

# Chapter 1

## Introduction of the Sun and Its Atmosphere

*The present chapter begins with an overview about the Sun and its various layers particularly both in its interior and exterior. We also provide some fundamental details of the solar magnetism. We outline the localized magnetic field properties in the quiet and active regions of the Sun, and the facts how they relate to various transients and eruptive plasma processes. Since, the present thesis aims on the modelling of solar jet-like features, particularly the cool chromospheric jets, we give a succinct overview of such solar jets. Thereafter, in particular we review the small scale cool chromospheric jets (e.g., spicule-like cool jets, fibrils, mottles, network jets, etc) and associated plasma processes on the basis of various ground and space-borne observations as well as theoretical and numerical models. At the end, we outline the summary of various chapters of the present thesis.*

## 1.1 Overview of the Sun

The highly dynamic Sun is the huge source of energy for the entire solar system. The physical processes occur on the Sun has a direct influence on space weather and our life. This fact makes it fascination and the most important star to study. The Sun's proximity provides on opportunity to study its physics in greater details. Moreover, its study further provides a chance to understand the physical behaviour of the others Sun-like stars where we can discern their surface characteristics and various other physical processes (e.g., star spots, stellar flares, coronal mass ejections (CMEs) etc). The continuous observations of the solar atmosphere from the space-borne and ground-based instruments led to the development of the ideas about radiative transfer in astrophysical plasma and a variety of dynamical plasma processes. The Sun is a huge magnetohydrodynamic (MHD) laboratory, exhibiting large-scale physical processes and events (e.g., solar filament eruptions, formation of magnetic fibrils, sunspots, prominence, coronal loops, eruption of coronal jets, solar flares energy release, CMEs, irradiance variations, solar wind, etc) and small scale (e.g., transients spicules, swirls, macro-spicules, network jets, pseud shocks, etc). The variation of its magnetic activity influences the overall magnetism, radiation flux, plasma processes and eruptions at the Sun. It produces a variety of large-scale structures, and lead a variety of eruptive and physical processes in the solar atmosphere. The terrestrial environment is impacted by solar activity in a variety of ways, including erratic power grid failures, space weather, and presumably overall climate. These disturbances propagating through the solar wind from the Sun's surface to the magnetic field of the Earth, creating energy difference in its radiation belts.

The magnetically active Sun is a G2V type, main sequence star. The stellar magnitude of the Sun is 4.8. The Sun is a fiery plasma ball that is rich in the elements hydrogen (71%) and helium (26%) as well as other elements including carbon, nitrogen, oxygen,

magnesium, neon, iron and silicon etc. The typical properties of the Sun is listed below (cf., Table 1.1).

Broadly, The Sun is classified into two main parts namely interior and its exterior. A brief introduction of various layers of the interior and exterior of the Sun is given as follows.

Table 1.1: The physical properties of the Sun (Credit: Priest 2014)

Physical Parameters	Physical Quantity
Age	$4.6 \times 10^9$ years
Solar mass	$1.99 \times 10^{30}$ kg ( $\approx 330$ times of the Earth)
Solar radius	695.5 Mm ( $6.955 \times 10^8$ m)
Solar mean density	$1.4 \times 10^3$ kg m <sup>-3</sup>
Photospheric temperature	5785 K
Solar surface gravity	$274$ m s <sup>-2</sup>
Escape velocity at solar surface	$618$ km s <sup>-1</sup>
Equatorial rotation period	26.24 days
Luminosity (Radiation)	$3.86 \times 10^{26}$ W
Mass-loss rate	$10^9$ kg s <sup>-1</sup>
Angular momentum	$1.7 \times 10^{41}$ kg m <sup>2</sup> s <sup>-1</sup>
1 arcsec	$\approx 726$ km

### 1.1.1 Interior of the Sun

The interior of the Sun cannot be directly probed because it is fully covered by opaque plasma underneath its surface, i.e. the photosphere. So, approaches like helioseismology are used to infer the internal structure of the Sun. However, we still have numerous questions about the actual processes that dominate below the surface of the Sun, i.e., photosphere. The center of the Sun's interior is known as core, wherein nuclear fusion reaction takes place. The radiative zone, tachocline and convection zone are successively at the top of the core in solar interior. The density at solar core is  $150 \text{ gcm}^{-3}$ , and temperature is about 15 million-degree Kelvin. In the presence of high density and temperature, the hydrogen nuclei ( $^1\text{H}$ ) there is converted into helium nuclei ( $^4\text{He}$ ) under proton-proton (p-p)

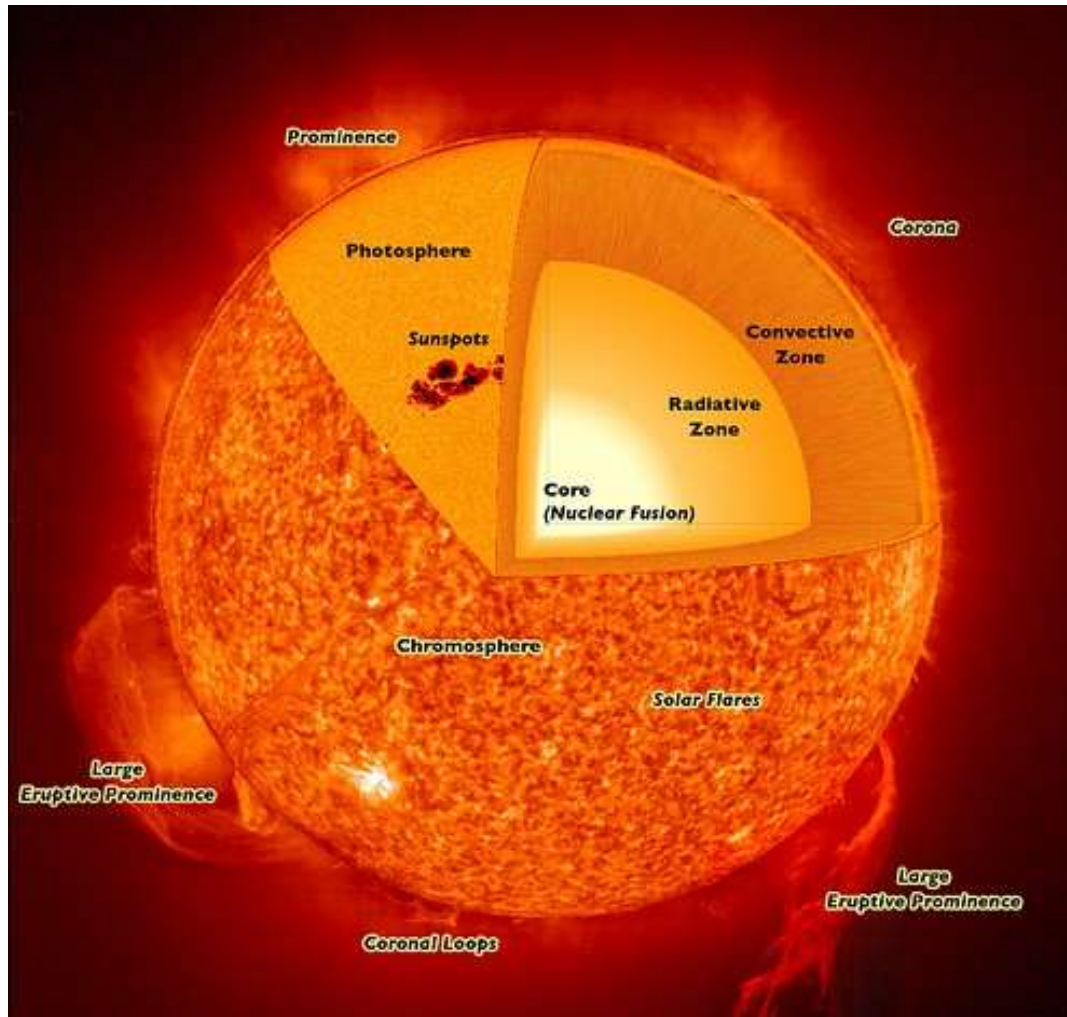
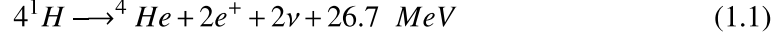


Figure 1.1: An illustration about the various parts of the Sun. The solar interior is categorized as core, radiative zone and convection zone. The central region of the Sun is known as core where nuclear fusion reaction takes place. The radiative zone is a layer from where the generated energy from the core is propagating outward in form of the radiation. The convection zone is a part of the solar interior from where the energy propagates up to the Sun's surface due to convection. The Sun's surface (i.e. photosphere), chromosphere, corona are shown. The sunspots, coronal loops, solar flares and eruptive prominence belong to different atmospheric layers of the solar exterior (Credit: NASA/anatomy of the Sun).

chain reaction. This reaction also produces two elementary particles as positron, neutrino and also the radiation energy as Gamma rays (Priest, 2014; Seeds, 1994). The (p-p) chain

reaction is expressed as follows (Priest, 2014):



In the solar core, the proton-proton (p-p) cycle produces almost 98 % of the nuclear energy, whereas the another reaction namely the Carbon-Nitrogen-Oxygen (CNO) cycle produces less than 2% energy. The generated neutrinos leave the Sun's interior unhindered since they do not interact with its opacity. The energy in the core constantly sweeps outward through the radiative zone by the radiative diffusion process. The photons in the radiative zone are absorbed and released several times, and it takes millions of years for them to pass through this layer. The energy that is radiating out then comes into contact with the Sun's outer layer (convection zone), where the gas is partially ionized. The hot blobs of the gas start to rise and the cold blobs start to sink because the gas in this region is not particularly transparent to the radiation. Therefore, convection is at work to transfer the energy coming from the radiative zone. The physical state of the solar interior can be understood by the standard model. According to standard model, the pressure ( $p$ ), temperature ( $T$ ), and density ( $\rho$ ) are the functions of radial distance ( $r$ ) as measured from the Sun's center. However, the use of the boundary conditions derived from the observations is a limitation of this model (Chitre and Dwivedi, 2008). The set of governing equations are adopted from Priest (2014). The ideal equation of state is given as follows:

$$p = \frac{k_B}{m} \rho T, \quad (1.2)$$

where  $m$  depicts the mean particle mass, and  $k_B$  the Boltzmann's constant. The mass conservation is described by the following equation:

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r), \quad (1.3)$$

where  $M(r)$ ,  $P(r)$ , and  $\rho(r)$  are respectively the mass, pressure and mass density variations of the spherically symmetric solar interior.

The pressure balance across the layers can be given as follows owing the hydrostatic equilibrium condition:

$$\frac{dp}{dr} = -\rho(r) g(r), \quad (1.4)$$

where  $g(r)$  depicts the gravitational acceleration which is equal to  $= M(r) G/r^2$ . The universal constant  $G$  is given as  $6.67 \times 10^{-11} \text{ N m}^2 \text{kg}^{-2}$ . Finally, the energy balance condition can be expressed as follows

$$\frac{dL(r)}{dr} = 4 \pi r^2 \rho \epsilon, \quad (1.5)$$

where the symbol  $\epsilon$  depicts the rate of produced nuclear energy per unit mass.  $L(r)$  represents the total luminosity, *i.e.*, outward flow of total thermal energy, which is equal to  $4\pi r^2(F_{convection} + F_{radiation})$ . Here,  $F_{convection}$  and  $F_{radiation}$  are the energy fluxes due to the convection and radiation respectively.

These governing equations keep maintaining the mechanical equilibrium (Eq. 1.3), hydrostatic equilibrium (Eq. 1.4) and thermal equilibrium (Eq. 1.5) in the solar interior. The aforementioned equations can be solved using the boundary conditions, *i.e.*,  $\frac{dT}{dr} = 0$ ,  $M = 0$ , at the center ( $r = 0$ ), and  $L = L_{\odot} = 3.846 \times 10^{26} \text{ Watt}$ ,  $M = M_{\odot} = 1.989 \times 10^{30} \text{ kg}$ , at the solar surface ( $r = R_{\odot}$ ) (Priest 2014). The solution provides a rough estimate about the size of solar core, *i.e.*,  $0.28 R_{\odot}$ . It also estimates the bottom of the convection zone, *i.e.*, top of the radiative zone extended up to  $0.7 R_{\odot}$ . The convection takes place from  $0.7 R_{\odot}$  up to the bottom of the solar surface (Fig 1.1). At the altitude of  $0.7 R_{\odot}$ , the typical temperature is  $T = 10^6 \text{ K}$ .

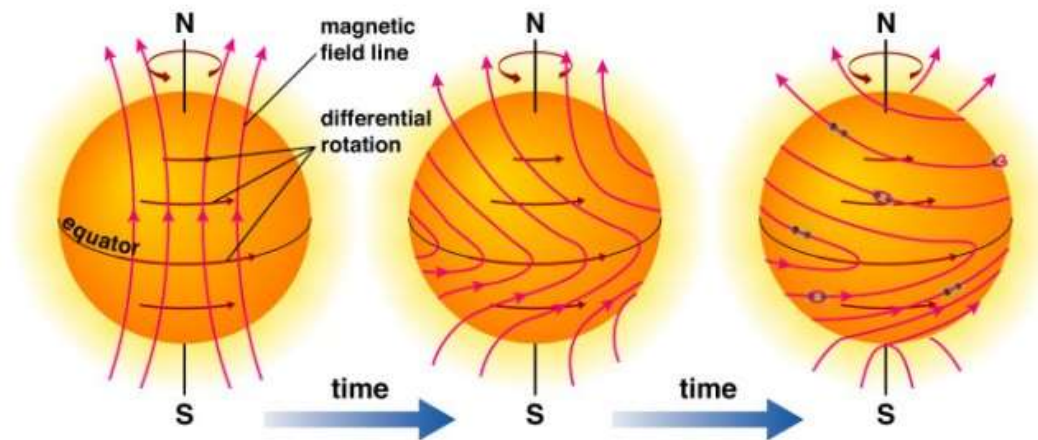


Figure 1.2: The differential rotation of the extensively conductive and rotating plasma gas revolving with the magnetic field in the Sun's interior. The magnetic polarity reverses between the two hemispheres. (Credit: Addison Wesley).

### 1.1.2 The Solar Magnetic Field

Another aspect of the interior of the Sun is generation of its magnetic field that has significant impact on almost all known physical processes. The solar magnetism is originated from the layer between radiative zone and convective zone (known as Tachocline Region). The magnetic field of the Sun is produced by the differential rotation of the poles and equator in the Sun's tachocline region. The kinetic energy that is released as a result of moving highly ionized plasma in a current creates the main mechanism of the generation of the magnetic field in the Sun. In this process, the electrically conductive gas rotates and is agitated by convective motion therefore, the kinetic energy converts into the electromagnetic energy (Seeds, 1994). This process is known as a dynamo process to generate the magnetic field (e.g., Choudhuri et al., 1995; Hathaway et al., 2003; Schrijver et al., 2002). The Sun's plasma consists of positive ions, electrons, and also some neutral atoms which shows the quasi-neutral properties, therefore, the solar plasma behaves like an electrically

conducting fluid. These fluids can either produce or being influenced by the magnetic fields. The different parts of the Sun have different rotation periods, for example equator of the Sun's photosphere rotates faster (24.5 days for one rotation) while at 45° latitude, the Sun's photosphere rotates slower and it takes 27.8 days for one rotation. This difference in the rotation of the various parts of the Sun is expressed as differential rotation. The differential rotation of the electrically conducting plasma, amplifies the magnetic field strength according to the Lenz law. The evolution of the solar magnetic field suggests that the Sun is self-sustaining dynamo. The detailed mechanism of the evolution of the solar magnetic field via dynamo process is proposed in a comprehensive manner (Charbonneau, 2010; Hathaway et al., 2003; Ossendrijver, 2003). The typical solar dynamo process is shown in the Fig. 1.2.

A highly strong localized magnetic field is created by a shearing plasma motion, which increases the magnetic field intensity. These localized magnetic field are sufficiently strong to cross the photosphere, and produce active regions where sunspots are emerged. The sunspots have 11-year cycle with minima and maxima. The maxima and minima of the sunspots is related to the magnetically driven eruptive and transients processes that occur in the Sun's atmosphere. During the sunspots maxima, the other magnetically driven activities such as CME eruptions, prominence eruptions, solar flares, etc become more intensive. The periodic behaviour of the various features (e.g., sunspots, magnetic network, plages, filaments etc) on the solar disk is called solar cycle, which is first proposed by Schwabe (1843). However, Hale (1908) has reported that the sunspots have strong magnetic field, and it's returns it's original position after 22 years. This variation is due to change from poloidal to toroidal magnetic field and thereafter again from toroidal to poloidal magnetic field (cf., Fig. 1.2).

The strength of the magnetic field in the tachocline region is  $\approx 10^5$  G while it is  $\approx 100$  G in the quiet-photosphere, few tens Gauss at the quiet-chromosphere, and  $\approx 5$  Gauss in

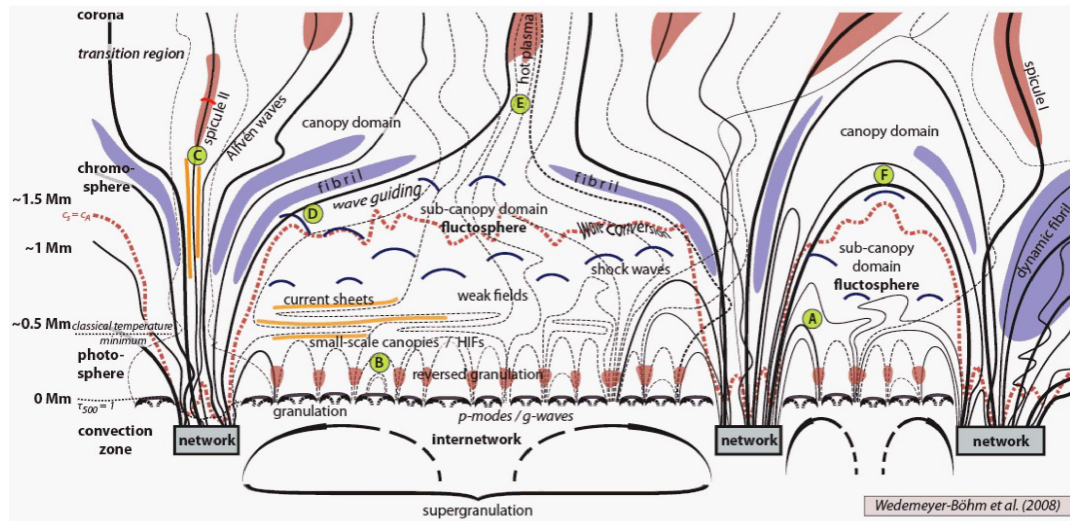


Figure 1.3: A schematic of the quiet-Sun's atmosphere. This shows the inside and outside strongest magnetic field intensity in magnetic networks exhibiting multiple physical processes coupling various parts of solar atmosphere. The magnetic field lines are shown by the solid and dotted black lines. The height range that ALMA mapped is shown in the left (Credit: S. Wedemeyer-Böhm)

the outer-corona (Solanki et al. 2006). The Sun's photosphere also consists of a magnetic flux tube like structures, which are the region of high magnetic field intensity surrounded by a low magnetic field intensity and magnetic loop like structures. The field intensity of such flux tubes is ranging between 1500 and 1700 Gauss in the lower photospheric region and 1000 to 2000 Gauss in the middle photosphere (Priest, 2014). It attains a value of 200-500 Gauss at the bottom of the chromosphere. Therefore, in these highly magnetized flux tubes, the magnetic field dominates over the plasma.

In conclusion, the tachocline region significantly influence the magnetism of the solar surface and the solar atmosphere since it has been considered as the source region of the dynamo process that generates the Sun's magnetic field. At this point, the highly essential effect of the tachocline region is to shift the uniform rotational motion of the radiation zone to a differential rotation in the convection zone. Therefore, the differential rotation is

found to be the source of the highly global and complicated magnetic field permeating the Sun (Fig 1.3). In the next sub-section, we briefly outline the exterior regions of the Sun.

### 1.1.3 Exterior of the Sun

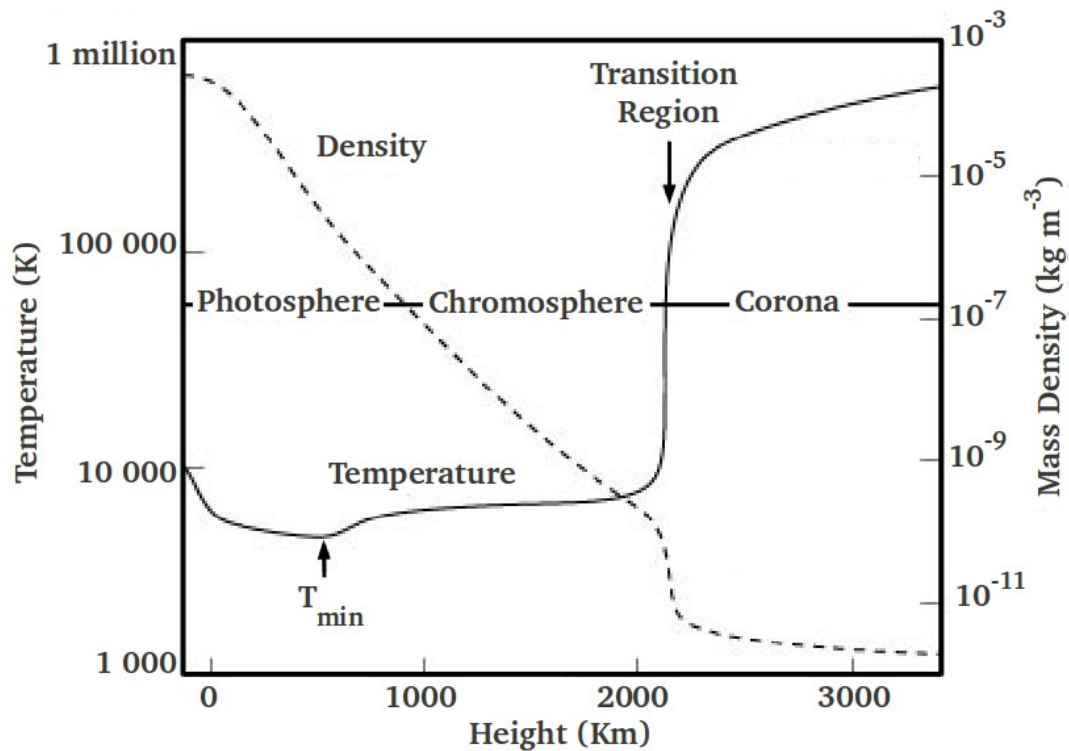


Figure 1.4: The temperature and density variations with height in the solar atmosphere (Credit: Eugene Avrett; Smithsonian Astrophysical Observatory).

The atmosphere of the Sun extends from its surface layer to a distance of millions of kilometers. The thickness of the various parts of the Sun's atmosphere, variation of its temperature and density are described by Vernazza–Avrett–Loeser (Vernazza et al. 1981; Avrett and Loeser 2008) model (cf., Fig 1.4). The different layers in the Sun's atmosphere can be distinguished as follows:

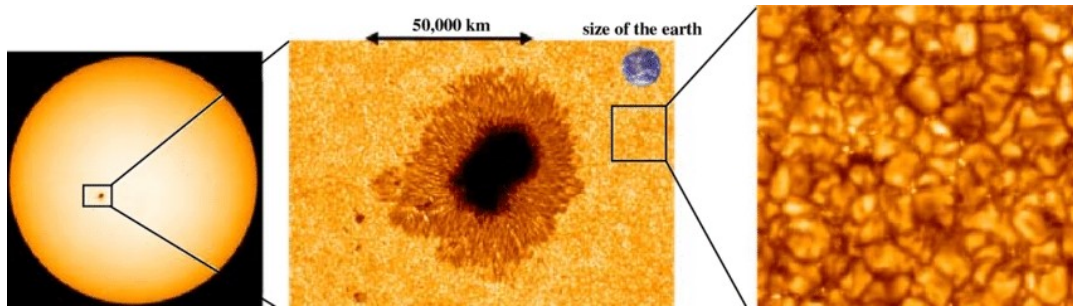


Figure 1.5: The left panel shows the full-disk visual surface of the photosphere. The right panel shows the magnified regions of the particular features of strongly magnetized active region (AR) sunspot surrounding the quiet-Sun (QS) granules (Credit: Hinode, S. Tsuneta, NAOJ, JAXA, and NASA).

## Photosphere

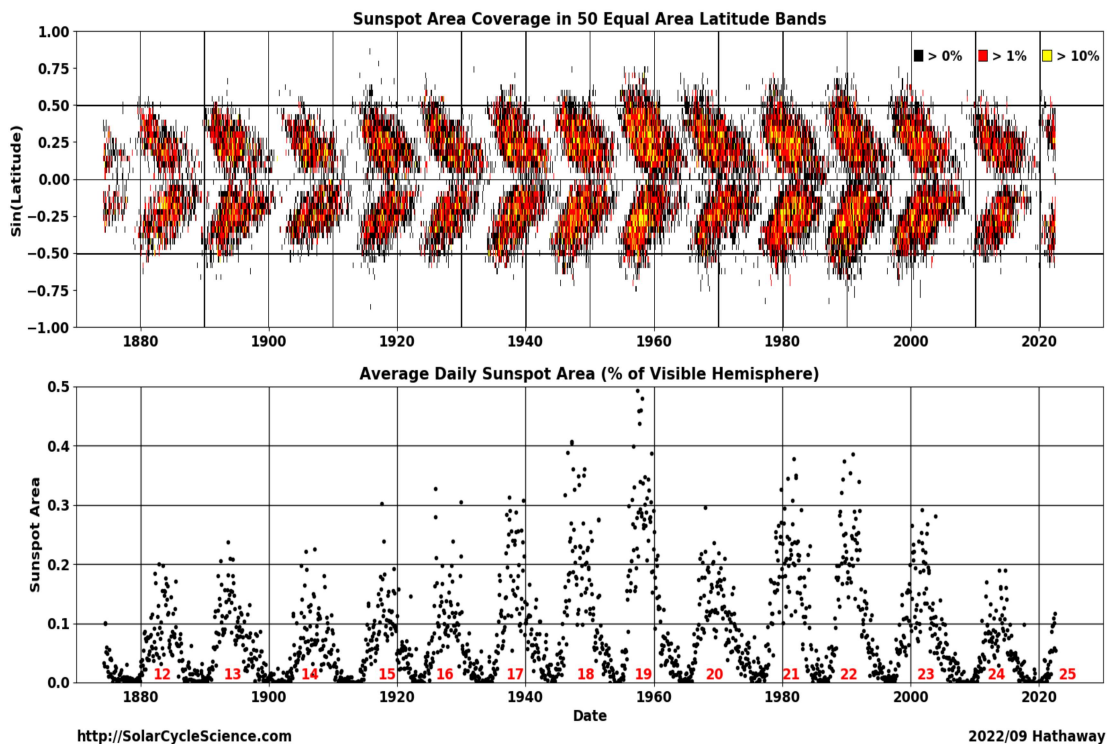


Figure 1.6: The Maunder butterfly diagram and variation of the sunspots on the solar disk. Top panel represents the area of sunspot with latitude and time. Bottom panel shows the data appears monthly averages of daily sunspot numbers which is a function of time (Credit: Hathaway 2022).

The photosphere (called after a Greek word for light) is the Sun's visible surface, with a thickness of  $\approx 500$  km (Priest and Forbes 2007). It radiates energy in the visible region (as a black-body) of the electromagnetic spectrum with temperatures ranging from 4300 K at the top to 6000 K at the bottom with an average value around 5800 K. Its average density is of the order of  $10^{-7} \text{ g cm}^{-3}$ . The range of emitted radiation from the photosphere is utilised in spectroscopy and imaging and magnetic measurements of the solar atmosphere. This layer displays on upper level of the convective zone as granulation, super-granulation, and faculae (near the limb) where convective flows operate as an active perturbation of the p-mode (3 mHz or 5 minutes) driven oscillations. The granulation in the convection zone shows the black dark lines and bright "bubbles" of the hot plasma when it rises, cool and then subsequently falls back down into the Sun's interior (cf., Fig 1.5). In each granular cell, the hot plasma materials move upward-horizontally with a velocity ranging from 0.5 to 1.5  $\text{km s}^{-1}$ . This hot moving plasma attains the typical diameter of 0.3-2.0 Mm. The average lifespan of the granular cell is 5 to 10 minutes. Several granules make up a giant cells of typical size of 20 to 70 Mm which is called as super-granular cells. In the super-granular cells, the hot plasma moves horizontally outward with a speed of  $\approx 350 \text{ ms}^{-1}$  and then cool, and falls down towards its boundaries. The lifespan of these giant cells is 24-48 hours with a mean life 38 hours. Recent high resolution observations show that bright spots with kilo-gauss (kG) field intensity and a size of around 100 km also exist near the edges of the super-granular cells.

Apart from the quiet Sun magnetic features (e.g., granulation, supergranulations, faculae, etc), the most visible and noticeable characteristics of the photosphere is the sunspots (cf., Fig 1.5). Sunspots are the extreme part of the complex structuring of the magnetic field and it is subject to constituting active regions which are about 5 % of the Sun's surface (i.e., photosphere). These structures have a black center called umbra consisting of the strong magnetic field lines fanning out from the solar interior. These

structures are substantially cooler ( $\approx 4000$  K) than the ambient photosphere. Outer region away from the umbra is known as penumbra that appears brighter. The penumbra has strong horizontal magnetic field lines, which is responsible for the formation of the canopy and penumbral filaments or fibrils. The umbra has a board range of the magnetic field magnitude of 1000-3000 G, while the penumbra has  $\approx 100$ -300 G magnetic field strength. The typical size of umbra lies between 5-25 Mm, and lifetime is about few hours to a days during their appearance on the photosphere. Sunspots are usually appears in their groups across  $\pm 40$  degree altitude from the equator. The sunspots are widely depicted as the solar activity features and they vary over the course of an 11-year cycle from maximum to minimum. The sunspots occur at higher latitudes at the beginning of the solar magnetic cycle, and become visible closer to the Sun's equator later in the cycle. After 11 year, it shift the locations which systematically appear resembling butterfly diagram, i.e., Maunder butterfly diagram (cf., Fig 1.6). The detailed descriptions of sunspot and solar cycles can be found in the review article by Hathaway (2010), Petrovay (2010) and references cited therein. Around the active regions on the photosphere, the newly developed sunspots which have no penumbra and have vertical magnetic field lines is called magnetic pores. Its typical lifetime is about few hours, field strength is  $\approx 1000$  G, and size is about few Mm. The plage region is also subjected to an appearance at the photosphere which have few hundred Gauss of average field strength. A broader region with a magnetic field intensity lies between 100 and 300 G, which can be found in the plage region. Therefore, the photosphere is made up of a variety of magnetic structures with varying spatial scales and magnetic field strengths and it exhibits a variety of physical, plasma and radiative processes.

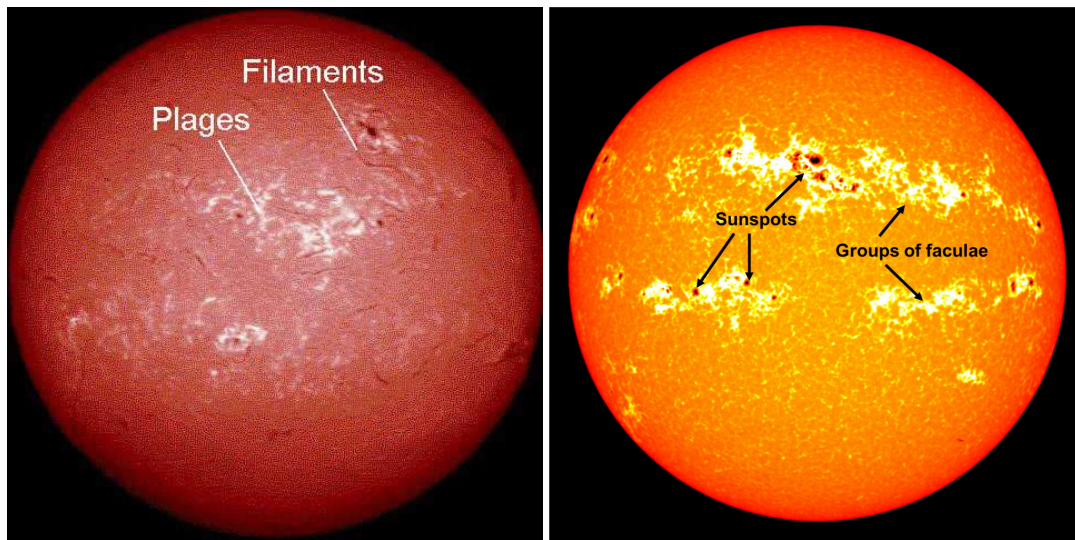


Figure 1.7: Left: The chromospheric layer with plage and filament magnetic structures. Right: The photospheric layer with sunspots and faculae (Credit: NASA/GSFC, Source data courtesy of HAO & NSO PSPT project team).

## Chromosphere

Above the photosphere, almost  $\approx 2000$  km thick layer is chromosphere. The name chromosphere after this layer comes from the Greek word "*chroma*", which describes as "color". It is much fainter ( $\approx 1000$  times) as compared to the photosphere. Its temperature varies from 4300 K at bottom to 25000 K at higher altitudes, and density sharply falls from the photosphere by factor of  $10^{-4}$ . This layer appears colorful (as a pink) during total solar eclipse because of three prominent emission lines (violet, blue, and red) in hydrogen Balmer  $H\alpha$  emissions.

The bright magnetic network consists of the supergranular boundary strongly emerged at the photosphere, and it is correlated with magnetic network at the chromosphere. Strong magnetic flux tubes are emerged at the supergranular borders in the photosphere and are in agreement with the vibrant magnetic network of the solar chromosphere. During the presence of vertical large scale magnetic flux tubes of kilo-Gauss field strength in the photosphere, the magnetic field elements are spatially correlated coupling the various layers

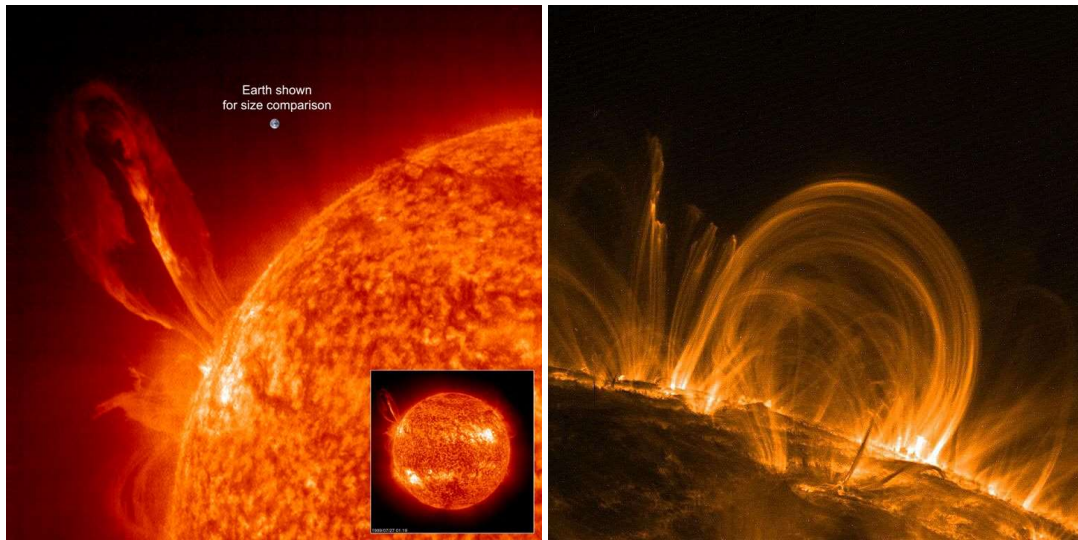


Figure 1.8: Left: An eruptive large prominence is observed in He II 304 Å with a comparative picture of the Earth. (Courtesy: Solar and Heliospheric Observatory (SOHO)/EUV Images Telescope (EIT); Big Bear Solar Observatory). Right: The magnetic loops of the solar active region are observed above the solar disk as detected by the Transition Region and Coronal Explorer (TRACE) on September 28, 2000. (Credit: M.Aschwandhan, LMSAL, TRACE, and NASA).

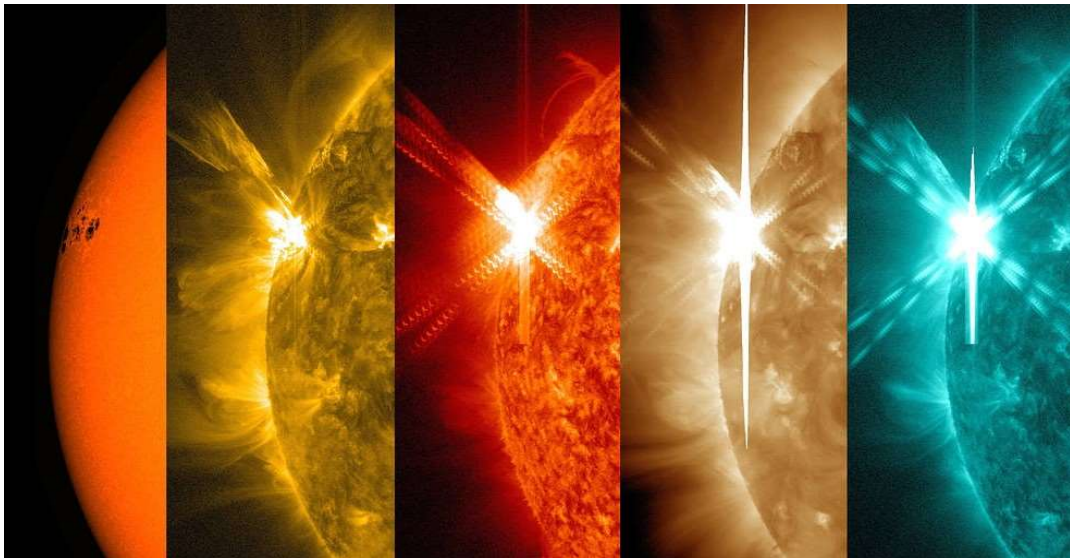


Figure 1.9: Multiwavelength observations of the solar flare on May 5, 2015. The flare is shown at different wavelengths from left to right at visible waveband, 171, 304, 193, and 131 Å (Credit: NASA/SDO/Wiessinger).

of the solar atmosphere. The chromosphere is filled with the vertical as well as horizontal field lines, which make the magnetic canopy structures causing the magnetic field of the chromosphere appearing more diffused than the one in solar photosphere. Therefore, chromosphere is extremely complex layer, particularly in terms of magnetic structuring and heat transport to the outer atmosphere. As a result, the complex structuring of the chromosphere plays an important role in the development of explosive events such as solar jets, spicule-like jets, filaments/prominences (cf., Figs 1.3 & 1.7). It also play a significant role in transporting the mass and energy via variety of waves, shocks, flows/jets, magnetic reconnection, etc to heat the overlying transition region and corona. The chromospheric features are observed typically in the  $H\alpha$  (6563 Å), Ca II (3943 Å), Mg K II (2795.528 Å) lines.

### **Transition Region**

Above the chromosphere, the plasma temperature increases rapidly from 25000 K to 1 MK (cf., Fig 1.4) over a very thin (about 200 km) layer known as solar transition region. It is sandwiched between the chromosphere and the outermost layer of the Sun's atmosphere, i.e., corona. The rapid rise of the temperature across this layer constitute the outstanding problem of coronal heating, whose exact physical cause is still debated. It mainly observed in the EUV pass bands by space-borne instruments. Observations reveal that its height varies across the different regions of the Sun such as its height in the quiet-Sun at  $10^5$  K is about  $1700\pm 800$  km, and it may be much higher in the coronal hole, lying between 1500 and 15000 km (Priest 2014). This layer may affect the various physical phenomena such as oscillatory motions, coronal thermal conduction, plasma condensation, inverse plasma motions, etc. These dynamical processes exhibit many discontinuities in local properties related to associated magnetic field and plasma in the transition region, which influence their temperature and energetics, etc (Priest and Forbes 2007).

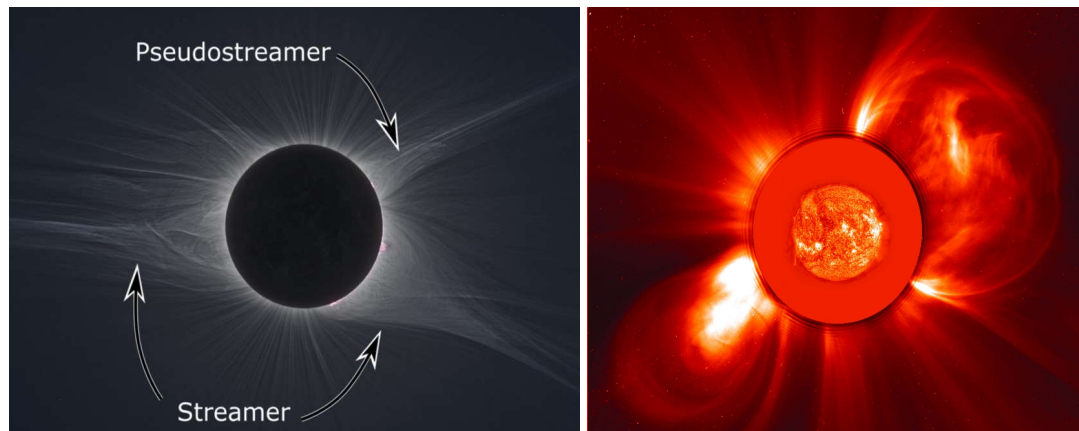


Figure 1.10: Left: coronal helmet streamer, and pseudostreamer. Right: CME seen with the LASCO instrument in the C2 coronagraph during total solar eclipse (Credit: NASA/COSMOS).

## Corona

The outermost part of the solar atmosphere is known as corona. The name "corona" is referred from the Latin as "crown of the Sun". It is an optically thin layer unlike the solar photosphere and chromosphere. Therefore, the radiations emitted from this layer come out without any absorption except the radio wavelengths. The temperature of the solar corona is about million-degree Kelvin (cf., Fig 1.4), which is about 300 times hotter than the photosphere. Therefore, it defies standard laws of thermodynamics and provides a challenge in determining the fundamental source of coronal heating. It consists of the fully ionized plasma. Therefore, coronal features *i.e.* plumes, coronal loops (cf., Fig 1.8, right panel), prominences (cf., Fig 1.8, left panel), helmet streamers (cf., Fig 1.10) are observed in the various Ultra-violet (UV)/Extreme Ultra-violet (EUV) and X-rays observations. The major part of the outer solar corona is understood using white light coronagraphs (cf., Fig 1.7). The smooth variations of the electron density and temperature of the corona are shown in Fig 1.4. It is dominated by magnetic pressure unlike the solar photosphere. It is broadly divided into the quiet-Sun, coronal-hole (CH), and active region (Aschwanden, 2004). The solar corona in active region consists of the coronal loops (cf., Fig 1.8, right

panel). The quiet-corona consists of prominences, overlying region above plages and magnetic networks etc (cf., Fig 1.7, right panel). The coronal-hole is basically the darker region with less UV/X-ray emissions and open magnetic field lines. The plasma dynamics and magnetic structuring of the inner active corona are linked with the eruptive processes such as solar flares energy release, and coronal mass ejections (CMEs) (cf., Fig 1.10). The larger scale outer corona is comprised with streamers and coronal rays upto several solar radius. The solar corona also expel out the supersonic solar wind. The solar wind, large-scale transients and powerful solar eruptions, all may sail through the corona and further interact with the interplanetary space. The study of solar atmosphere and its plasma and eruptive processes help us in understanding the prediction of space-weather as well as Sun-Earth connection. The present thesis aims to understand the physical processes in forming cool jets coupling various layers of the solar atmosphere. In next few sections, we provide an overview of various jets.

## 1.2 Solar Jets: A Brief Overview

The Sun frequently experiences small-scale transient plasma processes called as solar jets (e.g., network jets, spicules, macropicules, magnetic swirls, surges etc), which are released from the lower part of the solar atmosphere and ascend to the outer solar atmosphere (i.e., corona) (e.g., De Pontieu et al., 2007b, 2014a, 2004; Katsukawa et al., 2007; Kayshap et al., 2018; McIntosh et al., 2011; Nisticò et al., 2009; Raouafi et al., 2016a; Shibata et al., 2007; Singh et al., 2022; Srivastava et al., 2017, 2018; Sterling, 2000; Tian et al., 2014; Wedemeyer-Böhm et al., 2012, and references citet theirin). These jets can be occurred at diverse spatio-temporal scales even at photospheric level (i.e., sunspot penumbral jets), in the chromosphere (spicule-like jets), and large-scale coronal jets (Fig. 1.11). These jets can be one of the likely source to transfer mass and energy from the lower solar atmosphere to the upper atmosphere. Since past few decades, they have been noticed and

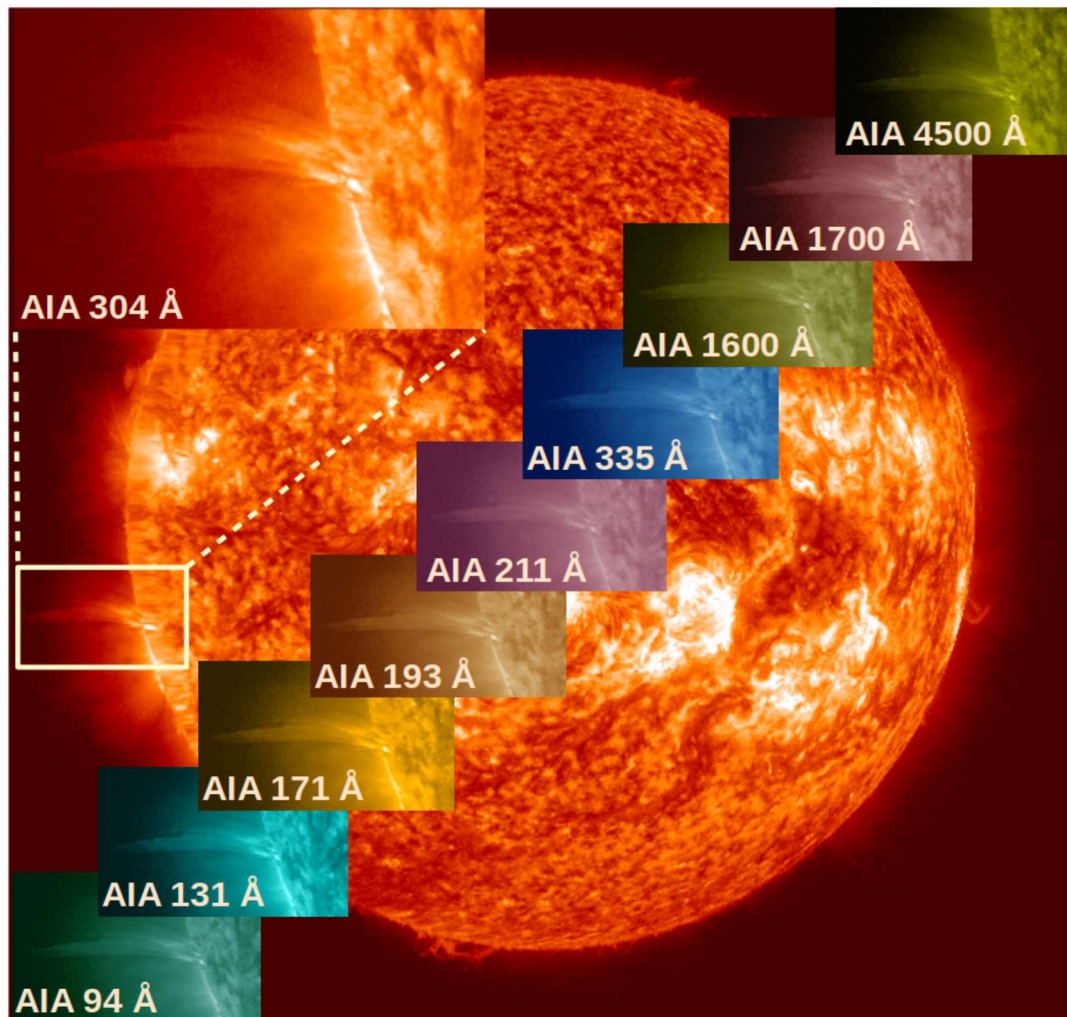


Figure 1.11: A typical coronal jet in the quiet-Sun atmosphere at the solar limb on July 7, 2014 at 14:16 UT observed with multiwavelength SDO/AIA channels (Credit: JHelioviewer; SDO/AIA, LMSAL).

widely investigated as the most exciting dynamical processes in the Sun's atmosphere. These jets may provide insight to understand the other plasma processes (i.e., waves, instability etc), heating, mass flows (e.g., Liu et al., 2014; Moore et al., 2010; Nisticò et al., 2009; Shibata et al., 1992b; Sterling et al., 2015). Despite substantial advancement in both theory and observations, additional observational data is still needed to understand the underlying physical mechanism for the triggering of these jets and associated plasma

processes (e.g., Nisticò et al., 2009; Pariat et al., 2007; Singh et al., 2022; Srivastava et al., 2018; Sterling et al., 2015; Tian et al., 2014; Wedemeyer-Böhm et al., 2012). The present high spatio-temporal resolution imaging, and spectroscopic observations continue to expand our understanding of solar jets. Furthermore, due to substantial advancement in computer facilities and computational numerical modeling of solar jets, this area of research has made significant progress since past several years. The study of solar jets is becoming a major research area in solar and heliospheric physics.

The improvement in the observational instrumentation ( e.g., Solar Dynamics Observatory (SDO; 2010 onward), Interface Region Imaging Spectrograph (IRIS; 2013 onward), Swedish Solar Telescope (SST), the 1.6-m Goode Solar Telescope (GST) and the 1-m New Vacuum Solar Telescope (NVST) since past few decades, the variety of jets have been found at board range of size from few hundreds of km to few Mm, as well as at board range of temperatures covering cool photospheric plasma to coronal plasma (e.g., Raouafi et al., 2016a; Shen, 2021; Shibata et al., 2007). Theses jets are observed as collimated beam like structures which show the impulsive plasma ejection in active as well as quiet-Sun atmosphere (e.g., Hong et al., 2011; Sterling et al., 2016). Solar jets are initially categorised based on their morphology as photospheric jets, chromospheric jets (i.e., cool jets), transition region jets, coronal jets (i.e., hot jets), and white-light jets (i.e., energetics jets). Prior to a few decades, solar jets were classified as jets at the coronal hole boundary, active-Sun jets (Raouafi et al., 2016a; Sterling et al., 2017) or jets from the quiet-Sun (e.g., Panesar et al., 2016), depending on the region where they are originated. On the basis of the recent high-resolution spectroscopic and imaging observations, solar jets are classified based on emission of various radiations e.g., extreme ultraviolet (EUV) jets (e.g., Innes et al., 2011; Nisticò et al., 2009; Sterling et al., 2015; Wang et al., 1998),  $H\alpha$  jets (e.g., Sterling et al., 2015), and X-ray jets (Innes et al., 2016; Shibata et al., 2007). These jet-like plasma ejecta may be accompanied by the Alfvén wave, magnetoacoustic waves, magnetic

reconnection process and magnetic flux emergence or cancellation. However, the exact cause of the formation of these jets are still a question for the solar physicists. In the next section, we briefly discuss about chromospheric cool jets.

### 1.3 An Observational View of Chromospheric Jets

Table 1.2: A list of the main characteristics of the chromospheric jets (e.g., spicules, mottles, and fibrils) based on their recent observations. (Credit: Skirvin et al. 2022)

Type of jet	Length [Mm]	Width [km]	Life-time [mins]	Velocity [km s <sup>-1</sup> ]	Reference
Type I	2-9	700-2500	3-10	10-30	Beckers (1968, 1972)
Type I	5-10	120-700	3-7	–	De Pontieu et al. (2007b)
Type I	4.2-12.2	300-1100	3-12	3-75	Pasachoff et al. (2009)
Type II	1-7	≤ 200	0.2-2.5	50-150	De Pontieu et al. (2007b)
Type II	5.5-7.75	300-350	1-4.5	30-70	Pereira et al. (2012)
Dynamic Fibril	4-10	≤ 300	0.5-1.5	80-250	Tian et al. (2014)
Dynamic Fibril	–	–	–	50-75	Roupe van der Voort et al. (2015)
Dynamic Fibril	0.025	–	2-20	10-30	Priya et al. (2017)
Mottle	–	–	2-15	10-30	Suematsu et al. (1995)
Mottle	4-6	–	1-5	3-18	Kuridze et al. (2012)

The chromospheric jets are observed over a broad range of multi-wavelength observations using space-born and ground based instruments (e.g., De Pontieu et al., 2007b, 2004; Hou et al., 2021; Liu et al., 2019; Mackenzie Dover et al., 2021; Martinez-Sykora et al., 2017; McIntosh et al., 2011; Panesar et al., 2020; Singh et al., 2022; Srivastava et al., 2017; Sterling et al., 2010, and references citet theirin). These jet-like features have a diverse nomenclature, but many of them refer to the same physical structure, depending on where and how they are observed. The small-scale cool jets found at the limb is called spicules. If found on the solar disk of the quiet chromosphere, then these structures are called mottles. They are called as fibrils in the on-disk solar active region. These spectacular cool jets have been studied as per the observational and modelling aspects since past few decade

by Beckers (1968); De Pontieu et al. (2007a, 2012); Handy et al. (1999); Rutten (2007b). These jets appear as straws and also exhibit rapid red/blue-shifted excursions (RBE/RREs). These jets may frequently show the quasi-periodically rise and fall in the solar atmosphere. De Pontieu et al. (2007a) have reported that the driving and evolution processes of mottles and fibrils are the same, despite the fact that magnetic field strength at the base of the mottles is much less than that of the fibrils. These chromospheric plasma features are efficiently connect with the corona via solar transition region. This is the region where the plasma beta changes from very small to large values crossing through its unity value for which the Alfvén speed is equal to the sound speed. They predominate in the solar chromosphere, which is extremely active and where 90% of the non-radiative energy is released into the inner solar corona. The observational characteristics of these chromospheric jets are previously reported by several authors (e.g., De Pontieu et al., 2007b; Kuźma et al., 2017b; Mackenzie Dover et al., 2021; McIntosh et al., 2011; Panesar et al., 2020; Singh et al., 2022; Sterling, 2000; Suematsu, 1998; Wilhelm, 2000; Zaqarashvili and Erdélyi, 2009, and references therein) The observed typical parameters of these jets are summarised in Table 1.2 as adopted by Skirvin et al. (2022). Here, we discuss the observational perspective of these small-scale jets (e.g., spicule-like cool jets, macrospicules, dynamic fibrils, mottles, network jets, etc), and associated plasma processes.

### 1.3.1 Spicule-like jets

Spicule-like jets are cool, thin structures present on the solar limb (cf., Fig 1.12). They are most prevalent and characteristic chromospheric jets, which are mostly observed in the chromospheric lines such as  $H\alpha$ , Ca II h/k, Mg II and Si IV (De Pontieu et al. 2007a, Pereira et al. 2013). These spicule-like jets have been firstly observed by Secchi (1875) and the name "spicule" is proposed by Roberts (1945). These spicule may rooted in the chromospheric network and occupy the solar chromosphere in both strong magnetic field

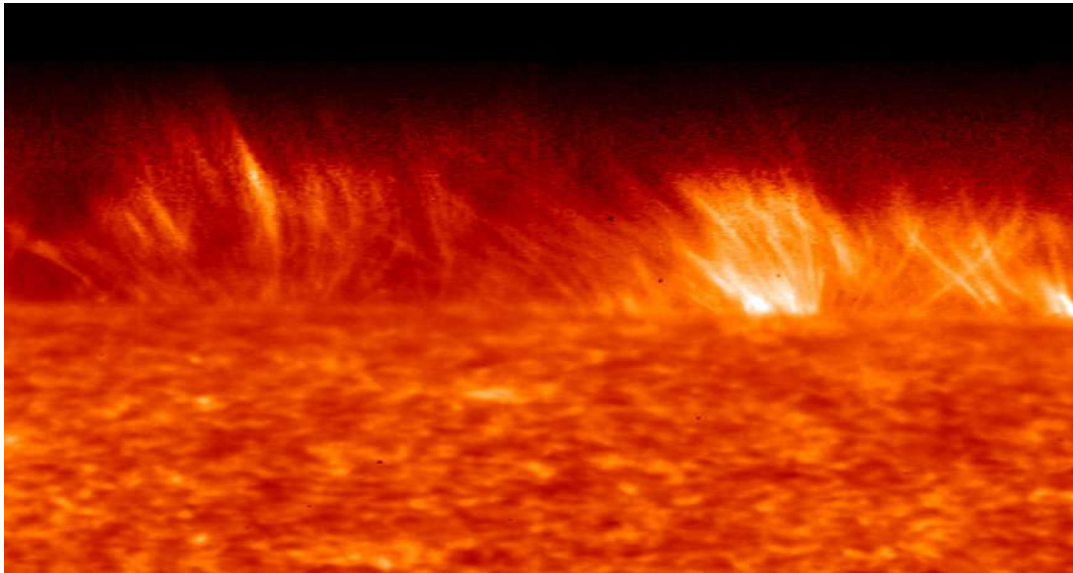


Figure 1.12: The thread-like features visible in this field-of-view as seen from the Japanese satellite Hinode are solar spicules. These ejecta are the plumes of gas transporting energy and mass into the localized solar atmosphere. (Credit: NASA /JAXA).

near the active region (AR) and weak magnetic field in the quiet Sun (QS). The typical parameters of these spicules are given in Table 1.2, and also described in various literatures (e.g., Kuźma et al., 2017b; Mackenzie Dover et al., 2021; McIntosh et al., 2011; Panesar et al., 2020; Singh et al., 2022; Zaqarashvili and Erdélyi, 2009, and references cited therein).

Recent studies from the high resolution observations with Swedish Solar Telescope (SST) described that the most of these spicule-like thin and cool jets emerge with double-thread apex, and exhibit bidirectional plasma flows. The deceleration of the vertical motion, assuming a parabolic trajectory, may be estimated from the observed upward and downward motions of these cool jets. The typical value of deceleration is about  $50\text{-}100\text{ ms}^{-2}$  (De Pontieu et al., 2007c). The apparent peak of these jets rises to a maximum height of around 7 Mm before falling back to the surface (Pereira et al., 2012), 2016). The width of these spicule-like jets lies between 700–2500 km reported by Beckers (1968). De Pontieu et al. (2007c) and Pasachoff et al. (2009) reported the width of spicules less than a few hundreds of kilometers.

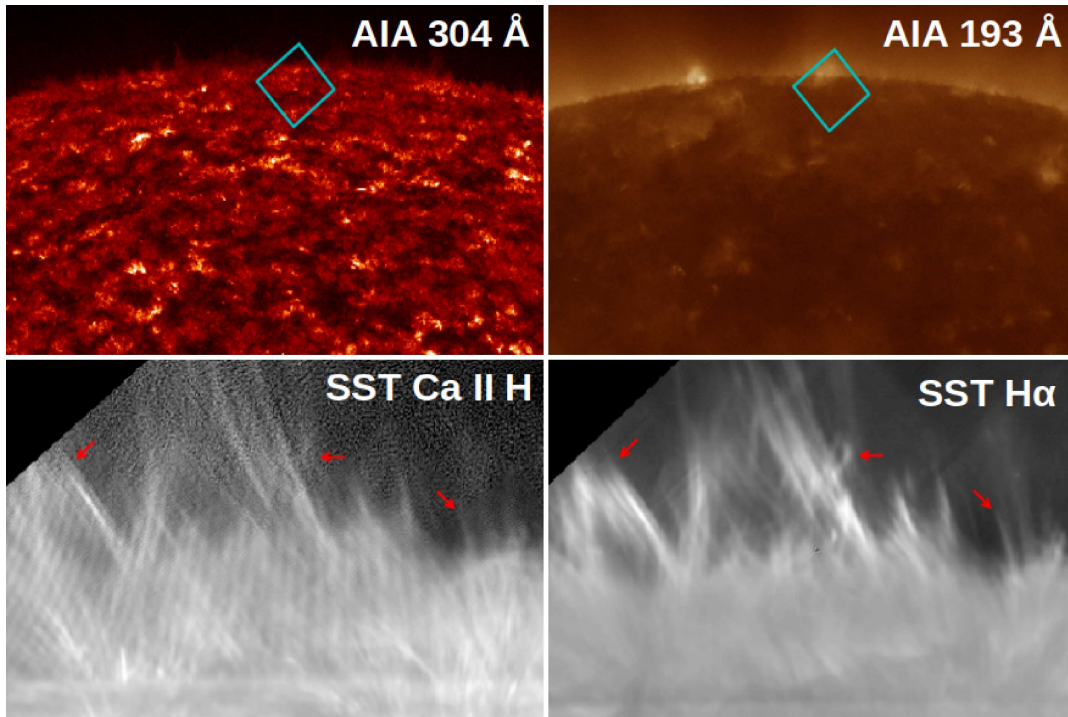


Figure 1.13: The hot component of spicule-like chromospheric jets are detected using AIA 304 Å (upper-left panel) and 193 Å filters (upper-right panel). The cyan square represents the SST CRISP field of view. The bottom panels display same structures in Ca II H (left) and  $H\alpha$  (right) as observed by Swedish Solar Telescope (SST). The red arrows show the bidirectional flow of plasma as a spicule-like jets. This observations is taken on June 17, 2014 at 10:30 UT. Radially filtered  $H\alpha$  and Ca II H images have been used to make spicules more visible. (Credit: Pereira et al. 2016).

A new form of spicule with a substantially larger velocity, shorter lifespan (compared to above mentioned type I spicules), and solely upward motion was described by De Pontieu et al. (2007c). Such spicules are known as type II spicules. It's typical lifetime is  $\approx 1$  min. The Ca II H observations (cf., Fig 1.14) show type II spicules with shorter life-time of about 50-150 s, lower heights of  $\approx 4$  Mm, and smaller width of  $\approx 200$  km. Type II spicules possess a typical speed of  $50-100 \text{ km s}^{-1}$ , that is substantially faster compared to the type I spicules (e.g., De Pontieu et al., 2004; Murawski and Zaqarashvili, 2010; Rouppe van der Voort et al., 2009). Type II spicule can be found in coronal holes, which may possess maximum height of around 5 Mm. However, they appear shorter in the active

region and in the quiet-Sun. De Pontieu et al. (2004), Judge et al. (2012) and Martínez-Sykora et al. (2017a) reported that these spicules have not been observed over the plage region. The triggering of type II spicules resemble with up flows of the plasma, which thereafter vanishes. Most-recent observations suggest that type II spicules rise in the Sun's atmosphere by constant acceleration, and heated to the temperature resembling that of the transition region (De Pontieu et al., 2011, 2009). According to Heggland et al. (2007), type II spicules frequently experience rapid chromospheric line fading at the end of their life-time. This may be an evidence of their heating above chromospheric temperatures.

In addition, all the spicule-like cool jets found in quiet regions and coronal holes display linear trajectory (Pereira et al., 2012). This linear trajectory depicts only upward motion of the plasma. According to Pereira et al. (2013), numerous spicule-like collimated and cool jets are observed in Ca II H line exhibiting the linear trajectory, while the multi-wavelength observations (e.g., Mg II k and Si IV lines) show their parabolic trajectory with higher formation temperature. They explained these findings as a result of the localized heating that occurred when type II spicules move in the upward direction in the solar atmosphere. The type II spicules follow a parabolic trajectory similar to the type I spicules, however, they are more violent and heated plasma ejecta.

### 1.3.2 Macrospicule

Apart from type I and type II spicules, their large-scale analogues are known as macrospicules (e.g., Bennett and Erdélyi, 2015; González-Avilés et al., 2021; Murawski et al., 2011; Wilhelm, 2000). The macrospicules have firstly been detected by Bohlin et al. (1975) using EUV observations of the solar limb. These giant features may also be found at the polar region of the coronal holes. It's typical velocity is  $\approx 10\text{-}150 \text{ km s}^{-1}$ , lifetime 3-45 min and height 7-70 Mm. They are larger cool jets of chromospheric plasma expelled into the quiet-Sun, reaching heights of several tens of megameter (Mm) before falling back or

fading (Priest and Forbes, 2007). These giant jets are observed with vertical flow rates exceeding  $200 \text{ km s}^{-1}$ , and they are found to be strongly associated with complex dynamics of magnetic fields (e.g., cancellation/emergence), and specific topological characteristics such as mini-filaments, small-scale loop and coronal holes (e.g., Bennett and Erdélyi, 2015; Bohlin et al., 1975; Parenti et al., 2002; Sterling, 2000; Wilhelm, 2000).

### 1.3.3 Dynamic fibrils

Spicules present at the solar disk in the active regions are called as dynamic fibrils. Dynamic fibrils appear as a dark structure observed in  $H\alpha$  observations and also in other wavebands (Anan et al., 2010). It is basically of two types: (i) the long fibrils, and (ii) short fibrils (Priya et al., 2017; Tian et al., 2014). Short fibrils have smaller lifetime and they appear as a dark structure in the quiet-Sun. The long fibrils protrude from the sunspot regions and arch over the supergranular cells. The dark structure of short fibrils is due to the fact that their cool plasma at optical depth of unity at the higher elevations than the ambient medium. The characteristics of fibrils are support to represent the family of on-disk type I spicules. Various observations suggest that dynamic fibrils show the multithermal nature at the same time (Chintzoglou et al., 2021). It's typical velocity is  $\approx 10\text{-}30 \text{ km s}^{-1}$ , and lifetime is  $\approx 2\text{-}20 \text{ min}$  (Hansteen et al., 2006; Langangen et al., 2008b,c; Priya et al., 2017). These fibrils are also considered as the counterpart of mottles in the active regions, which follow the parabolic trajectory.

### 1.3.4 Mottles

Another type of spicule-like jets are referred as mottles, which are present at the quiet-Sun disk. These plasma ejecta are seen as dark features observed in Ca II H emission. Mottles are observed along the boundary of the network cells and represent the disk-counterpart of solar spicules (e.g., Kuridze et al., 2013; Morton et al., 2012; Suematsu et al., 1995).

The typical parameters such as life time, velocity, width etc are given in Table 1.2. The chromosphere mostly consists of two different types of mottles: (i) short dynamic mottles, and (ii) long horizontal dark mottles (De Pontieu et al., 2007a). However, it is unlikely to observe the single mottles unlike dynamic fibrils present in an active region. Suematsu et al. (1995) reported that mottles have parabolic trajectory with upward and downward motions.

### 1.3.5 Network jets

Network jets are a sub-family of cool chromospheric jets that have been observed and modelled in the solar atmosphere. Its morphological features, and dynamical characteristics show that it may have an impulsive origin. (e.g., Bennett and Erdélyi, 2015; De Pontieu et al., 2021; González-Avilés et al., 2021; Kayshap et al., 2018; Murawski et al., 2011; Pereira et al., 2014; Rast et al., 2021; Wedemeyer-Böhm et al., 2012; Wilhelm, 2000; Zhang et al., 2012, and references cited therein). The observations recorded using from the IRIS show the thin jet-like plasma ejecta triggered from the coronal hole (CH) as the network jets primarily as a transition region process (Tian et al., 2014) accompanied with footpoint brightening. Its apparent terminal speed is  $\approx 80\text{-}250 \text{ km s}^{-1}$ . The network jets may also be triggered from the quiet-Solar atmosphere, however, they are longer and faster in coronal holes (Narang et al., 2016). Recent studies of the network jets reveal their average length  $\approx 3.0 \text{ Mm}$ , apparent speed  $\approx 140 \text{ km s}^{-1}$ , and lifetime  $\approx 105 \text{ s}$  (Kayshap et al., 2018). The morphological features of the network jets (e.g., speed, length, lifetime, etc) show some resemblance to the spicule-like jets, and it may be responsible for the TR heating (Pereira et al., 2014). More-recently, Chen et al. (2019) detected double peaked Si IV 1393.755 Å profiles or enhancements in both line wings at the network lanes, which correspond to the footpoints of the network jets or transient and compact quiet-Sun brightening.

### 1.3.6 Other cool jet-like structures

The recent observations show various thin and bright features observed in Ca II H line. These structures referred as straws (Rutten, 2007a). Straws are the on-disk analogue of the type II spicules. The observations in Ca II H blue wing reveal that thin and dark features also found at the counterpart of the spicules known as rapid blue-shifted excursions (RBEs) (Langangen et al., 2008a). The typical length of the RBEs is  $\approx 1.2$  Mm, lifetime 45 s, and width about 500 Km. These features show the similar  $H\alpha$  observations in its blue wing (Roupe van der Voort et al., 2009).

## 1.4 Solar Chromospheric Jets: Theoretical and Numerical Understanding

Despite the fact that cool solar jets are still not fully understood, the mechanism of chromospheric jets has been the subject of a great deal of theoretical and computational research. In this section, we review a few extensive theoretical and numerical models for the triggering and evolution of chromospheric jet/jet-like processes. We discuss here the following models: (i) Magnetic reconnection model, (ii) Alfvén wave model, (iii) Acoustic wave model, (iv) Pressure-pulse model, (v) Effect of the non-ideal processes in solar plasma.

### 1.4.1 Magnetic reconnection models

Magnetic reconnection model describes the formation of chromospheric cool jets (e.g., De Pontieu et al., 2007a; González-Avilés et al., 2017; Heggland et al., 2009; Innes et al., 1997b; Karpen et al., 1995; Leake et al., 2012; Pontin and Priest, 2022; Shibata et al., 2007; Takasao et al., 2013; Yang et al., 2013, and references citet theirin). The reconnection is a process of the reorganization of magnetic topology in which two anti-parallel field

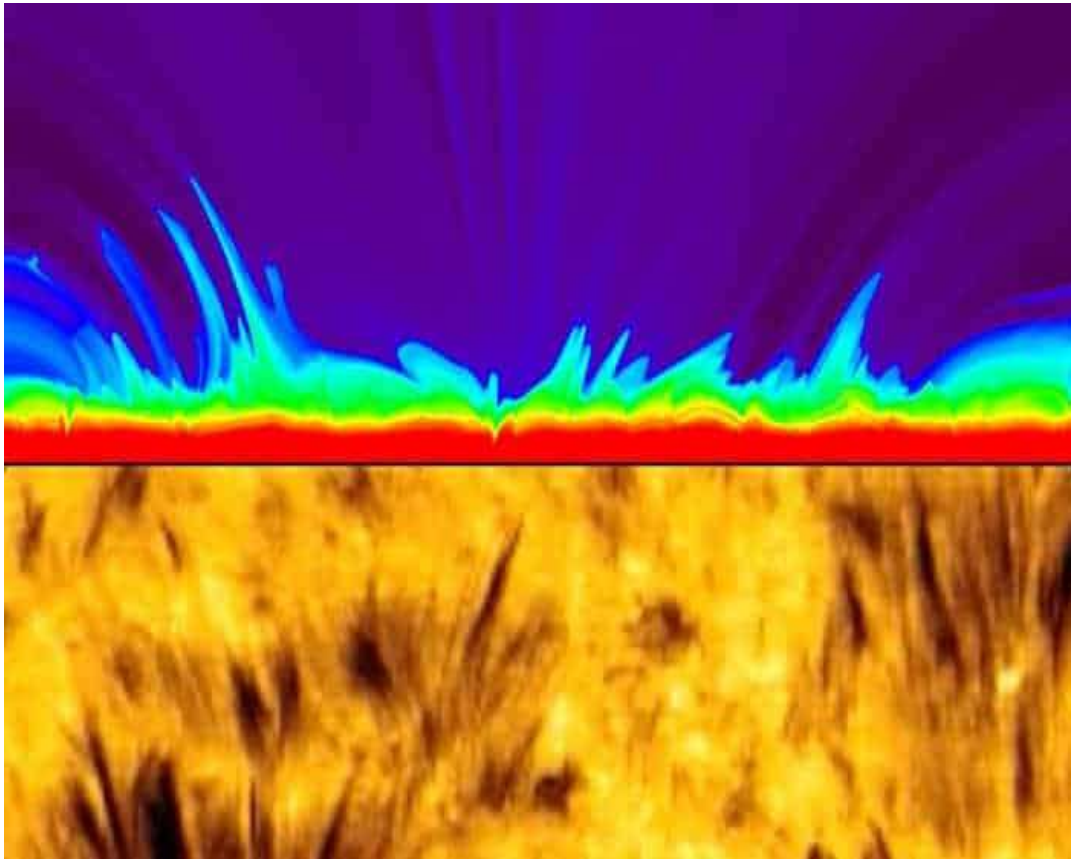


Figure 1.14: Observation (bottom), and simulation (top) of the spicule-like jets. (Credit: University of Oslo/Swedish 1-m Solar Telescope).

lines interact with each other. According to this model, the chromospheric plasma may be accelerated by the magnetic tension force and also by the evolved magnetoacoustic shocks (Takasao et al., 2013). Sometimes, the magnetic reconnection shows the heating scenario before formation of these jets at their foot points. De Pontieu et al. (2007a) and Moore et al. (2011) reported that magnetic reconnection occur in the solar chromosphere, and act as a driver of the type II spicules. The solar chromosphere consists of neutrals and ions that undergo in the collisions. Therefore, the occurrence of rapid reconnection in the chromosphere is not clearly depicted unlike the corona. Shibata et al. (2007) reported that certain structures match the current sheet in the observations of jets near the sunspot, which are the likely sites for the magnetic reconnection. In this context, three dimensional

magnetic reconnection governed by the torsional motion in the jet is proposed by Yokoyama and Shibata (1995). According to their models, the formation of X-ray coronal jets and  $H\alpha$  surges are produced by the interaction of the emerging magnetic flux with the background field (Moore et al., 2011; Shibata et al., 2007). The various models also reveal that the vortex in the photosphere causes kink instability in the flux tube leading the jet eruptions (e.g., Pariat et al., 2010, 2015).

The magnetic reconnection is also responsible for the evolution of the penumbral chromospheric jets caused by sheared magnetic field lines as reported by Katsukawa et al. (2007). Parker (1963) and Brandenburg and Zweibel (1994) proposed that ambipolar diffusion causes the formation of a smaller current sheet, which improves the magnetic reconnection. Leake et al. (2012) predicted rapid reconnection using two-fluid (ions and neutrals) MHD simulations leading to the localized heating and plasma dynamics. More-recently, González-Avilés et al. (2017) have proposed an extensive model for the triggering of spicule-like jets by performing the numerical simulation using resistive magnetic reconnection. This simulation may also describe the evolution of cool jets.

### 1.4.2 Alfvén wave models

Alfvén waves are also proposed as one of the possible drivers of spicule-like cool jets (e.g., Haerendel, 1992; Hollweg et al., 1982; Hollweg, 1992; Kudoh and Shibata, 1999; Singh et al., 2022, and references cited therein). Hollweg et al. (1982) performed the first detailed set of 1.5-D simulations, and proposed that Alfvén pulse/waves is a driver to generate spicule-like cool jets. They perform the simulation by launching a transverse velocity pulse in the azimuthal direction and allow the plasma motion in the vertical direction. In this model, the evolved generated Alfvén waves couple with the fast magnetoacoustic shocks followed by the motion of chromospheric as well as transition region plasma as a thin and cool jets. After a few years, Hollweg (1992) extended these investigations by studying

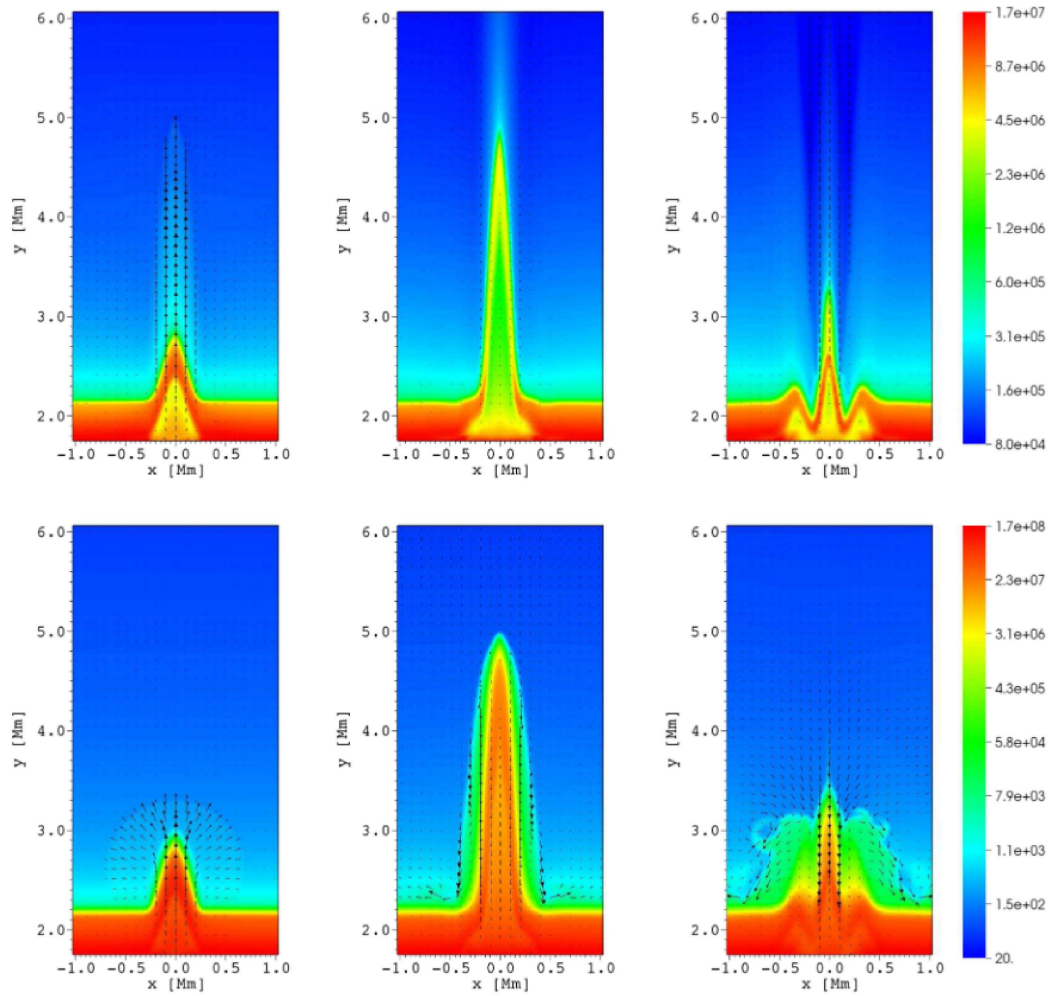


Figure 1.15: The snapshots show the temporal evolution of cool jets in two-fluid model (ions+neutrals). The logarithm of density map of ions are shown at  $t=70$  s,  $210$  s,  $320$  s (from top-left to top-right), whereas snapshots from bottom-left to bottom-right display the logarithm of density map of neutrals at the same time. Ion and neutral velocity vectors are shown by arrows in x-y plane. On the colormap, the warm coronal plasma is represented by blue color, the cool chromospheric plasma by orange-red, and the plasma in the transition region as green (Credit; Kuźma et al. 2017b, ApJ, IOP publishing).

the MHD slow-mode shock, which is generated as a result of the non-linear growth of the Alfvén waves. They describe the structures of the spicule-like jets which reach to the insufficient height in the solar atmosphere. This effect may arise due to the reason that spicules contain cool materials.

Mariska and Hollweg (1985) performed the numerical simulations that incorporate radiative loss also. This simulation shows further reduction in the height of the solar spicules. However, that analysis assumed an initial solar atmosphere resembling an active region loop rather than a quiet Sun atmosphere. Suematsu et al. (1982) and Sterling and Hollweg (1988) suggest that longer spicules may not be predicted when the transition region is at a lower height in the model solar atmosphere (similar as in case of an active region). However, while assuming an initial atmosphere more similar to quiet-region or coronal-hole, the adiabatic simulation of Alfvén wave model reported by Hollweg et al. (1982) and Hollweg (1992) even got failed to yield an acceptable spicule. These models discussed above mostly focus on the Alfvén waves, which have a low frequency. Haerendel (1992) and De Pontieu (1999) suggest about the production of spicules/spicule-like jets due to the dissipation of high frequency Alfvén waves. The damping is mainly due to the ion-neutral collisions as spicular jet ascends through the partially-ionized middle chromosphere. This sort of damping causes the plasma to experience a net upward-directed  $j \times B$  force, which pushes the spicules further in the upward direction. However, James and Erdélyi (2002) reported that the primary mechanism for the triggering of the chromospheric jets is the creation of shock waves due to the turbulent interaction of the Alfvén waves. More-recently, Singh et al. (2022) proposed an extensive model of triggering of the quasi-periodic spicule-like jets. They performed 2.5-D ideal MHD simulations by implementing random Alfvén pulses that trigger the spicule-like jets.

### 1.4.3 Acoustic wave models

Other class of the models for the formation and evolution of spicule-like cool jets lie in the realm of acoustic wave models. According to such model, the acoustic perturbations are generated inside the flux tube caused by the photospheric convective motions, and spread out along the magnetic field lines. Therefore, the magnetic field lines serve as a

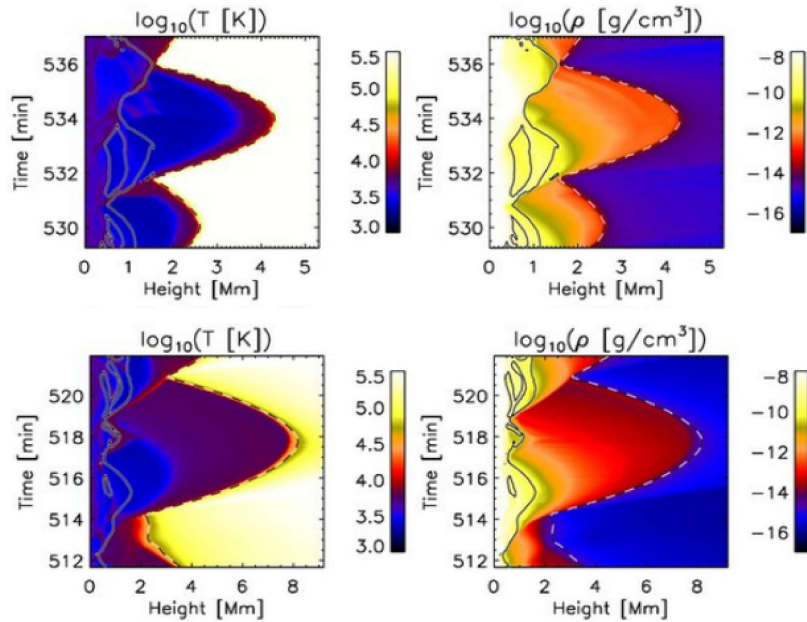


Figure 1.16: Time-distance map of spicule-like jets as shown in temperature ( $T$ ) and mass density ( $\rho$ ). The solid line represents the position of plasma beta equals to 1. The transition region ( $T = 40,000$  K) is shown by the dashed line (Credit: Iijima 2016).

wave guide for slow-mode acoustic waves (e.g., Heggland et al., 2007; Rouppe van der Voort et al., 2007; Shibata and Suematsu, 1982; Sterling et al., 1993; Suematsu et al., 1982, and references citet theirin). The acoustic waves propagate higher in the density stratified chromosphere where they get amplified quickly and form shock waves. It is considered that the chromosphere, transition region and corona are the contact discontinuity where the chromospheric shock waves collide. When the shock interacts with the transition region, this thin atmospheric layer is raised high (Hollweg, 1982) and therefore, chromospheric jet-like structures are formed. Heggland et al. (2007) proposed a new deceleration mechanism named as shock deceleration theory. According to this theory, deceleration of the shock should be proportional to the maximum upward velocity, which is consistent with the observed dynamics of mottles and fibrils. De Pontieu et al. (2007a) proposed that dynamic fibrils and mottles are caused by the p-mode oscillations.

Hollweg (1982) proposed the rebound shock model for the formation of chromospheric jets. They gave an acoustic wave model where as implementation of low frequency velocity pulse of magnitude  $1 \text{ km s}^{-1}$  at the photosphere and lower chromosphere yield the cool jets. This low frequency pulse may indicate the granular motion that are building the magnetic flux tubes, which would explain the spicules-like structures. In this model, the velocity pulse launches an acoustic wave. These waves of higher frequency are trapped in the photosphere and launch a wave train of the small amplitude shocks propagating upward. This upward propagating wave is known as magnetoacoustic gravity wave. In this case, the transition region gradually pulls upward due to a constant interaction with the rebound shocks.

#### **1.4.4 Pressure pulse model**

The concept of the pressure pulse to launch the chromospheric jets is similar to the chromospheric evaporation. The pressure pulse lunched in the middle chromosphere creates the under pressure region, and it becomes responsible for the triggering of the chromospheric jets (e.g., Singh et al., 2019; Sterling et al., 1993; Suematsu et al., 1982, and references citet theirin). In this model, the bulk of the energy due to the pressure pulse is directly deposited in the middle chromosphere resulting spicule-like jets and other small scale eruptions (Singh et al., 2019). In such models, when pressure pulse is applied in the middle chromosphere, there are two processes that occur therein. First is the expansion of the localised region where the pressure pulse is applied, and second the generation of the magnetoacoustic shocks. Therefore, theses two mechanisms launch two types of cool jets. The first mechanism launches directly the transition region plasma in the upward direction, and generates the spicule-like jets akin of the shock tube jets. The other mechanism suggests that the pressure pulse produces a slow shock wave that ejects mass through the

transition region. This jet is known as a crest shock jet. Therefore, the triggering of jets depends on the height of the energy deposition in the solar chromosphere.

### 1.4.5 Effect of the non-ideal processes

The theoretical and numerical investigations listed above use models in the ideal regime of the solar plasma. In case of the real solar atmosphere, and for the quantitative understanding of chromospheric jet-like features, numerous non-ideal physical processes including thermal conduction, radiative cooling, latent heat from partial ionization, multidimensional interaction of MHD waves, and heating/cooling imbalance should be implemented in the numerical models (e.g., González-Avilés et al., 2021; Isobe et al., 2007; Pariat et al., 2009, 2010, and references cited therein). Recently, Navarro et al. (2021) and Navarro et al. (2021) reported the models for the formation of spicule-like cool jets in non-ideal regime using Gaussian pulses. As a result, thermal conduction was found to change several features of the evolved jet including its shape, height, order of transferred mass and energy. They also found that the jet seems more collimated and has the ability to penetrate higher into the solar corona. Incorporating thermal conduction into their model should enhance the energy and mass flux transport by these jets. Another more complex numerical models of type II spicules incorporate the impact of partial ionization, radiation, and ambipolar diffusion in addition to the components of thermal conductivity and resistivity (e.g., De Pontieu et al., 2017a,b; Martínez-Sykora et al., 2009, 2011).

More-recently, Kuźma et al. (2017b) performed the two-fluid numerical simulations in 2-D including adiabatic and non-adiabatic terms for the evolution of spicule-like jets driven by the velocity perturbations. They reported that when the velocity pulse acts into the chromospheric plasma, it steepens into a shock further creating quasi-periodic rebound shocks. They infer from their model that the dynamics and evolution of the

produced spicule-like jets are not significantly influenced by the radiative cooling and thermal conduction.

## 1.5 Evolution of Dynamical Processes in Jets

Jets are also subjected to the associated plasma and wave dynamics at diverse spatio-temporal scales. The waves and oscillations as well as evolution of instabilities are two such important processes that are described below.

### 1.5.1 Oscillations in the jets

The observations show that various MHD oscillation modes in the jet-like structures are caused by the inhomogeneous and complex motions of the plasma. These oscillations are produced by shearing motion in the ambient plasma of the jet's spire or by very complicated plasma motion close to the regions of concentration of the field lines. As a result, the various forms of generated oscillations greatly enhance the perspective of the jets (De Pontieu et al. 2003, Xia et al. 2005). It is possible to study more about the features of wave propagation in these jets by making observations in two separate spectral lines that are created at two different heights (Jess et al., 2012). Jess et al. (2012) reported the observed transversal oscillations in the jet-like features using spectral observations of  $H\alpha$ . These oscillations show the periodic behaviour which may be Alfvén waves or kink waves or Alfvénic waves.

A range of transverse oscillations are reported type II spicule with 1-10 minutes periods, 10-20 km s<sup>-1</sup> velocity amplitude, and apparent speed of 30-110 km s<sup>-1</sup> (De Pontieu et al., 2007c; Zaqarashvili and Erdélyi, 2009). These results are also reproduced using extensive numerical simulation of spicules that have short lifespan. Such oscillations were regarded as upward, downward, and standing Alfvén waves (e.g., Okamoto and De Pontieu, 2011;

Tavabi et al., 2015). Additionally, numerical models of jet-like features show how waves behave throughout their evolution. González-Avilés et al. (2019) reported 3D numerical modeling of the jet similar to the type II spicules displaying torsional as well as rotational motions. This model suggests that Alfvén waves propagate in the overlying corona through jets's spire.

### 1.5.2 Instability in the jets

Recent high resolution observations from the Solar Dynamics Observatory (SDO) and Interface Region Imaging Spectrograph (IRIS) show the vortex-like structures evolved at the boundary of the solar jets, which are interpreted as the formation of gravity driven interface instability caused by significant shear between two flows (Li et al. 2018, Zhelyazkov and Chandra 2018). In addition, the numerical modelling suggests that the formation of such instability is caused by a velocity discontinuity at the flux tube's boundary in the Sun's atmosphere. Therefore, these flux tube might be used to study instability in the spicule-like jets (e.g., Zaqarashvili et al., 2010, 2014; Zhelyazkov and Zaqarashvili, 2012). Zhelyazkov et al. (2015b) studied Kelvin-Helmholtz (KH) instability in the cool jets (solar surges) using moving twisted magnetic flux tube with twisted and homologous magnetic field. The numerical experiment demonstrate that the KH instability occurred in the magnetic field conditions for axially propagating MHD waves when both magnetic fields were twisted. The threshold velocity for the formation of KH instability is much lower than the Alfvén speed. Antolin et al. (2018) observed that the transverse waves in cool spicule-like jets are responsible for the formation of vortices in the spicule-like jets and development of the KH instability. Such instabilities are observed in a variety of cool jets at diverse spatio-temporal scales (e.g., Kuridze et al., 2016; Zaqarashvili et al., 2010, 2014; Zhelyazkov and Zaqarashvili, 2012; Zhelyazkov et al., 2015b).

## 1.6 Outline of the Thesis

The solar chromosphere launches various types of cool plasma jets (e.g., spicule-like jets, network jets, mottles, dynamic fibrils, small scale surges etc). These jet-like structures may carry the mass and energy in the overlying TR and corona. These jets are associated with various types of complex plasma processes (e.g., MHD waves and oscillations, instabilities). The origin of jets, their complex plasma processes and associated mechanisms are at the forefront of solar physics research. These jets can be impulsive, collimated, high-velocity plasma ejecta, which have been observed using multiwavelength observations. Origin and plasma processes of such jets can be further investigated by performing the numerical modeling. The numerical models and associated theoretical concepts are helpful in understanding the intricate relationship between complex structuring of the magnetic field and plasma flow within the jets. Also, this one of the most stringent topics in solar physics focuses on understanding the mechanisms of energy release and the ensuing localized chromospheric and coronal heating. The generation of waves and instabilities are also intimately related to the processes by which such jets are formed. For a complete comprehension of the solar atmosphere, the jets at diverse spatio-temporal scales must be understood quantitatively. In the present thesis, we aim to study the cool chromospheric jets using numerical MHD models. At the end, we also discuss the evolution of KH instability in large scales cool jets in multiwavelength observational perspectives.

The origin and formation of chromospheric jets, particularly spicule-like cool jets, have been studied. This issue is dealt by a number of extensive and realistic MHD models. In this thesis, we proposed a few extensive MHD models in ideal and non-ideal regime that clearly describe the origin, kinematics and energetics along with the evolution of plasma processes eventually occurred in spicule-like cool jets. We made these models utilizing PLUTO code, which describe quantitative analysis of cool jets and associated plasma dynamics in the chromosphere. The present thesis begins with a brief introduction to the

Sun and its atmosphere in *Chapter 1*. It further elucidate the observations, basic facts, as well as numerical and theoretical models of the cool spicule-like jets.

In *Chapter 2*, we describe observational data from space-borne instruments (IRIS SJI and spectrograph, and SDO/AIA) and associated data analysis techniques. We also describe briefly the methodology of magnetohydrodynamic (MHD) simulations.

In *Chapter 3*, we delineate the work on the numerical simulation of spicule-like cool jets driven by Alfvén pulses. This study is based on a 2.5-D ideal MHD simulation describing the formation of spicule-like jets. We conclude that these spicule-like jets may carry sufficient amount of mass and energy to the localized coronal heating.

In *Chapter 4*, we elucidate the numerical modelling of the pressure pulse driven cool jets. We describe the kinematics and evolutionary properties of these jets. The model suggests that pressure pulse is sufficiently deposit the energy in the middle chromosphere to launch the cool jets in the solar atmosphere.

In *Chapter 5*, we present the scientific result of the impulsive origin of cool jets. These jets are reported earlier by the Chen et al. (2019) using high-resolution spectroscopic observations. We perform the numerical simulation of cool spicule-like jets in both ideal and non-ideal (including thermal conduction, radiative losses, and combined effect of both) solar atmosphere. We compare the morphology, kinematics, and energetics of the jet both in ideal and non-ideal solar plasma.

In *Chapter 6*, we describe 2-D magnetohydrodynamic (MHD) simulations that provide a comprehensive view of the evolution of multiple cool jets in the solar chromosphere. We studied the oscillations in two cool jets moving up to the higher heights. The propagating transverse kink waves are found in the first dense and cool jet, which was generated along significantly curved magnetic field lines. However in the second cool and denser jet, the initially evolved collective kink oscillations no longer sustain beyond their one cycle and damped quickly without propagation. We provide the basic physical cause of the evolution

of these decaying transverse oscillations in fine-structured cool jets triggered due to the complex velocity fields.

In *Chapter 7*, we report the evolution of Kelvin-Helmholtz (KH) instability in the cool coronal jet. We investigate the evolution of the KH instability in the jet-like structure using multiwavelength imaging observations from the Atmospheric Imaging Assembly (AIA) on board Solar Dynamics Observatory (SDO). This jet-like eruption show bidirectional plasma flows that interact with one another within an extended spine of the jets. This process generates shear motion and the evolution of the KH instability in the jet above its fan-spine topology.

In *Chapter 8*, we summarize the significance of the original research works presented in this thesis, and finally describe the future plans.