

## Preface

The sun, an active magnetic star, is crucial for life on Earth as it provides essential energy and constitute our solar system. It releases solar wind, electromagnetic radiation, and energetic particles that affect both our earth's outer atmosphere and the heliosphere. With its various behaviors, studying the sun helps us understanding not just our solar system, but also celestial bodies across the universe. By directly observing the sun, we can investigate its activities in various parts of atmosphere, often at diverse spatio-temporal scales, which helps us grasp fundamental physical processes. Many space missions and observations provide plenty of data revealing a variety of physical conditions in its atmosphere and surroundig space. By understanding the dynamics of the sun's atmosphere and simulating them using computers, we can uncover the physics of important plasma processes and heating aspects. Serving as a natural laboratory, the sun allows detailed examination of how its magnetic fields impact life on Earth and its surroundings, through phenomena like electromagnetic radiation, highly energetic particles, and varying thermal plasma.

The magnetic field of the sun, which is created through a process called dynamo action, has an impact on layers like the photosphere, chromosphere, and corona. The sun's magnetic activity, characterized by sunspots and bright coronal loops goes through a cycle that lasts periodically at the scale of 11 years. Scientists have always been intrigued by the magnetism found in sunspots and other parts on the sun. Furthermore, events including coronal mass ejections (CMEs) and solar flares have presented their own set of challenges to understand their physics. Space missions like SOHO, TRACE, Ulysses and Yohkoh etc in 90's and Hinode, STEREO, SDO, Solar orbiter etc after 2k have provided insights into these phenomena. The study of prominences and solar flares makes exploring the sun fascinating. The sun is incredibly interesting because its different layers behave in diverse ways and possess peculiar properties and dynamical plsama processes. Scientists

find it challenging to understand these layers due to their complicated magnetic and plasma structures. The sun's atmosphere is always active, making it hard for scientists to figure out how energy and mass transported. The photosphere and chromosphere have temperatures ranging from 4300 K to 10000 K, but as we approach the transition region, just a few hundred kilometers thick, temperatures spike to millions of degrees Kelvin in the outermost layer, corona. This sudden spike in temperature does not follow the usual rules of heat flows, therefore puzzling scientists since decades. Researchers have been trying to figure out the exact mechanism of coronal heating for a long time. Regular heat transfer methods can not explain this sudden increase in temperature. It does not obey the rules of thermodynamics. Hence, scientists are exploring non-thermal phenomena that do not invoke only the heat flows and thermal energy. By using space based observations, scientists have discovered that the coronal heating is connected to its magnetic field activity, and magnetohydrodynamic plasma processes. They broadly classified these mechanism in two categories namely, (i) the magnetic reconnection, and (ii) magnetohydrodynamic waves.

Understanding the physics of different dynamical plasma processes in the solar atmosphere requires detailed information in form of imaging, spectroscopic, spectropolarimetric, and magnetic measurements and associated observational data. Thanks to the observations from space-based observatories and ground-based observatories (e.g., IRIS, SDO, TRACE, SOHO, BBSO, SST, DST, etc), our knowledge of the underlying physics of various plasma processes has significantly improved in recent decades. The sun emits radiation across the entire electromagnetic spectrum, however, ground based observations mostly use visible and radio wavelength spectrum including some infraed lines emitted also from its atmosphere. Instruments in space, though, can observe the sun in various wavelengths throughout the entire electromagnetic spectra. Each wavelength provides information about different parts of the solar atmosphere. For example, the Solar Dynamics Observatory

(SDO) takes images using its Atmospheric Imaging Assembly (AIA) telescope that possesses ten different filters, observing the solar atmosphere in Extreme Ultraviolet and UV continuum. Each of these filters corresponds to various solar temperatures, enabling the retrieval of the information of various plasmas maintained at different temperatures in the localized solar atmosphere or in different magnetic structures. Additionally, the Helioseismic and Magnetic Imager (HMI) onboard SDO focuses on tracking how the sun's surface moves and observe its magnetic field giving us crucial information about its magnetism. To advance our understanding of the solar atmosphere, it is crucial to combine multi spectral line diagnostics and magnetic field measurements. These diagnostics should ideally be sensitive to different conditions, covering a broad spectrum of densities, temperatures, and magnetic field topologies. Joint observations from ground and space-based telescopes allow the simultaneous acquisition of data for the diagnostics of the solar plasma and magnetic field. Telescopes in space provide access to the short wavelength regime (mostly X-ray and UV predominantly), offering a clear view of the chromosphere, transition region, and corona. On the other hand, ground-based telescopes offer high resolution photospheric and chromospheric diagnostics, as well as detailed polarimetric measurements of the magnetic field. Coordinated observations greatly enhance our ability to uncover physical processes in the solar atmosphere, spanning from the photosphere through the chromosphere and finally transition region to the corona. Such multiwavelength and multi-instrument observations are important for understanding the atmospheric coupling and therefore studying the mass and energy transport processes in the sun.

The coronal heating problem, originating almost seven decades ago, addresses the mystery of the sun's outer layer being maintained at multi-million degrees. Solar physicists then aimed to understand the physical mechanisms balancing thermal conduction, radiation, and solar wind losses. Magnetic processes and energy from the solar surface plasma motions play an important role, but the exact mechanisms are still unclear and

highly debated. Despite advancements, the exact processes contributing to the plasma heating still remain a mystery. Proposed mechanisms include magnetic energy conversion in form of heat and kinetic energy, wave energy dissipation, and mass flow cycles between chromosphere and corona. The existence of solar corona requires additional non-thermal energy, a small fraction of total solar output, suggesting feasible heating mechanisms. Observing specific heating mechanisms is challenging due to concurrent processes at the diverse spatio-temporal scales. Heating involves three phases *viz.* energy generation, transport, and dissipation in the solar magnetic structures. Heating mechanisms are classified based on the involvement of complex magnetic fields, e.g., strong and weak magnetic field regions, and their plasma processes can be characterized by the magnetohydrodynamics (MHD). MHD models propose dissipation through Joule heating or viscosity, involving energy carriers like MHD waves and dissipative current sheets via reconnection processes. Alternative heating processes involve the selective decay of the turbulent cascades in the magnetic fields.

After scientists started looking into why the outer layer of the sun is so hot, they began to pay attention on the role of waves and its heating capabilities. Some early ideas suggested that sound waves from deep inside the sun might be responsible for the heating of the outer layers of its atmosphere. Others proposed that magnetic reconnection could also play a role in generating heat and bulk plasma motions in the corona. As researchers started observing the sun more closely since last two decades using spacecraft like Hinode, Solar Dynamics Observatory (SDO), Solar TERrestrial RELations Observatory (STEREO), and Interface Region Imaging Spectrometer (IRIS), Solar orbiter and many and ground based observatories like SST, DKIST, etc they discovered that waves are indeed ubiquitously present in different layers of the sun. These findings challenged the previous notion that waves did not contribute much to the heating of the solar atmosphere. Observations also revealed that waves and oscillations provide valuable information about the structure of the

localized solar atmosphere and help in diagnosing plasma conditions by the mean of MHD seismology. Scientists have identified different types of magnetohydrodynamic (MHD) waves in large scale corona (e.g., fast and slow magnetoacoustic waves, Alfvén waves), which help us understand how these waves are evolved and dissipate their energy moves in the solar atmosphere. Using the advanced and complimentary imaging and spectroscopic observatories on the ground (e.g., GST/BBSO, DKIST, SST, GREGOR, etc), we can now directly observe and measure the evolutionary properties, propagation and energetics of these waves with a great precision. These exclusive observations also confirm the presence of waves in various parts of the solar atmosphere, each revealing unique aspects of its physical properties, such as in the network regions, internetwork regions, sunspots, coronal holes, spicules, and other cool/hot jets, coronal loops, plumes, etc.

Turbulent convection in the sub-photospheric layers triggers sound (acoustic) waves with different frequencies, known as p-modes, which travel through the solar interior. The interaction of these waves causes a global oscillation at the scale of approximately five minutes, making the solar surface vibrate accordingly. As these waves move through the solar atmosphere, where the magnetic field is stronger, they may be directed by the magnetic field lines in the upper part of the atmosphere. This makes them abbreviated as slow magnetoacoustic waves propagating along the field lines and cause the periodic compression & decompression in the plasma gas. There is strong observational evidence indicating the presence of slow magnetoacoustic waves in different magnetic structures, like sunspots, coronal plumes, and coronal loops. Propagating acoustic waves were believed to be the sources of heating in the solar chromospheric regions where surface magnetic fields are weak and these perturbations can be converted into the shocks. In sunspot umbra, continuously propagating magnetohydrodynamic (MHD) waves generated below the photosphere may cause 3-minute sunspot umbral oscillations, influencing spectral line profiles due to temperature, density, and velocity variations in the emitting plasma. While

extensive observations and models have explored the nature of the 3-minute oscillation and its connection with the coronal heating problem in recent decades, the lack of direct observations of temperature and magnetic field variations in the chromosphere has made it challenging to fully address these problem.

Waves are ubiquitous in the solar atmosphere and can propagate from the photosphere to the chromosphere, the transition region, and the inner corona. These waves can dissipate energy and may contribute to chromospheric and coronal heating. Wave propagation is determined by the medium's property, i.e., the acoustic cut-off frequency. Classically, its value is reported as 4mhz, which means that only waves with frequencies greater than 4 mhz can propagate in the chromosphere; otherwise, waves are evascent. In that respect, the acoustic cut-off frequency is critical in determining the wave propagation conditions in the solar atmosphere. Nevertheless, acoustic cut-off reduces in the presence of a strong or tilted magnetic field. Strong magnetic fields can affect the radiative relaxation time, lowering the acoustic cut-off. The inclined magnetic field affects the acoustic cut-off by the cosine angle generated by the magnetic field lines with the vertical direction. Therefore, strong magnetic field yield propagation of long-period waves in the chromosphere as the cut-off period increases. This is known as photospheric oscillations leaking into the chromosphere. In this thesis, we examined wave propagation conditions using estimated cut-off values at different atmospheric heights.

In recent years, solar physics has made significant strides, especially in our understanding of magnetohydrodynamic (MHD) waves and associated plasma processes in the solar corona. Detailed imaging and spectral data have uncovered various types of MHD waves across different parts of the electromagnetic spectrum, confirming their presence in the solar atmosphere. This breakthrough has also revealed more about the development and physical characteristics of quasi-periodic pulsations (QPPs). These pulsations often manifest as fluctuations in the emission of solar flares and can last from short periods to several

minutes. The duration of QPPs may indicate different processes occurring in the solar atmosphere and provide insight into their inherent physical properties. The most notable QPPs are observed in the radiation emitted by non-thermal electrons during flares, spanning microwave, hard X-ray, and white light wavelengths. These pulsations occur throughout all stages of a flare, from its onset to its dissipation. Two main mechanisms contribute to the generation of long-period QPPs, namely, MHD oscillations and waves occurring within or in close proximity to the active magnetic structures, alongside repetitive cycles of magnetic reconnection and non-thermal particle acceleration. Accurately understanding the physical conditions in regions experiencing flares, as well as the underlying eruptive processes, relies on correctly identifying the physical mechanisms responsible for these pulsations. While the occurrence of QPPs in solar flares or eruptions has been extensively studied and documented, their presence in solar jets remains relatively unexplored due to limited observational studies. In this thesis, we have also explored the occurrence of Quasi-Periodic Pulsations (QPPs) during the onset of blowout jets.

This thesis is centered on the spectroscopic study of the propagation of magnetoacoustic waves in different layers of the solar atmosphere and Quasi-periodic pulsation in jets forming region in the solar corona. Different key aspects, such as the origin and propagation of magnetoacoustic waves, are rigorously studied. The high-resolution spectroscopic and imaging data from the Interface Region Imaging Spectrometer (IRIS) are utilized for the studies related to the wave propagation from photosphere to the solar transition region, as well as understanding the physical nature of transition region (TR) oscillations. The uniqueness of the thesis is that extensive spectroscopic data is analyzed in making statistical studies of the wave properties and understanding their propagation scenario in the lower solar atmosphere. The imaging data from Big Bear Solar Observatory (BBSO) are utilized for the studies of sunspot umbral oscillation to understand the origin of these umbral oscillations. The imaging data from Atmospheric Imaging Assembly (AIA) and

spectroscopy data from IRIS are utilized to study the quasiperiodic plasma processes in the solar atmosphere. The present thesis is organized in the form of the following chapters:

### **Chapter 1: Introduction of the Sun, Waves and Quasi-Periodic Pulsations**

In this chapter, we present an overview of the sun and its different layers, both in its interior and exterior. Our main focus is on the solar atmosphere, specifically examining the processes of coronal and chromosphere heating. We discuss various non-thermal heating mechanisms, placing a greater emphasis on wave propagation scenario because the research in this thesis is centered on detection and propagation of waves statistically using mainly the spectroscopic observations. Our discussion covers waves in uniform and inhomogeneous plasmas both. We also delve into the observable characteristics of these waves. Briefly, we review different types of plasmas, with a primary focus on the solar atmosphere and its observable features like quiet-sun and sunspot. We also discuss the sun's localized magnetic field and its connections to different plasma processes, including quasi-periodic pulsation. Finally, we outline the structure of the thesis.

### **Chapter 2: Outline of Observational Data and Analysis Tools**

In this chapter, we briefly elaborate on various space-borne and ground-based observatories, as well as their onboard instruments whose data we have utilized in the present thesis. We also discuss the spectroscopic techniques that we used to measure the oscillations in intensity and Doppler shift. Additionally, we delve into the analysis tools, such as the wavelet tool, cross-wavelet tool, and employed different noise/significance models that we used to conduct the necessary analysis.

### **Chapter 3: The Quiet-Sun Solar Transition Region Oscillations as Observed by IRIS using Si IV Spectral Line**

In this chapter, we have investigated the physical characteristics of oscillations occurring in the solar transition region (TR). Our analysis is centered on the examination of observations recorded by the Interface Region Imaging Spectrometer (IRIS), specifically by using the spectral line Si IV 1393.755 Å. Utilizing wavelet tools such as wavelet power, cross-power, coupled with a comprehensive noise model (power law + constant), we explored the fundamental properties of TR oscillations. For each selected location in the quiet-sun (QS), we determined the periods of both intensity and Doppler velocity oscillations. Moreover, we calculated the phase difference between intensity and Doppler velocity oscillations at each location. The statistical distribution of phase differences suggested that the observed oscillations are basically the signature of propagating slow magneto-acoustic waves. Additionally, some locations may also be associated with standing slow waves.

### **Chapter 4: Statistical Study of the Propagating MHD Waves in the Quiet-Sun Using IRIS Spectroscopic Observations**

In this chapter, we utilized observations of the quiet-sun captured by the IRIS instrument to explore wave propagation above the inter-network region. We examined various spectral lines corresponding to different atmospheric heights, including the photosphere, chromosphere, and TR. Using a wavelet analysis tool, we calculated the dominant oscillatory periods present at different heights. Moreover, by deducing the phase difference between two Doppler velocity time-series obtained from different heights, we estimated the cut-off frequency. This analysis disclosed a noteworthy correlation between 3-minute periods in the transition region and photospheric oscillations, suggesting a possible propagation of these oscillations from the photosphere to the solar transition region (TR). The transition region also exhibits long-period oscillations which might be generated *in situ*

there.

### **Chapter 5: Study of Sunspot Umbral Oscillation as Observed by Goode Solar Telescope (GST) at Big Bear Solar Observatory**

In this chapter, we studied the intensity oscillations in the sunspot. We utilized the  $H\alpha$  line data observed by the BBSO observatory/The Visible Imaging Spectrometer installed at the Goode Solar Telescope to investigate the solar umbra chromospheric oscillations above sunspot. Employing wavelet tools, including power, cross-power, wave coherence, and phase difference, along with a generic noise model (specifically, power law + constant), we analyze the properties of these umbral oscillations. Our findings reveal the dominance of 3-minute period across all passbands of  $H\alpha$  within the umbral region. To discern wave modes, we conduct a phase difference analysis. This involves estimating the phase difference between intensity from various bandpasses (such as  $H\alpha$  line core,  $H\alpha\pm 0.2\text{\AA}$ ,  $H\alpha\pm 0.4\text{\AA}$ ,  $H\alpha\pm 0.6\text{\AA}$ ,  $H\alpha\pm 0.8\text{\AA}$ , and  $H\alpha\pm 1\text{\AA}$ ) and Doppler velocity oscillations. The statistical distribution of phase differences falls within the range of  $-180^\circ$  to  $180^\circ$  for all bandpasses. The characteristic 3-minute umbral oscillations are indicative of resonant modes within the sunspot.

### **Chapter 6: Quasi-periodic Pulsation at the Base of a Kink-unstable Jet**

In this chapter we examined a blowout jet on the west limb of the Sun on August 29, 2014, using high-resolution imaging and spectroscopic data from the Solar Dynamics Observatory and the Interface Region Imaging Spectrograph respectively. We analyze the blowout jet that forms from kink instability at the west limb of the Sun using IRIS spectral observations. Time-distance diagrams revealed quasi-periodic fluctuations (QPPs) with a dominant period of 3 minutes. We observe a signature of bi-directional flows in various line spectra using IRIS (e.g., Si iv, C ii, and Mg ii), and these line profiles also

show a very broad and complex shape. Bidirectional flows and complex line profiles both are the signature of magnetic reconnection. Additionally, we see that line broadening occurs periodically with a period 3 minutes, and plasma upflow occurs whenever the line width is high, indicating multiple reconnection may produce periodic line broadening. Emission measure (EM) curves across temperature ranges displayed the same 3 minute period, suggesting multiple magnetic reconnection events. Using SDO/AIA data, we see the signature of magnetic reconnection as well. Both spectral and imaging analysis reveal multiple magnetic reconnections in the blowout jet, triggering quasi-periodic pulsations (QPPs).

### **Chapter 7: Conclusions and Future Plan**

In this chapter, we summarize the scientific findings presented in this Ph.D. thesis. As we draw our discussion to a close, we encapsulate our results and offer insights for prospective analyses, observations, and the development of optimal observing capabilities. We finally conjecture the future plan of the research carried out in this thesis and its relevance to the solar physics research scenario.

