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

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2022

Chapter 8

Conclusions and Future plan

In this chapter, we briefly describe the summary and conclusions of various scientific works presented in this thesis. We also outline the future prospects of these scientific works.

8.1 Summary and Conclusions

The present thesis has presented extensively the modelling of the spicule-like cool solar jets ($T<10^5$ K) and associated plasma dynamics. The main aim of the present thesis is to model these cool plasma ejecta in MHD regime in the realistic solar atmosphere with appropriate temperature profile. Various cool jets are driven by different velocity and pressure pulses applied in the solar chromosphere. Our models clearly describe the origin, formation and evolution of cool solar jets (Chapter 3-6). Moreover, we understand the kinematics and energetics of such cool jets in the two dimensional magnetized solar atmosphere (Chapter 3-5), as well as their oscillatory properties (Chapter 6). Our MHD models are also motivated with various observations (e.g., IRIS) of cool solar jets (Chapter 5). Some of these scientific findings are helpful in understanding the relationship between plasma flows and complex structuring and strength of the magnetic field leading to the evolution of perturbations/processes triggering of these jets in the solar atmosphere (cf., Chapter 4). This also provides clues about their significant role in energy flux and mass transport into the lower solar corona (cf., Chapter 3, 5). The Chapters provides a unique observations of the evolution of Kelvin-Helmholtz instability evident in cool component (AIA 304 Å) of the plasma moving in form of a coronal jet in fan-spine topology.

More-specifically, Chapter 3 described a detailed mechanism about the origin of spicule-like cool jets in the ideal regime of solar plasma, due to the Alfvén pulses implemented in the chromosphere. The applied Alfvén pulses in form of velocity driver V_z influence plasma system in the chromosphere in the frame-work of 2.5-D numerical simulation, which allow the evolution of the field aligned perturbations in upward direction. This further launches the magnetoacoustic shocks and vertical flows due to the ponderomotive force and eventually the spicule-like jets along the open expanding magnetic field lines. This is a novel example of the formation of the spicule-like jets and associated their quasi-periodic rise and fall as evident in the observations (e.g., Khutsishvili et al., 2014; Samanta et al., 2015). These quasi-periodic oscillations of the solar transition region at a time-scale of 4.0 min due to continuous rise and fall of jets are well evident in model atmosphere. Such cool jets are capable of transporting the mass and energy into the transition region and corona.

On the other hand, the Chapter 4 described formation of cool-jets due to the pressure pulses at two different strength of quiet-Sun magnetic field. This further suggests that pressure pulses deposit sufficient energy in the chromosphere to launch the cool jets. Our results clearly describe that pressure-pulse driven cool solar jets. The pressure perturbations in the model atmosphere may represent the after effects of the localized heating at the jet footpoint in the solar chromosphere. These perturbations successfully launch the cool jet in the solar atmosphere. Later on, these perturbations are transformed into the magneto-acoustic shocks that propagate in the vertical direction along the magnetic field lines in the solar atmosphere. In this case, the low-pressure region is created below the shock front that lead the motion of cool plasma along the magnetic field lines and subsequently forming the jets. The detailed kinematics of such jets are studied in this chapter.

Ahead of this thesis, the Chapter 5 outlined basically a numerical model of spicule-like cool jets in the non-ideal regime of the solar plasma including the thermal conduction and radiative losses. Such jets are previously reported by Chen et al. (2019) using the observations of the coronal hole in Si IV 1393.755 Å line profile and SJI Si IV 1330 image data. The observational scenario of these jets shows the localized impulsive energy release at their footpoints as a main cause of their formation. Such energy release further caused the velocity enhancement that is recorded in Si IV 1393.775 Å spectra. We model such an observed event (i.e., cool jet) in the adiabatic (ideal) and non-adiabatic (non-ideal) model solar atmosphere by implementing an observed velocity enhancement (i.e., vertical velocity perturbations of 68 km s^{-1}). This perturbation launches the thin spicule-like cool jet in the solar atmosphere very similar to the one observed by IRIS. Our results show that the non-ideal processes such as thermal-conduction, radiative-cooling, and combined effect of both, affect the jet propagation, its mass flux, and kinetic energy density. We also found that transported massflux and kinetic energy density during the evolution of the jet are significant to fulfill the localized coronal losses.

Later, Chapter 6 reported the kink oscillations in the cool jets triggered due to the effect of multiple vertical velocity pulses applied in the solar chromosphere around the null point structuring of the magnetic field. In the simulation of these oscillating jets, the fine-structuring in the mass density is developed across the jet. Other physical properties (e.g., magnetic field, Alfvén speed etc) are also structured across the modeled jets. The transverse kink oscillations are evolved in these jets, which show the damping. The curvature in the magnetic field of jet's spine and radial structuring of the plasma, magnetic field, and characteristic speeds may likely cause the dissipation of kink waves.

At the end, Chapter 7 elucidated the observations of Kelvin-Helmholtz instability in the cool counterpart of a jet-like structure using multi-wavelength EUV observations taken from SDO/AIA. These results clearly show that multithermal plasma started lifting up as a jet-like structure from the fan plane in the corona, and interact within the ambient hot elongated spine. The K-H vortices are formed due to a significant velocity difference in two layers of the jet-like plasma ejection, which is clearly evident in AIA 304 Å passband representing a competitively cooler plasma. Our results provide on observational evidence of the evolution of K-H instability in the cool counterpart of the jet-like structure evolved in the magnetic the fan-spine topology in localized corona. The present work is an unique example of the complex plasma motions in the localized magnetically active solar atmosphere that generates K-H instability. The observations clearly demonstrate on evolution on the linear phase of the K-H instability and its stability phase in corona. Such plasma processes (e.g., K-H instability) are also well observed and modelled in a variety of chromospheric cool jets at a diverse spatio-temporal scales, and are one of the most prominent research topic in the solar physics.

8.2 Future Plans

Solar chromospheric jets are the spectacular plasma ejecta that supposed to transport mass and energy in the overlying solar atmosphere. Understanding their driving mechanism, and physical properties are at the forefront of solar research.

The data-driven numerical modelling of these plasma ejecta vis-á-vis ultra-high resolution observations will provide a better understanding of their drivers and plasma dynamics with next generation telescopes (e.g., 1-m Swedish Solar Telescope (SST), 4-m Daniel K. Inouye Solar Telescope (DKIST), upcoming 4-m European Solar Telescope (EST), 2-m Indian National Large Solar Telescope (NLST) etc). Numerical simulation will be utilised to add new physical insight to the investigations of find-structured chromospheric plasma dynamics and their response in the solar corona. The following course of actions in future will shed new lights on the physics of various cool chromospheric jets.

- The detailed numerical simulations will be made with an appropriate comparison of upcoming high-resolution observations of the cool jets and associated plasma dynamics.

- The appropriate magnetic structuring of the different regions of solar atmosphere such as active-Sun/sunspots, coronal hole, and quiet-Sun network, enhance the better understanding about the modelling of chromospheric dynamical processes, such as cool jet like motions and waves/instabilities processes theirin.

- The stringent 3-D numerical simulations will help in understanding the various physical processes, waves and plasma motions in such jets at diverse spatio-temporal scales and their underlying physical conditions. This will also enhance our existing knowledge about understanding the mass and energy transport by these jets into the overlying solar atmosphere.

- The cool spicule-like jets are subjected to various waves, oscillations, and instabilities. Therefore, the high-resolution spectroscopic/spectropolarimetric and imaging observations will provide new clues to numerically model these dynamical processes in jets.

- The solar chromosphere consists of ions, electrons and neutrals. Therefore, the single fluid MHD regime which only considers the ion, may not fully explain the dynamics, energatics, and plasma evolution in the cool chromospheric jets. Therefore, the two fluid model can provide additional physics (e.g., ion-neutral collision, ambipolar diffusion etc) to better understand the physics of such jets. Also, multiple species affect the radiative heating/cooling terms and opacity of the solar chromosphere, therefore, these effects may play the significant role in the formation of jets and various associated physical processes (e.g., waves and instabilities).

In conclusion, the high-resolution observations of the complex magnetic field structuring with the embedded mass motions will provide information about various ongoing physical processes coupling the different layers of the Sun's atmosphere. The multi-wavelength observations will enhance the knowledge about a variety of jet-like plasma flows, associated waves and oscillations, instabilities, at diverse spatial and temporal scales. The presented MHD models will provide a ready reference to further combine the high-resolution and high cadence observational data to their refined numerical models, to better understand the dynamics of solar chromosphere and their response in the overlying TR and corona. Our original scientific works presented in this thesis will serve as a ready reference to the current and future observations with cutting-edge solar observatories (e.g., IRIS, SDO, Solar Orbiter, Aditya-L1, Solar-C, SST, ROSA, DKIST, EST, NLST etc).