Chapter 8

Conclusion and Future Works

8.1 Summary and Conclusions

In this thesis, we have presented the peculiar dynamical behavior of the eruptive solar prominences using multiwavelength imaging observations from SDO, STEREO, and supporting ground-based observatory (BBSO Hα). This thesis addresses some important physical aspects related to the dynamics of solar prominence. It deals with the dynamics of the variety of solar prominences that are evolved internally and externally, and their response into the outer corona and interplanetary space. The high resolution and high cadence images obtained from the spacecrafts (e.g., SDO, STEREO) provide an opportunity to estimate the density and magnetic field on small and highly dynamic structures of sufficiently dense and ionized (or neutral) solar prominences. We have explored the internal and external dynamics of the different types of solar prominences (e.g., active-region, quiescent, and polar) that show distinct types of dynamics due to their relative strength of the magnetic fields. In Chapter 3, we provided the first observational evidence of the internal dynamics of MRT unstable plumes and hybrid KH-RT instability in a loop-like solar prominence. Chapter 4 explored the internal and external dynamical behavior of an eruptive polar prominence in terms of magnetic reconnection in the solar corona.

Chapter 5 described a novel physical scenario for the first observational evidence of forced magnetic reconnection in the solar corona, where plasma dynamics and reconnection are forced externally by a moving prominence. In Chapter 6, we discussed the evolution of MRT instability from outer corona to the interplanetary space in an active region eruptive prominence. Finally, Chapter 7 showed the linkage of the geoeffective stealth CMEs associated with the eruption of a filament-like coronal plasma channel (CPC) and a jet-like structure. These scientific findings are concluded below in the perspective of their physical significance. Based on these novel scientific findings, the future works are also discussed in Section 8.2.

High-resolution imaging observations obtained from different ground-based observatories and spacecraft revealed that the solar prominences possess marvelous dynamics such as MHD instabilities (e.g., gravity-driven and current-driven instability), internal dynamics, oscillations, counter-streaming flow, and turbulent dynamics, etc on the different spatio-temporal scales in the solar atmosphere. Recent observations conclude that gravity-driven instabilities (e.g., RT, MRT, KH instability) have been evolved in the solar prominences. The first observational evidence of the evolution of plumes in solar prominence was investigated by Stellmacher and Wiehr (1973) that was found to be Rayleigh-Taylor unstable (Ryutova et al., 2010). High-resolution HINODE/SOT observations of hedgerow prominences revealed the two new modes of Rayleigh-Taylor instability (i.e., multimode and single-mode plumes; (Ryutova et al., 2010)). The dark, hot, and turbulent upflows known as plumes were found to be Rayleigh-Taylor unstable (Berger et al., 2008, 2010; Ryutova et al., 2010). These plumes are 20-125 times hotter than the surrounding prominence and trigger from the prominence-cavity interface. The prominence-cavity interface supports the magneto-thermal convection process, which acts as a buoyancy to launch the plumes (Berger et al., 2011). The concept of hybrid instabilities in the astrophysical plasma is new. Berger et al. (2017) provides the first observational evidence of hybrid KH-RT instability evolved at the interface of prominence and cavity. The observational growth rate estimation is a very complicated process as the linear stage of the instability ends when the width of the plumes is equal to its height (Hillier, 2018; Ryutova et al., 2010). In chapter 3, using high-resolution EUV images obtained from the SDO/AIA provides an opportunity to observe the sequential development of magnetic Rayleigh-Taylor unstable plumes in its linear phase (i.e., multimode plumes), nonlinear phase (i.e., single-mode plumes), and stability phase (i.e., the formation of vortex-like rolled plasma structure at the prominence-cavity interface) in the lower corona. However, even after the full development of MRT instability (i.e., linear, nonlinear, and stability phase), the overlying prominence has not erupted. We have estimated the observational growth rate by tracking the height of plumes of ten different locations and times, which shows lesser errors as compared to the previous results (Hillier, 2018; Ryutova et al., 2010). **Vickers et al. (2020) have used our estimated observational growth rate to derive the dispersion relation for a given time in terms of magnetic field inclination and propagation direction. Therefore, in the future, the present observation will also be useful to provide a deep understanding of the theoretical and numerical modeling aspects of the magnetic Rayleigh-Taylor instability.** The estimated observational growth rate and the theoretical growth rate are consistent with each other. Later, an MRT unstable tangled thread propagates through the rising segment of the prominence and causes for peculiar dynamics such as shearing, vortex formation, fixation of plasma, MRT unstable bubbles formation, and propagation, and their merging at the prominence-cavity interface. It is also responsible for the onset of hybrid KH-RT instability and eruption of the prominence. Therefore, we conclude that hybrid KH-RT instability is more energetic than the normal MRT instability, which triggers the prominence eruption.

The tornado-like motion in prominences is evolved via two mechanisms i.e., the apparent rotational motion of the helical flux-rope (Li et al., 2012; Panesar et al., 2013; Pant et al., 2018; Su et al., 2012; Yang et al., 2018), and oscillation or counter-streaming flows in the prominence spines or barbs (Levens et al., 2016a,b; Panasenco et al., 2014; Su et al., 2014). The apparent rotating motion of the prominence barbs acts as a channel to transfer the cool plasma and shearing in the overlying prominence (Su et al., 2014). In chapter 4, we have explored the detailed internal and external dynamics of polar prominence before and after the eruption. Several internal dynamics such as large-scale vortex motion, swirl-like notion, tornadoes-like motion horns, cavity, etc. appear during the evolution of prominence. This polar prominence is evolved due to the apparent rotating motion of prominence legs. The slow shearing motion at the footpoint twists the prominence legs oppositely and responsible for the two-stage of magnetic reconnection (Kusano et al., 2002, 2004; Nemati et al., 2015) above the polarity inversion line (PIL). The first stage of the reconnection is governed by the tearing mode instability, which triggers multiple plasmoid ejection along the elongated current sheet within the prominence. The estimated reconnection rate $(0.05-0.2)$ is consistent with the Petscheck-type reconnection. The ejected plasmoid is destroyed the current sheet and responsible for the collapse of multiple magnetic arcades near the X-point. The external reconnection is initiated by the reconnection between collapsing magnetic arcades and overlying prominence, which leads to the eruption of the prominence.

In the solar corona there exist two possibilities of magnetic reconnection, i.e., ”spontaneous reconnection” and ”forced reconnection”. The observational and theoretical aspects of the spontaneous reconnection is well developed in the solar corona (Baty, 2000; Furth et al., 1973, 1963; Innes et al., 1997; Masuda et al., 1994; Petschek, 1964; Schmieder et al., 2013; Shibata et al., 1995; Shibata and Tanuma, 2001; Sterling et al., 2015; Su et al., 2013; Sweet, 1958; Tian et al., 2014; Xue et al., 2016). However, the forced reconnection, which was introduced theoretically for the first time by Hahm and Kulsrud (1985) have no direct observational evidence in the astrophysical plasma. However, the theoretical and modeling aspects of the forced magnetic reconnection is remarkably developed (Birn et al., 2005; Jain et al., 2005; Potter et al., 2019; Vekstein, 2017; Vekstein and Jain, 1998). Chapter 5 provides the first detailed observational detection of the forced magnetic reconnection in the large-scale solar corona, and thereafter the data-driven numerical modeling of its physical properties. An eruptive prominence associated coronal field lines expand and forced a reconnection with the overlying coronal field lines. A temporary X-point has formed in the solar corona, where the plasma dynamics is governed by the moving prominence acting as an external driver for the reconnection. Near the X-point, the prominence-driven magnetic field lines come first with constant speed, followed by the inflows, and the outflow is occurred along and perpendicular to an elongated current sheet. Using the ratio of inflow and outflow, the estimated reconnection rate was found to be $0.15-0.27$, which indicates that the reconnection may happen with the high rate even when the natural diffusion is not dominant. The unique observational finding is supported by the numerical MHD model of the forced reconnection. This work opens a new insight that all the transient events that are subjected to the reconnection may be verified in the light of forced reconnection. Moreover, the role of the forced reconnection in the coronal heating must be quantified in greater details.

The active region prominences are the most dynamic, violent, and short-lived. Therefore the observational evidence of magnetic Rayleigh-Taylor instability is rare for the active region prominences (Berger, 2014; Hillier, 2018). Innes et al. (2012) used high-resolution images of SDO/AIA to investigate the fragmented active region eruptive prominence and found that during the breakup and downfall of the plasma several MRT unstable morphological structures like fingers, horns, spikes, etc. are evident. The downfalling of plasma bubbles is also subjected to Rayleigh-Taylor instability (Carlyle et al., 2014). In chapter 6, we have discussed the first observational evidence of the evolution of magnetic Rayleigh-Taylor instability from lower corona to the interplanetary space. We have used STEREO-A&B to observe the sequential development of MRT instability from their linear phase, nonlinear phase, turbulent phase, and their effect when they interact with the Earth's atmosphere. Different MRT unstable morphological structures are evident (e.g., finger-like structures in linear phase in the intermediate corona→ mushroom-like structures in nonlinear phase in the outer corona→ plasma spikes due to turbulent mixing in the interplanetary space) depending upon the local plasma conditions and continuously decrement in the magnetic field with height in the solar atmosphere. Using linear stability theory, we have also probed the required magnetic field to suppress the MRT instability upto $4R_{\odot}$ in the solar prominence, which is consistent with the previously reported results. We have also found firstly evidence that the MRT unstable and growing chunks of the prominence propagate in the interplanetary space and impinged on the Earth in form of plasma spikes, and there was a clear signature of their interaction with Earth as seen in heliospheric imager (HI-2) onboard STEREO. Although, we could not establish their role that whether they could generate geoeffectiveness at Earth or not, however, in the coming time in future such plasma spikes (which could act as a new but episodic space weather candidates) may get some attention in the context of Geoeffectiveness and space weather at Earth's outer atmosphere. We leave this topic for the future research of the space weather community though. In conclusion, the present work enhanced our understanding of the evolution of MRT instability and its different phases in an eruptive prominence from inner to the outer corona.

The large-scale eruptions of the solar prominence/flux-ropes are associated with the coronal mass ejections (CMEs) that may be responsible for the space weather activities when they interact with the Earth's atmosphere. In chapter 7, we understand the dynamical behavior of the filament channel and their association with a geoeffective stealth CME. We explore the linkage of geoeffective stealth CMEs, which is associated with an eruption of filament associated Coronal Plasma Channel (CPC). The CPC is similar to the filament channel, which contains hot coronal plasma and does not carry cool prominence plasma. It may be observed in terms of confined magnetic field lines. Initially, the CPC erupts with a very low coronal signature in the lower corona. However, the spreading of the CPC and post-eruption arcade indicate that an eruption may have occurred from this region. Later, above the spreading CPC, a thin flux rope evolves and erupted with a very faint signature in the lower corona. The spreading CPC interacts with a coronal hole, which is responsible for the triggering of a rotating jet-like structure. These three eruptions are associated with the stealth type CMEs and a rotating jet-like CME. The compound CME interacts with the Earth's atmosphere and responsible for the third intense geomagnetic storm of the solar cycle 24 with Dst index=-176 nT, Kp index=7, and [B_z]=18. In this chapter, we set an argument that geoeffective CMEs may also arise due to the complex and multiple eruptions in the solar corona.

These results give us new insights to understand the dynamical nature of the prominences/filaments in terms of instabilities, reconnection, and their responses from lower corona to the interplanetary space. We have conducted the detailed observational analysis of different types of prominence, associated dynamics, and their association with other eruptive phenomena and space weather candidates. However, there are still many questions remain that need to be addressed in future to understand the physics behind the formation, magnetic stabilization, destabilization, magnetic field, internal dynamics, as well as eruption of the prominences. Some of the outstanding problems and cutting edge issues that I would like to continue in my future research work are listed below.

8.2 Future Plans of Various Scientific Works

Depending upon my previous research in this thesis, I propose my future plans that explore refinements in our understanding about the prominence/filaments formation and their eruptions. I will study in greater details about the MHD instabilities and hybrid instabilities at different spatio-temporal scales in the solar atmosphere in prominence as well as in the normal coronal plasma. I will also advance the newly established aspect related to the observations of the forced reconnection in the solar corona in different explosive and eruptive events, and shed new lights on its various physical scenario. I will use high resolution observations from space-borne satellites such as IRIS, SDO, Solar Orbiter, upcoming Aditya-L1, and contemporary ground-based observatories like 4-m Daniel K. Inouye Solar Telescope (DKIST), 1-m Swedish Solar Telescope (SST), upcoming 2-m Indian National Large Solar Telescope (NLST), 4-m European Solar Telescope (EST) to understand the fine-scale internal dynamics of the solar prominences and their magnetic structures. Some details of my future works are briefly described below:

(1) MHD Instabilities and Hybrid Instabilities

Solar prominences show specific dynamical behavior in terms of turbulent motions, gravity-driven instabilities (e.g., RT, KH, etc,), MHD instabilities (e.g., Kink, Sausage, etc.,) and hybrid instabilities (e.g., KH-RT, Kink-RT, etc.,) at different Spatio-temporal scales in the solar atmosphere. Understanding of these instabilities will enhance our knowledge about the prominence formation (e.g., thermal instability), associated internal dynamics and changes, and their role in the onset of the solar eruptions. These instabilities can be used as a tool to diagnose the internal plasma dynamics and magnetic structures of the prominence and solar coronal structures. The observations of instabilities, specifically the hybrid instabilities in the solar atmosphere, is very least explored. However, the hybrid instabilities are more energetic and explosive than the normal instabilities. High-resolution observations from space (e.g., Solar Orbiter, SDO, IRIS) and ground (e.g., 4m-DKIST, 1m-SST) along with other space and ground-based observations will be used to understand the MHD instabilities and internal dynamics of the prominence, as well as their initiation and evolution. It will enhance our knowledge about the formation and prominence eruption.

I will also conduct data-driven numerical MHD simulations (MPI - Adaptive Mesh Refinement – Versatile Advection Code) for different types of instabilities to understand their formation and eruption. The archival data will be used, and the observational campaigns will also be conducted by me in order to obtain the required observational sequences and related high-resolution data. The observational results will also be used to initialize the stringent MHD simulations, and new scientific results will be derived combining both the observations and modeling.

(2) Formation of Prominences/Filaments and Their Magnetic Stabilization

I will also focus on the study of the formation and stabilization of the prominence in the solar atmosphere. The structural component of the prominence (e.g., barbs, spine, filament channel, etc.) will be studied to constrain and diagnose the local plasma conditions and magnetic field geometry. Space-borne instruments (e.g., SDO, Hinode, IRIS, Solar Orbiter, etc) and contemporary ground-based observation (e.g., 4m-DKIST imaging and spectropolarimetric observations, etc.) will be used with advanced observational analysis techniques, to study the dynamical behavior of the prominence plasma and their formation. The multi-wavelength observational study will be pursued for their dynamics and appearance in EUV filters from the lower solar atmosphere to the corona. The observational study will also be pursued to understand the initiation and formation of the prominence barbs and condensation of cool and dense plasma in the magnetic dip. The prominence magnetic structure (e.g, barbs, spine, threads, etc) and cool and dense plasma accumulation will be studied by observing the magnetic field behavior near to polarity inversion line (PIL) and foot-points of the prominence. Using the 2D NLTE radiative transfer code of MPI-AMRVAC and IRIS spectroscopic analysis along with 4m-DKIST spectropolarimetric and imaging observations from the ground, we will provide a tool to diagnose the mass motion, prominence parameter, and formation and stability of the prominence. MPI-AMRVAC has the capacity to model a 3D single thread. The modeling of 3D prominence thread will provide the information about the morphology and distribution of solar prominence. High-resolution DKIST Cryogenic Near-IR Spectro-Polarimeter (DKIST Cryo-NIRSP) will provide an opportunity to understand the orientation and structuring of the prominence threads and barbs. High-resolution and high-cadence vector magnetograms (e.g., SDO/HMI) will be useful to understand the dynamical changes that occur with large-scale eruptions (e.g., prominence, flares, CMEs). Contemporary, future Indian mission ADITYA-L1 and its Solar Ultraviolet Imaging Telescope (SUIT) will be useful to understand the formation and the magnetic structure of prominence and their relationship with the birth of Coronal Mass Ejection using Visible Emission Line Coronagraph (VELC). The high-resolution fine-scale prominence dynamics will also be studied by upcoming 2m-National Large Solar Telescope (NLST) at Hanle, and Multi-Application Solar Telescope (MAST) at Udaipur Solar Observatory in India. My planned future work on this important topic will not only provide the new scientific information about the prominence formation and their stabilization, but it will also utilize Indian and international state-of-art observational facilities to facilitate the scientific works.

(3) Observations of Forced Magnetic Reconnection in the Solar Corona

Direct observational evidence of forced magnetic reconnection in the large-scale solar corona is recently reported for the first time in the solar corona. Basically, there exist two possibilities for current-sheet formation during the magnetic reconnection, i.e., ”free or spontaneous reconnection” and ”forced reconnection”. In the spontaneous reconnection, some MHD instabilities are responsible for the current-sheet formation. However, some current-sheet has appeared in the MHD stable equilibrium system. Such current-sheets are formed due to the forced reconnection in the solar corona. Some external drivers or perturbations force the system to reconnect and form an elongated current-sheet. The forced reconnection is initiated by some external eruptions, displacement in the photospheric foot-points, and newly emerging flux, etc. We will explore the possibilities of solar eruptions like flares and coronal mass ejections and small-scale explosive events caused by the forced reconnection in the solar atmosphere. The high-resolution observations will be used to observe the dynamics of the small-scale current sheets in order to constrain the quantitative estimations of their dynamics and to reveal the physical scenario of the forced reconnection.

In conclusion, I will combine the high-resolution observations from space and ground-based instruments as well as stringent numerical models in my future works to understand the prominence formation, their internal dynamics and eruption. My upcoming research works will provide state-of-art scientific results as well as knowledge resources to the national and international solar physics community. Moreover, my scientific works performed in my doctoral research as well as planned future works will collectively act as a ready reference for the scientific objectives of different existing and upcoming observatories both at national and international levels.