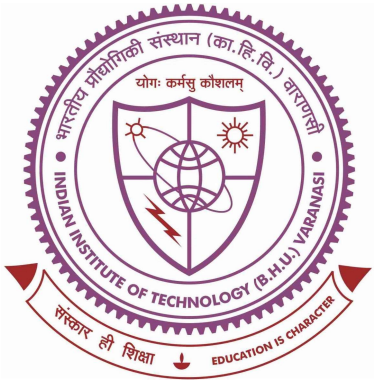
Study of Cool Jets and Evolution of Kelvin-Helmholtz Instability in the Solar Atmosphere



Thesis submitted in partial fulfillment for the Award of Degree

Doctor of Philosophy

by

Balveer Singh

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CERTIFICATE

It is certified that the work contained in the thesis titled **Study of Cool Jets and Evolution of Kelvin-Helmholtz Instability in the Solar Atmosphere** by **Mr. Balveer Singh** (Roll No. **17171020**), in partial fulfillment of the requirement for the award of the degree of Doctor of Philosophy at the **Indian Institute of Technology (B.H.U.), Varanasi** is a record of his own work carried out under my supervision and guidance and this work has not been submitted elsewhere for a degree.

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I, **Balveer Singh** (Roll No. **17171020**), certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of ***Dr.* Abhishek K. Srivastava** from July 2017 to August 2022 at the *Department of Physics*, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers whenever and wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any other's work, paragraphs, text, data, results, *etc.*, reported in journals, books, magazines, reports dissertations, thesis, *etc.*, or available at websites and have not included them in this thesis and have not cited as my own work.

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In the Honour

***o*f**

***M*y Loving Family**

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Department of Physics, IIT (BHU) **Balveer Singh**

Preface

Human nature has always been fascinated about ongoing events in the natural world. As a result of this curiosity, many things have been discovered, and mankind have been able to explain a variety of natural phenomena occurring around themselves and in their nearby space. This leads to the development of basic sciences, which in turn caused the growth of human civilization. The development in the basic science and its understanding is further translated into the relevant technological developments.

We know a lot about the cosmos from past research since it contains a millions of stars, planets, and other similar objects that form galaxies, and there are a millions of galaxies in the universe. Today, the technology have advanced to a point where we can now investigate far-flung parts of the universe (e.g., galaxies, Sun and Sun like stars, planets etc.) revealing a range of exotic physical processes at disparate spatio-temporal sizes and energy levels. In the frame-work of astronomy and astrophysics, technological and scientific advancements have provided more insight into the dynamics and formation of interstellar medium, nebula regions, galactic, active galactic nuclei (AGNs), black holes, supernovae, various types of stars, planets, and other massive energetic objects. These modern technologies have revealed that 99.99 percent of the particles in the universe are in the plasma state, which is always in motion. These accomplishments help us to advance many other area of research while also bringing in a wide range of new technologies to the mankind, such as detector technology and improved sensitive cameras, modern optics, cutting-edge software etc. With the appearance of telescopes a few millennia ago, the first object in the near by space, our parental star "The Sun," was explored in greater details. People's impression of the Sun is that it is a source of light and heat and supports our life on the Earth. Scientifically, It's estimated that the Sun is 4.2 billion years old, and it is a magnetically active young star that is in the middle of its life cycle. Furthermore, the Sun's conditions are so dynamic and

complicated that our intuition frequently fails to forecast their precise causes. As a result, many physical processes at the Sun were not predicted prior to their observation, and we continue to strive to comprehend them. These physical processes take place on spatial and temporal scales that are too enormous to investigate under terrestrial conditions, and they are too complex to numerically simulate. Our parent star has a vast spectrum of physical processes in its electrically conductive plasma with mass density and temperature varying by many orders of magnitude and spatial scales ranging from atomic to hundreds of Mm.

The Sun's complex magnetic structuring, which is formed by appropriate dynamo action, has been discovered to impact the dynamics of its numerous gaseous atmospheric layers (e.g., photosphere, chromosphere, transition layer, and outermost layer, corona). These complex/complicated motion of the particle fluid at the Sun are responsible for the formation of waves, small-scale transients, various eruptions, all electromagnetic radiation, and the emission of high-energetic particles that make up the Sun-Earth connection, heliospheric environment, and interplanetary magnetic fields. These ejected radiations, high energetic charged particles, explosive plasma eruptions, and supersonic flows enter into the Earth's upper atmosphere (e.g., ionosphere, magnetosphere) that are responsible for the powerful solar storms. These high potential solar storms have the ability to damage space satellites that we rely on for navigation and communication system. It can also cause possible threats to the space stations, astronauts, Earth's satellites as well as impair power networks that provide our electricity, air-travel, and communication. Therefore, these events/effects can be predicted by studying space weather candidates like eruptive prominences, coronal mass ejections, and solar flares. Recently, significant observational studies demonstrated that multiwavelength emissions from various parts of the Sun, reveal the dynamics of many small-scale transients/eruptive processes and their physical ramifications. As per modern technology, understanding the physical mechanism of such events

is required in order to apply rigid constraints to numerous transients/eruption models, allowing scientists to better understand and anticipate the mechanism of transients/eruptive processes and their spread in the heliosphere. As a result, these active stars, which have a hot plasma and a denser magnetized atmosphere, produce magnetic waves and explosive eruptions on a wide scale, which affect the weather in space. The relationship between the Sun and the Earth was established when such high-energy dynamical magnetic fields reconnected with planetary magnetic fields (e.g., Aurora etc.) and enter the high-energy particles and radiation in the Earth's atmosphere. However, not only the interplanetary space is influenced, but the Sun's strong magnetic fields affect cosmic bodies on both large as well as small scales. Therefore, Earth's magnetic fields habitable as a magnetic protection from the Sun's highly dynamic magnetic fields and high-energy radiation and particles.

The dynamics and characteristics of different layers differ greatly, making the Sun more fascinating. Its various atmospheric layers are complex in terms of magnetic and plasma structuring. The complex structure and highly dynamic nature of its atmosphere often limits our scientific ideas to predict the exact causes of energy and mass transport, and transient processes that take place in its atmosphere. As far as we know, the photosphere and chromosphere have temperatures ranging from 4300 K to 10000 K. The temperature abruptly increases as moves near the transition region, which is about a few hundreds kilometers thick, and reaches millions degrees Kelvin in the outermost layer i.e., corona. The large temperature difference between the photosphere and the corona violates the standard laws of thermodynamics, posing a challenge for cutting-edge researchers. This is the one of a big mystery for the solar scientists. Therefore, understanding of the physical processes for heating and mass transport may significantly contribute to the development in understanding the dynamics of the solar atmosphere, its connection to the heliosphere. Another key question in heliophysics is how solar wind originates and accelerates from

the solar atmosphere, which is addressed in this order. In the field of solar physics, this is likewise an unsolved problem.

The another fundamental question concerns how the mass cycle and its transformation with supersonic speed in the solar atmosphere is well established. These fundamental questions raise greater concerns for solar scientists for few decades. Despite the fact that there are two types of physical processes that deal with the aforementioned problems, one relating to direct current dissipation in the magnetic plasma known as magnetic reconnection and second is conveying energy in the form of an alternating current source associated with magnetic waves, none of them fully explain the aforementioned fundamental problems. These two mechanisms (magnetic waves and magnetic reconnection) helps to understand about all possible dynamical plasma processes in the Sun's atmosphere. These fundamental plasma processes also deals the energy and mass transport from photosphere to corona coupling various layers at disparate scales. Therefore, the small and large scale transients and eruptive processes and their association with planetary space, occur in the highly dynamic, and million-degree hot solar atmosphere reveled by the physical plasma processes which are based on the magnetic recconection and magnetic waves. The supply of mass and energy into the upper layer from the solar chromosphere via heat flow, solar winds, cool jets, spicules and other plasma ejecta maintained the energy balance in the solar atmosphere. The magnetic reconnection and various kind of MHD waves are fundamental processes that deals the localized atmospheric heating coupling various layers of the Sun's atmosphere.

Recently, various extensive high-resolution space-borne and ground based observatories (e.g., Solar and Hemispheric Observatory (SOHO), Interface Region Imaging Spectrograph (IRIS), Solar Dynamics Observatory (SDO) etc.) reveled transportation of mass and carry

energy which described the subsequent localized heating. The observations from these instruments also reveal that coronal holes have various flux tube-like structures anchored in the solar photosphere's strongly magnetic regions. Therefore, the plasma flows and jet like plasma ejecta also occur from the footpoint of these flux tube like structures in the solar atmosphere. Solar active regions, which have a high magnetic field and complicated plasma processes, also play an important role in localized heating. In the solar active regions, magnetic loop-like structures emerged at various scales, which is connected with localized heating via various plasma processes such as global energizing, p-mode leakage, Alfvén wave mode conversion etc. The active regions above sunspots, consist of hot plasma flows, diverse MHD waves and oscillations, shocks, and complicated plasma dynamics which may be triggered by the magnetic recconection. Another aspect of the locally plasma flows, waves and dissipation of magnetic topology occur in the solar atmosphere which are subsequently described the localized heating.

Although, for two decades, several high-resolution instruments (e.g., IRIS, SDO, SST, ROSA, 4m-DKIST, Solar Orbiter and Parker's Solar Probe etc.) have been already addressed a variety of small scale transient and wave processes and have ability to determine the various plasma properties of the Sun's atmopshere currently, yet the cutting-edge scientists and researchres developing more observational facilities (e.g., 4m-DKIST, 1m-SST at La Palma, 4m-EST, 2m-NLST, (upcoming) Solar Orbiter etc.) to anticipate deeply about these plasma processes at very fine scales in the solar atmosphere. In this series, Indian space agency (ISRO) is also developing the solar space mission, Aditya-L1, to contribute in the deep understanding about these small scale plasma processes at high cadence. Aditya-L1, carry the various instruments such as SUIT, etc to established the observations of the various plasma processes of the Sun's lower atmosphere at finer scales. Therefore, Aditya-L1 has substantial scientific goals in the frame-work of studying the

waves/ shocks/ magnetic reconnections/plasma flows, plasma ejection and their associated plasma processes which helps to understanding the localized coronal heating and mass transport. Therefore, the developing/upcoming solar missions will more capable to answer the fundamental problems such as coronal heating, origin of solar wind and its acceleration, and how the mass and energy transport into the upper region of solar atmosphere occur.

In analogy, it may also be very significant in understanding the various plasma processes at laboratory scale. In particular, several models were presented to understand localized plasma flows and ejecta such as solar jet, spicules, and their associated plasma dynamics that responsible for enforcing the energy and mass supply from the lower solar atmosphere to the inner corona is the main body of this thesis. In order to make numerical simulations and observations of solar chromospheric jets, associated waves, oscillations and instabilities give a better insight onto the problems of chromospheric/coronal heating, associated energy and mass transfer coupling the quiet solar atmosphere. The results of the scientific works included in this thesis, will help to explain the various plasma dynamics occurring in the solar atmosphere, and formulated theories for interpretation of the current as well as future solar observations (e.g., SST, ROSA, DKIST, EST, Indian NLST, Aditya-L1) that identify the main energy sources in the Sun's atmosphere. The complex structuring and highly dynamical nature of the Sun's atmosphere allows the triggering of various localized transient plasma processes (e.g., spicule-like jets, network jets, mottles, dynamic fibrils, surges etc). These spectacular plasma jets/flows could be responsible for transporting mass and energy in the overlying solar atmosphere. Such plasma jets may also be associated with various types of waves and oscillations, shocks, and instabilities. Understanding the formation, dynamics, and energetics of these solar jets are the front line scientific problem in the area of solar physics. For a complete comprehension of the mass and energy transport in the Sun's atmosphere, these solar jets must be understood

quantitatively using the models and observations.

Solar jets are high-velocity plasma ejections that are impulsive and collimated along the magnetic field lines in the Sun's atmosphere. Small-scale cool jets ($T<10^5$ Kelvin) and associated plasma dynamics have been detected in multiwavelength observations using various ground and space-borne observatories. Their physics can be understood in depth by performing the numerical modelling using theory of magnetohydrodynamics (MHD). In this thesis, we have described few extensive MHD models in ideal and non-ideal regime that demonstrate origin and evolution of these cool jets and associated plasma processes. Our findings are consistent with various observations of cool solar jets. These scientific findings are helpful in understanding the intricate relationship between plasma flows and complex structuring of magnetic field leading the evolution of various triggering processes of these jets in the solar atmosphere. This also provides clues of their significant role in energy and mass transport into the lower solar corona.

This thesis aims to provide the physical understanding of jet-like plasma features in the dynamic magnetic solar atmosphere. These cool jets are often triggered from the chromospheric layer and observed on the solar limb and also on the solar disk. These jets have been observed in both in the active and quiet regions of the Sun's atmosphere. These small scale spicule-like plasma motions have been recorded with a notion of their quasi-periodic rise and fall in the Sun's atmosphere at diverse spatio-temporal scales. The different incarnations of plasma are revealed in these jets. More-specifically, we address the formation of such spicule-like cool jets and associated plasma dynamics using 2-D and 2.5-D MHD modelling. The triggering mechanism (driver), dynamical evolution, kinematics, and energetics of such plasma ejecta in the solar atmosphere are the main theme of this thesis. While, all the chapters (Chapters 3-6) are basically related with the MHD model of

the jet evolution and its dynamical behaviour, the Chapter 7 demonstrates specifically the observations of a cool coronal jet possessing the Kelvin-Helmholtz Instability. The present thesis is organized in form of the following chapters:

Chapter 1: Introduction of the Sun and Its Atmosphere

In this chapter, we discuss a brief overview of the Sun and its different layers particularly both in its interior and exterior. We outline the Sun's localized magnetic field and the facts that how they relate to various transient plasma processes. We give a succinct overview of the solar jets 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 append the structure of the present thesis and its various chapters.

Chapter 2: Overview of the Observational Data, Analysis Techniques and Numerical Methodology

In this chapter, we briefly elucidate on various space-borne observatories and onboard instruments whose data were used to study the solar cool jets at diverse spatio-temporal scale as outlined in Chapter 5 and 7. We also discuss data calibration tools and analysis techniques. At the end, we describe the numerical simulation method and techniques used in the modeling of these cool jets.

Chapter 3: Spicule-like Cool Jets Driven by Alfvén Pulses in the Solar Atmosphere

In this chapter, we have discussed the detailed mechanism of the formation of spicule-like cool jets driven by Alfvén pulses using 2.5D ideal MHD simulation. These spicule-like cool jets are triggered in the solar atmosphere by initial implementation of multiple transverse velocity pulses in the z-direction (i.e. V_z), which mimic the Alfvén pulses. We found that if the transverse velocity pulses have a large enough amplitude (50–90 km s^{-1}), they

produce field-aligned magnetoacoustic perturbations in the solar chromosphere through Ponderomotive force, which is later responsible for the formation of spicule-like cool jets. The Alfvén pulses were implemented at chromospheric heights between 1.5 and 2.0 Mm. The evolution, kinematics, and energetics of these spicule-like jets are investigated. We found that transported massflux and kinetic energy density are significant to fulfill the localized coronal losses. These mass motions cause *in-situ* quasi-periodic oscillations of the period of 4.0 min in the transition region.

Chapter 4: Kinematics and Evolutionary Properties of Impulsive Jets Driven by Pressure Pulse in the Solar Atmosphere

In this chapter, we have discussed the kinematics and evolutionary properties of impulsive cool jets in the Sun's atmosphere using 2-D numerical simulation at two different magnetic field strengths (B=56 gauss and B=112 gauss) of the quiet-Sun. These cool jets originate due to pressure pulses implemented at the chromospheric height (1.8 Mm), which mimics the after-effects of the localized heating in the solar chromosphere. We studied the parametric behaviour of these cool jets in the gravitationally stratified model atmosphere with realistic temperature model. This model suggests that pressure pulse is sufficient to produce the required perturbations in the middle chromosphere to launch the cool jets in the solar atmosphere.

Chapter 5: Impulsive Origin of Spicule-like Jets in the Solar Atmosphere

In this chapter, we studied the impulsive origin of cool jets which is previously observed by Chen et al. (2019) using high-resolution spectroscopic observation of the coronal hole in Si IV 1393.755 Å line recorded from Interface Region Imaging Spectrograph (IRIS) on 8th October 2013. The non-Gaussian line profiles show unusual line broadening, which correspond to the plasma velocity enhancement. We revisit the observations of Chen

et al. (2019) with a new method of spectral fitting, and analyze a specific event associated with a cool jet. The non-Gaussian profiles in the Si IV 1393.755 Å line, for a lifetime of 3.0 min and Doppler shifts reaching 68 km s^{-1}, is associated with a spicule-like jet of length 8.0 Mm. We model this jet by implementing the observed velocity enhancement in a magnetized and gravitationally-stratified solar atmosphere. The velocity perturbation of 68 km s^{-1}, resembling the observed velocity enhancement, launches a thin spicule-like jet whose properties closely match with the observed jet. We also show that non-adiabatic conditions (e.g., thermal-conduction and radiative-cooling) affect the jet propagation, mass flux, and kinetic energy density. We found that these jets transport mass and energy into the overlying atmosphere. It also demonstrates that the cooling atmosphere affects the kinematics and energetics of the jets.

Chapter 6: Decaying Kink Oscillations in the Fine-structured Cool Solar Jets

In this chapter, we perform a 2-D magnetohydrodynamic (MHD) simulations that provide a detailed picture of the evolution of cool jets caused by initial vertical velocity perturbations in the solar chromosphere. We implement random multiple velocity (V_y) pulses of amplitude 20-50 km s^{-1} between 1.5 and 2.0 Mm in the solar atmosphere below the transition region (TR), which subject to the different switch-off period for the phase of the perturbations between 50-300 s. These applied vertical velocity pulses create series of magnetoacoustic shocks steepening above TR, and interacting with each other in the inner corona leading a complex localized velocity fields. The propagation of such perturbations create low-pressure regions behind and generate a variety of cool jets and plasma motions. We aim to study the oscillations of two cool jets J_1 and J_2 that move upto the height respectively 6.2 Mm and 5.4 Mm above TR. These jets are fine-structured radially in density and Alfvén speed. The highly dense J_1, which triggered along the significantly curved magnetic field lines, support the propagating transverse kink waves of period ≈195 at a

speed of $\approx$ 125 km s^{-1}. In the case of J_2, the evolved collective kink oscillations no longer sustain beyond its one cycle, and dissipated quickly. At the later stage, instead of collective oscillations of jet's spine, its outer surface possesses transverse oscillations locally without significantly perturbing the inner core of the jet. The different fine structures of the jet's spine oscillate locally in a transverse manner especially near the surface. We describe that the radial structuring of density and characteristic Alfvén speed within J_1 and J_2, as well as the curvature of the magnetic field cause onset of the resonant conversion and leakage of the wave-energy outward to dissipate these transverse oscillations.

Chapter 7: Kelvin–Helmholtz Instability in the Cool Plasma Jet in the Solar Atmosphere

In this chapter, we have studied the development of the Kelvin–Helmholtz (K–H) instability in the jet-like cool plasma ejection using EUV observations taken from SDO/AIA instrument on 2015 March 10. This plasma ejection resembles a jet-like flow and is located close to an active region (AR 12279) with a fan-spine structure rooted in a nearby sunspot. We found that this fan-spine configuration contains both cool and hot plasma simultaneously. However, we emphasize here the dynamics of the cool plasma component of the jet. The magnetic configuration consists of two layers of cool plasma, which flow in parallel and interact with one another inside the extended spine. The impulsive plasma flows upward with a speed of 114-144 km s^{-1} from below and interact with the slower plasma flow (5 km s^{-1}) that is the reflected stream along the spine's field lines from the top. This process causes a shear motion around the outer spines, which then causes the K-H instability to evolve and seen in comparatively cooler plasma. We also show the cause of the velocity difference between two layers. The velocity of K-H unstable vortices, are greater than the Alfvén speed in the second denser layer, satisfying the criterion of K-H instability growth. Our finding suggests that the fan-spine topology may rapidly heat up in

the presence of complex structuring of magnetic field and plasma flows.

Chapter 8: Conclusions and Future Plan

In this chapter, we focus on the summary of scientific works presented throughout this Ph.D. thesis. In the conclusion, we summarize our results and provide some valuable remarks for future observational capabilities from the current/upcoming national and international space and ground based observatories and their various instruments (e.g., IRIS, SDO, Solar Orbiter, upcoming Aditya-L1, Solar-C, SST, ROSA, DKIST, EST, upcoming Indian NLST etc), and model simulations supporting the novel observational findings. Our findings will be utilized to explain the physics of cool jets in the Sun's atmosphere, as well as to provide a theoretical foundation for interpreting present and future solar observations. It will also help in understanding the mechanisms of the primary energy sources and mass transport as well as the fundamental physical processes (e.g., waves, instabilities, confined flows, etc) in the localized solar atmosphere.

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Nomenclature of Symbols

$R_\odot$	Radius of the Sun
$M_\odot$	Mass of the Sun
ρ	Mass density
$L_\odot$	Radiation Luminosity of the Sun
g	Solar gravity
K_B	Stefan-Boltzmann constant
κ	Opacity
n	Number density
v_A	Alfvén velocity
v_s	sound speed
p	plasma pressure
β	plasma beta
η	Magnetic diffusivity
k	Wave vector
θ	Angle between the magnetic field (B) and wave vector
A	Atwood number
R_m	Reynolds number
R_i	Temperature response
γ_{Obs}	Observed growth rate
γ_{Th}	Theoretical growth rate
λ	Characteristic wavelength of the KH instability