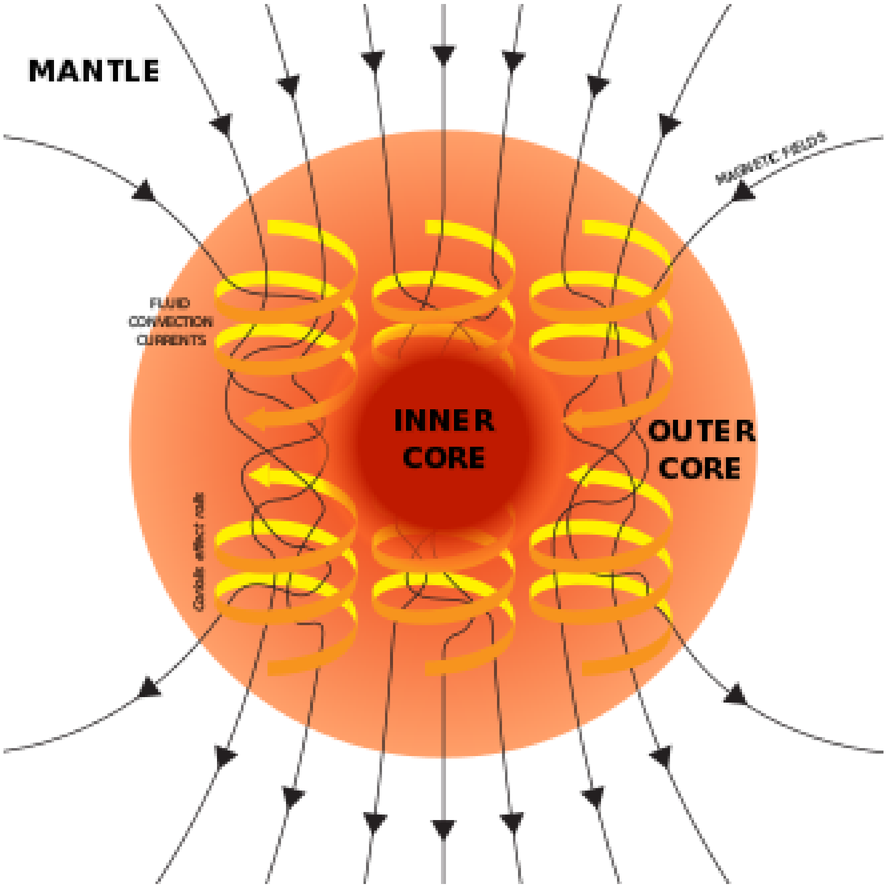

Figure 4.1: Illustration of the dynamo mechanism

The term "sun dynamo" refers to the solar dynamo, a concept in solar physics that explains how the Sun generates its magnetic field. The Sun is a massive ball of hot, ionized gas (plasma), and it exhibits a complex magnetic behavior, which influences various solar phenomena like sunspots, solar flares, and the solar cycle.

The solar dynamo theory proposes that the Sun's magnetic field is generated by the motion of charged particles (plasma) within its interior. The process involves the interaction between the Sun's rotation, convection, and magnetic fields.

The outer layer of the Sun is called the convection zone. Here, hot plasma rises from the Sun's interior, cools near the surface, and sinks back down. This convective motion generates "turbulent cells" of circulating plasma.

The Sun does not rotate uniformly; different latitudes rotate at different speeds. The equator rotates faster than the poles. This differential rotation is crucial for the dynamo process.

The interaction between the convective motion and differential rotation creates electric currents in the plasma. The rotation of charged particles generates currents, which, in turn, produce magnetic fields.

The generated magnetic fields get amplified and twisted due to the Sun's differential rotation. This process, known as the "magnetic winding," can further strengthen the magnetic fields. This is called Amplification.

At certain points on the Sun's surface, the amplified magnetic fields become buoyant and break through the surface, creating sunspots and other magnetic features. This is termed Emergence.

The Sun's magnetic field undergoes a cycle that typically lasts about 11 years. The magnetic field lines become more tangled and complex during the cycle, reaching a maximum intensity (solar maximum) and then weakening (solar minimum) before repeating the cycle.

The solar dynamo is a complex and active area of research in solar physics. Understanding the Sun's magnetic behavior is crucial for predicting space weather and its potential impacts on Earth and space-based technologies. Scientists use various observations and numerical models to study the solar dynamo and improve our knowledge of the Sun's magnetic behavior.

Limb Darkening

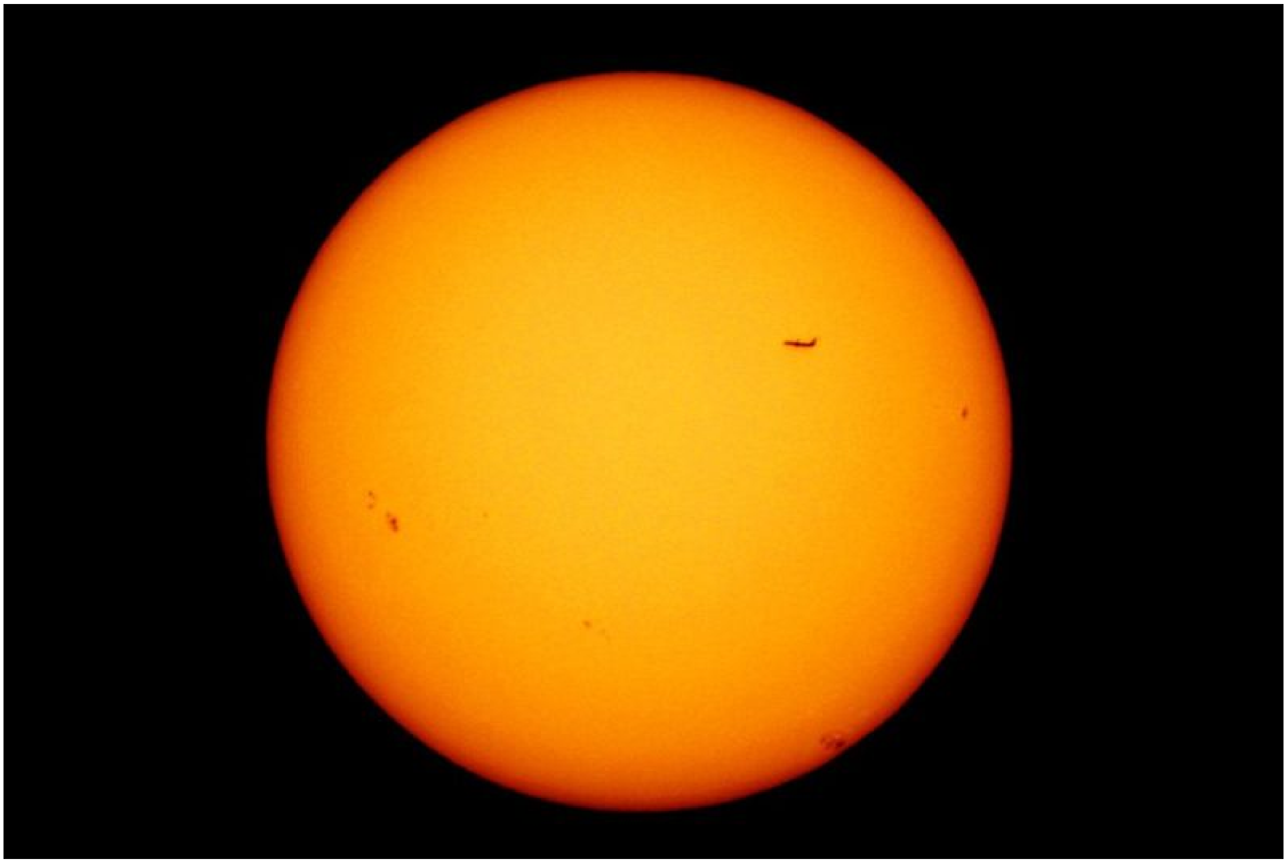

Figure 5.1: Image of the sun

Notice that when one observes the sun, we see that as we move from the center to the edges (called limbs) of the sun, the colour of the sun, gradually changes. This phenomena is generally called limb darkening.

Limb darkening is a well-documented optical effect observed in stars, including our Sun, and planets, where the central part of the disk appears brighter than the edge or limb. This phenomenon arises due to the variation in temperature and density across the stellar or planetary disk, leading to a non-uniform intensity distribution of emitted radiation.

Limb darkening was first recognized by early solar astronomers during solar eclipses, where the solar disk exhibited a gradient in brightness from the center to the limb. Over time, the phenomenon has been observed in other stars and even planets in our solar system.

The fundamental cause of limb darkening can be attributed to the variation in temperature and density across the stellar or planetary disk. In stars, the core is characterized by higher temperatures and densities than the outer layers. Consequently, photons emitted from the central regions traverse a shorter distance through the hotter and denser material, experiencing less absorption and scattering. This leads to a higher intensity of radiation at the center compared to the limb.

Limb darkening is most prominently observed during eclipses or transits of stars and planets. When a star is observed directly, its central region appears brighter than the outer region, causing the apparent disk to be darker at the limb. During planetary transits, the central part of the planet appears brighter than its edges, leading to deviations in the light curve during the transit event. These observations provide crucial information about the properties of stars and exoplanets.

Limb darkening observations played a pivotal role in early solar astronomy by providing valuable insights into the temperature distribution within the Sun's atmosphere. The phenomenon was instrumental in the development of solar models, allowing researchers to refine their understanding of the Sun's structure and energy transport mechanisms.

Limb darkening significantly contributed to the advancement of the theory of radiative transfer. By incorporating limb darkening into radiative transfer models, astronomers gained a deeper understanding of how light interacts with matter in the atmospheres of stars and planets. The theory of radiative transfer is fundamental in explaining how photons are absorbed, emitted, and scattered as they traverse through a medium, and its application to limb darkening models has been crucial in astrophysical research.

Limb darkening has been instrumental in characterizing stellar atmospheres and refining stellar models. By deducing temperature and density profiles of stars and planets, astronomers have gained a more accurate understanding of the physical properties of these celestial bodies. Limb darkening observations also facilitated the determination of stellar parameters, such as surface temperature, effective temperature, and metallicity.

In modern astronomy, limb darkening remains a relevant area of research. With the advent of high-precision observations and space-based telescopes, limb darkening is used to infer atmospheric properties of exoplanets and refine models for stellar and planetary atmospheres. It continues to be a valuable tool for characterizing celestial objects and advancing our knowledge of the universe.

Limb darkening is a fascinating optical effect that has profound implications for our understanding of stars and planets. The mathematical models used to describe this phenomenon, along with its observation during eclipses and transits, have significantly contributed to the development of astrophysical theories, such as radiative transfer. By deepening our knowledge of the structure and properties of stars and planets, limb darkening continues to be an essential aspect of modern astronomy and astrophysics research.

A really good animation for this: https://www.youtube.com/watch?v=ur0fATmsVoc

Differential Rotation of Sun

Differential rotation is a fundamental phenomenon observed in various celestial objects, revealing essential insights into their internal dynamics and structure. We investigate the underlying mechanisms, its significance in the evolution and stability of these objects, and the shearing effects observed in fluid systems like accretion disks.

Differential rotation refers to the variation in angular velocities or rates of rotation at different latitudes and/or depths within rotating celestial bodies. The presence of differential rotation indicates that these objects are not solid throughout and can be attributed to their fluid-like properties.

Differential rotation arises due to the conservation of angular momentum in rotating systems. Different regions of a celestial body possess varying masses, densities, and radial distances from the center, resulting in diverse angular velocities. Internal processes, such as convection and turbulence, play significant roles in setting up and maintaining differential rotation in fluid objects.

Galaxies are immense systems of stars, gas, and dust, exhibiting differential rotation on various scales. Spiral galaxies, like our Milky Way, showcase differential rotation of their spiral arms, where stars and gas move at different speeds as they orbit the galactic center. Elliptical galaxies can also show differential rotation, but with a less pronounced structure.

During the early stages of star formation, protostars are embedded within dense molecular clouds. As these protostars accrete mass, they can undergo differential rotation, which impacts their final stellar properties and disk formation.

The phenomenon of differential rotation is no just restricted to the sun. Several bodies like Jupiter, Saturn, Milkyway, etc show it too.

- **Jupiter:** As a gas giant, Jupiter exhibits strong differential rotation. Its equatorial region rotates at a faster rate than its polar regions, completing a rotation in about 9.9 hours. This differential rotation is responsible for the distinct bands seen in Jupiter's atmosphere.
- **Saturn:** Similar to Jupiter, Saturn is a gas giant with a noticeable differential rotation. The equatorial region rotates faster than the poles, with a rotation period of approximately 10.7 hours.

In fluid systems like accretion disks around black holes or protostars, differential rotation leads to shearing. Shearing occurs when adjacent layers of the fluid slide past each other due to their varying rotational speeds. This creates friction and generates turbulence, influencing the dynamics and evolution of the disk.

Understanding differential rotation in celestial objects is vital for comprehending their internal structure, stability, and long-term evolution. It helps explain the formation of prominent features like spiral arms in galaxies, and the diversity of atmospheres and magnetic fields on planets like Jupiter and Saturn. Differential rotation also impacts energy transport processes within stars and plays a significant role in the accretion of material onto forming celestial bodies.

Differential rotation is a widespread phenomenon observed in galaxies, protostars, and several objects within our Solar System. This dynamic behavior provides valuable information about the internal characteristics and evolutionary processes of these celestial bodies. Further research into differential rotation can lead to a deeper understanding of the universe's complexities and the fundamental processes shaping celestial objects.
More reading:

- `https://en.wikipedia.org/wiki/Differential_rotation`
- `https://cesar.esa.int/upload/201710/suns_differential_rotation_students_guide_intermediate_level_008.pdf`

References and Further Reading

Hope you liked the module. For further reading, you can check out:

- Solar Dynamo: `https://en.wikipedia.org/wiki/Solar_dynamo`
- Solar Dynamo: `https://solarscience.msfc.nasa.gov/dynamo.shtml`
- Limb Darkening: `https://en.wikipedia.org/wiki/Limb_darkening`
- Limb Darkening: `https://web.iucaa.in/~dipankar/ph217/contrib/limb.pdf`
- Differential Rotation of the sun:`https://en.wikipedia.org/wiki/Differential_rotation`
- Differential Rotation of the sun: `https://cesar.esa.int/upload/201710/suns_differential_rotation_students_guide_intermediate_level_008.pdf`