Preface

The presence of flows carries a basic signature of any dynamic system, and it provides the clue to unraveling the ongoing physical processes there. Therefore, the study of flows is of universal importance, which holds the key to the inference of physical parameters and underlying physical conditions in any dynamic scenario either in day-to-day life such as different kinds of machines and technology, or planetary, interplanetary, solar and stellar atmospheres, laboratory and cosmic plasmas. The 99.9% of the matter in the universe remains in the plasma state, where the flows at diverse spatio-temporal scales constitute multitude of dynamics and energetic processes. A few novel examples at the larger dimensions are the outflows from the star forming regions, flows of the solar and stellar winds, the accretion flows and relativistic jets associated with active galactic nuclei (AGNs), shock related flows due to supernova explosions, etc. There are many more such examples that basically constitute a variety of exotic physical processes existing in the universe. However, when we look at a more confined dimensions in space, we also find the intriguing role of the energetic plasma flows. The circulation of ionized fluids inside the interior of the star (e.g., our Sun) generates and transports its magnetic fields. This is not only responsible for constituting a hot and magnetized atmosphere of such a magnetically active star, but also provides a platform for violent eruptions, magnetic waves, and emission of high-energy particles and radiation constituting the heliospheric environment, interplanetary magnetic fields, and space weather (e.g., Sun-Earth connection). Large-scale dynamic magnetic reconnection and flows of the stream of energetic particles also determine the shape of the planetary magnetosphere and secondary energetic plasma processes (e.g., Auroral dynamics and emissions), and in case of Earth it is one of the outer enveloping atmospheres along with ionosphere to keep it a habitable planet by providing a magnetic shielding from high energy particles and radiation.

When human crossed their confinements and saw the outer space in their surroundings, the Sun was the first observable in their close proximity as a cosmic laboratory emitting entire electromagnetic radiation and energetic particles from its atmosphere. It is a magnetically active star whose outer atmosphere is magnetized as well as maintained at million-degree Kelvin temperature. A major outstanding question still remains as to how the temperature of the outer atmosphere of the Sun, namely "corona", is maintained at mega-Kelvin temperatures when the surface photosphere, lying a few thousand kilometers deeper, has an average temperature of 5800 K ! In a close connection with this outstanding question, yet another novel question is put forward as to how the mass cycle of the solar atmosphere is established, and as to how the mass is transported at the supersonic speed as the solar wind. This paradox scenario stands as one of the outstanding problems in solar astronomy for the last seven decades without any firm scientific answer yet. However, broadly two types of physical mechanisms seem to be at work in which the first is related to the direct dissipation of the current in the magnetized plasma, while the second carries energy in the form of alternating current source. The former is known as famous magnetic reconnection process, while the latter represents magnetic waves. These two broader mechanisms are supposed to be in the background of all kinds of dynamical plasma processes, as well as mass and energy transport in the various layers of the solar atmosphere at diverse scales. In conclusion, the physical state of the Sun's million-degree hot, dynamic, and magnetized atmosphere, determines the interplanetary space and magnetic fields; spiraling solar wind stream; solar eruptions and their interaction with the planetary magnetic fields.

Energy and mass transport in the form of radiation/heat flows, and mass loss in the form of nascent solar wind from the Sun's chromosphere and corona, require a large input of energy $\approx 10^2$-10^4 W m^{-2} to balance these losses. The role of MHD waves, and magnetic reconnection leading to localized or bulk heating at diverse spatio-temporal scales, has been explored for decades as the primary candidates to cause the energy and mass transport in the various layers of the solar atmosphere. However, the detailed role of these energy sources and their dissipation is not yet fully understood in the highly structured solar atmosphere, with a continued compelling debate on the outstanding problem of the Sun's atmospheric heating and origin of the solar wind. Current high-resolution space and ground-based observations have revealed that energy, mass transport and subsequent heating processes in the quiescent solar atmosphere and in coronal holes are associated with fluxtubes (open funnels or closed quiescent loops) which are rooted into the strongly magnetized regions at the solar photosphere. They result in the coupling of various layers of the solar atmosphere and supporting various waves and flows/jets. As far as the complex and strongly magnetized solar active regions are concerned, the hot plasma is embedded in the corona through magnetic loops, requiring different scales of heating and associated physical processes. These processes may be inferred from the evolution of the hot plasma flows, waves and oscillations, shocks, and the reconnection-driven plasma dynamics above the sunspots where the footpoints of the solar loops are anchored. Global energizing processes e.g., magnetic reconnection, p-mode leakage etc., play an important part in heating the large-scale corona. However, energy and mass transport may also occur locally via shocks, waves or flows, or the evolution and dissipation of highly sheared magnetic fields in the solar atmosphere. In addition, heating candidates and subsequent plasma flows could originate *in situ* in the inner corona, or might be forced from the sub-photospheric layers/photosphere/chromosphere. A full picture of various energy sources/heating and mass transport processes, global vs local, their origin and role in the extent of the heating of various layers of the Sun's atmosphere, is still not clear. The present thesis addresses some associated novel scientific issues with new results, exploring the multitude of physical processes and resultant plasma dynamics to understand as to how the plasma flows begin in the formation of cool loop systems in the solar chromosphere and Transition Region (TR) by using high-resolution observations from the Interface Region Imaging Spectrograph

(IRIS), Solar Dynamics Observatory (SDO), combined with the latest theoretical/numerical models. Moreover, the present thesis also provides some new information about the flow structures in open loop arches embedded in the moss regions on the solar-disk, as well as revealing the understanding of small-scale energy release in the quiet-Sun and associated supersonic plasma motion in the form of a collimated jet. In summary, it deals with the spectroscopic and imaging analyses of the variety of plasma flows in closed and open magnetic structures, which might be linked to the localized heating processes in the lower solar atmosphere. It also emphasizes on the possible physical role of such localized plasma dynamics in various layers of the solar atmosphere.

With the advent of high-resolution EUV imager and spectrometers/spectrographs during and after the era of Solar and Heliospheric Observatory (SoHO), the UV and EUV wavelength domain ranging from wavelength 465 Å to 1550 Å and 1600 Å to 3000 Å respectively dominated by chromosphere-corona and transition region lines are extensively observed, although some chromospheric and coronal lines are also recorded in this range. Therefore, plenty of UV/EUV emission lines over the entire wavelength range have now provided a vital information about plasma conditions, heating and mass transport processes, and dynamical and eruptive processes etc., for more than two decades. Earlier studies such as the significant blue-shifts at Ne VIII formation height at inter-network regions along with magnetic-field extrapolations show the association of blueshifts with the legs of coronal loops providing mass and energy transport in the overlying localized corona. Some loops exhibit blueshifts at both ends of the coronal loops while some show blueshifts at one and redshifts at another where the plasma motions are driven by siphon flows or small-scale energy transients. However, persistent redshifts are observed in the TR lines. Previously, there were plenty of such frontline scientific discoveries which have shed more light on the physics of such energy transients contributing to the plasma flows. The deviation of temperature for the dynamical plasma in models of coronal loops is demonstrated by many solar spectroscopic observations and in models of the IRIS Si IV and O IV emission lines recently. The stable structures such as sunspots, prominences are identifiable with an image while transient events such as jets are accessible only through high-temporal cadence image sequences, and also using high-resolution spectroscopic measurements with the new generation of spectrometers/spectrographs, e.g., Hinode/EIS, IRIS, etc. Specific observations leading to plasma flows and their corresponding signatures in variety of magnetic structures are extensively studied in this thesis using latest magnetic, imaging, and spectroscopic observations, with a blend of some numerical modeling. Such small-scale impulsive energy transients have the potential to maintain the background temperature of the corona due to their ubiquitous energetic presence in the quiet-Sun and active region, and they may also contribute to fulfill the mass losses to the nascent wind. The inhomogeneous small-scale energy transients are also explored here as they contribute significantly to the mass and energy transport in the outer atmosphere.

As described above, the crucial developments took place in the last twenty five years on the understanding of the localized heating and mass motions, coupling various layers of the solar atmosphere. However, the lack of high-resolution observations earlier significantly limited and constrained our understanding of the physical properties of these candidates in the Sun's atmosphere. This was a major gap in the knowledge to clearly address the studied scientific problems. This issue is currently being addressed with the advent of new high-resolution observatories which are capable of measuring both the magnetic and plasma properties of the Sun's atmosphere from a few hundred kilometer down to a few tens of kilometer e.g., IRIS, SDO, SST, ROSA, 4m-DKIST, etc. The international solar physics community is also progressing and developing major observational facilities e.g., 4m-DKIST (first light is already in place !), 4m-EST, 2m-NLST, Solar Orbiter etc., to understand the energy and mass transport processes at smallest spatial scales in the localized solar atmosphere. The instruments (SUIT, VELC) to be flown onboard the Indian solar space mission, Aditya-L1, are also having this as one of its major scientific objectives. Most of the high-resolution solar observatories from ground and space, in the present state-of-art research, are also stressing upon the study of wave/reconnection/shock associated heating processes as well as associated mass/plasma transport phenomena (e.g., flows, jets, swirls, dynamical cool loops etc.) at diverse spatio-temporal scales. This provides the opportunity to understand the energy generation and transport in the localized solar atmosphere coupling the different layers of the solar atmosphere, and it becomes a frontline science topic to understanding the chromospheric/coronal heating. The billion dollars space-borne observatories e.g, Hinode, STEREO, SDO, IRIS, Solar Orbiter and Parker's Solar Probe have already been commissioned during the last fifteen years to study the physical significance of heating and mass transport processes in the solar atmosphere along with a variety of other primary scientific objectives. Apart from space-based telescopes, the modern technique of adaptive optics, modern data acquisition system, etc have also been utilized in the modern ground-based telescopes and related backends, e.g., ROSA, 2m-SST at La Palma, 4m-DKIST at Hawaii, 20 inch-MAST at Udaipur, 4m-EST and 2m-NLST (upcoming!) to understand the energy and mass transport processes and dynamics of the lower solar atmosphere at high cadence and smallest spatial scales. These developments are also established to answer the viable facts as to how energy and mass transport processes couple photosphere/chromosphere to the overlying solar atmosphere to energize it locally.

More specifically, the localized plasma flows in the atmosphere of magnetically active Sun establish its mass cycle, which is somehow linked to the localized energy and mass transport processes there. In this thesis, we investigate such plasma flows and some of their roles in the formation of the building blocks of its atmosphere, i.e., magnetic loops which may confine the dynamic, hot and magnetized plasmas. The solar atmosphere is a magnetically structured hot and dynamic plasma exhibiting many exotic structures resulting in various manifestations. The study of plasma flows therein provide a unique opportunity not only to probe it but also their effects in characterizing a host of associated physical processes such as formation of cool and hot loops, capable of transporting mass and energy into the various layers of the solar atmosphere, and providing clues to ongoing transient energy release and heating processes at diverse spatial scales. This thesis contains seven chapters and we summarize their contents very briefly as under:

Chapter 1: Introduction

We give an overview of the Sun's atmosphere, specifically focusing on the recent progress in the understanding of the plasma flows in the confined closed and open magnetic structures. We discuss the variety of the regions, e.g., Active Regions, Quiet-Sun, and Coronal Holes in terms of their magnetic structuring, emissions, and flow structuring. We also describe the transient energy release and associated jet-like motions and plasma flows in the lower solar atmosphere. In the light of these fundamental facts and their introduction, we finally discuss the physical implications of our studied plasma flows in a variety of the chosen magnetic structures (e.g., cool and hot loops, quiet-Sun) followed by an outline of the thesis.

Chapter 2: Space-borne Observations and Some Analysis Techniques

We describe briefly about various observatories (e.g., Solar Dynamics Observatory; Interface Region Imaging Spectrograph), and their instruments (e.g., Helioseismic Magnetic Imager; Atmospheric Imaging Assembly; IRIS Slit-Jaw Imager and Spectrograph) from where the variety of the observations are used to pursue the scientific studies in this thesis. We also describe the employed data analysis techniques, e.g., image calibration and processing; analysis techniques of magnetogram data; spectral fitting procedure and related diagnostics; Differential Emission Measure (DEM), and wavelet technique.

Chapter 3: Plasma Flows in Cool Loops

We have outlined the work related to the study of the dynamics of low-lying cool loop systems as observed by the Interface Region Imaging Spectrograph (IRIS). Such flowing cool loop systems are observed in the chromospheric/TR emissions by IRIS in recent years, which add a new dimension on the mass and energy transport processes in the solar chromosphere/TR/inner corona. Moreover, the formation of these dynamic loops and plasma flows therein are also linked with the local heating and energization process in the lower solar atmosphere. Radiances, Doppler shifts, and line widths are investigated in and around the observed cool loop systems using various spectral lines observed by IRIS formed between the photosphere and transition region (TR). Footpoints of the loop threads are found to be either dominated by blueshifts or redshifts. The cospatial variation of velocity above the blueshifted footpoints of various loop threads shows a transition from very small upflow velocities ranging from (-1 to +1) km s^{-1} in the Mg II k line (2796.20 Å formation temperature: log (T/K) = 4.0) to the high upflow velocities from (-10 to -20) km s^{-1} in Si IV. Thus, the transition of the plasma flows from redshift (downflows) to blueshift (upflows) is observed above the footpoints of these loop systems in the spectral line C II (1334.53 Å log (T/K) = 4.3) lying between Mg II k and Si IV (1402.77 Å , log(T/K)=4.8). This flow inversion is consistently observed in multiple data sets of the cool loop systems as observed by IRIS. The other footpoint of these loop systems always remain redshifted, indicating downflowing plasma. The multispectral line analysis provides a detailed scenario of the plasma flows inversions in cool loop systems leading to the mass transport and their formation. The impulsive energy release due to small-scale reconnection above the loop footpoint seems to be the most likely cause for sudden initiation of the plasma flows evident at TR temperatures. This work has been published in The Astrophysical Journal (2019).

Chapter 4: Modelling the Origin of Plasma Flows in Cool Loop System

We have presented the imaging and spectral observations of a flowing cool loop system whose footpoints have been seen to be active and associated with the unusual broadening of the Si IV 1330 Å line profiles. This large broadening of the TR line is a most likely signature of the underlying explosive events (EEs) occurred at the footpoints of such loop system which have caused the plasma flows and thereby the formation of such loops. Observations of the plasma flows in a cool loop system using the Slit-Jaw Imager on board the Interface Region Imaging Spectrograph (IRIS) have been presented. We have chosen one such unidirectional flowing cool-loop system as observed by IRIS where one of the footpoints is associated with significantly broadened Si IV line profiles. The line-profile broadening indirectly indicates the occurrence of numerous EEs below the transition region (TR), while it directly infers a large velocity enhancement/perturbation, further causing the plasma flows in the observed loop system. The observed features are implemented in a model atmosphere in which a low-lying bipolar magnetic field system is perturbed in the chromosphere by a velocity pulse with a maximum amplitude of 200 km s^{-1}. The data-driven 2D numerical simulation shows that the plasma motions evolve in a similar manner as observed by IRIS in the form of flowing plasma filling the skeleton of a cool-loop system. We compare the spatio-temporal evolution of the cool-loop system in the framework of our model with the observations, and conclude that their formation is mostly associated with the velocity response of the transient energy release above their footpoints in the chromosphere/TR. Our observations and modeling results suggest that the velocity responses most likely associated with the EEs could be one of the main candidates for the dynamics and energetics of the flowing cool-loop systems in the lower solar atmosphere. Such flowing loops and their detailed dynamics have already been observed and presented in Chapter 3. Here, we present the modeling of the formation of flowing cool loop system due to the velocity enhancement at their footpoints most likely due to the indirect response of the impulsive energy release and heating by the EEs. This work has been published in The Astrophysical Journal (2020).

Chapter 5: Flows in Quiescent Coronal Loops

We have presented the signature of the plasma dynamics above the footpoints of the quiescent hot loop arches that are anchored on the moss region in an AR. The observations of the quiescent coronal loops have been presented using multi-wavelength observations from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) on 13 April 2016. The flows at the foot points of such loop systems are studied using spectral data from the Interface Region Imaging Spectrograph (IRIS). The Doppler velocity distributions at the foot points lying in the moss region show the negligible or small flows at the Ni I, Mg II k3, and C II lines corresponding to the upper photospheric and chromospheric emissions. Significant red shifts (downflows) ranging from 1 to 7 km s^{-1} are observed at Si IV (1393.78 Å ; log(T/K)=4.8), which is found to be consistent with the existing results regarding dynamical loop systems and moss regions. Such downflows agree well with the impulsive heating mechanism reported earlier that has already occurred there and formed such active loop systems. However, as usual such loops are exhibiting the consistent downflows at the TR and chromospheric levels that basically demonstrate the ongoing cooling and condensation phase there. This work has been published in Annales Geophysicae (2019).

Chapter 6: Supersonic Plasma Flows due to Magnetoacoustic Shocks

We have presented the work related to the generation of an impulsive plasma outflow in the quiet-Sun using multiwavelength observations from the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) on 2011 March 30. This supersonic outflow rises to the upper solar atmosphere with a high terminal speed of 1250 km s^{-1}, and a sharp increase of the multitemperature EUV emissions as captured by multiple SDO/AIA channels sensitive to the temperatures between log T(K)=4.7 and log T(K)=7.0 demonstrates its highly impulsive origin. Differential Emission Measure (DEM) has also confirmed that outflow is made up of the multitemperature plasma. The careful investigation of SDO/HMI magnetic field data at its footpoint depicts that the emerging flux of negative polarity is oscillating at the period of 442 s. The oscillations are also observed in the intensity of 1600 Å almost co-temporally at the base of the outflow with the almost same period ($\approx$ 416 s). The 7.0 min periodicity in the magnetic flux and 1600 Å flux of SDO/AIA is present both prior to and during the onset, and even after the outflows for the duration of $\approx$ 1 h. The inference drawn from this observation is that the magnetoacoustic waves are generated and are present at the base of the outflow which interact with the localized small-scale current sheet and associated X-point. Magnetoacoustic waves encounter with the discontinuity at the X-point that may further develop into the fast magnetic shocks leading to the formation of the observed shock cusp and triggering of the impulsive plasma outflows. In conclusion, this new finding demonstrates that small-scale oscillatory magnetic reconnection enabled by the wave perturbations may trigger very gigantic and highly impulsive individual jets and associated flows in the solar atmosphere, which may propel the hot flowing plasma into the overlying solar atmosphere fulfilling some fraction of its mass and energy locally. This work has been published in the Monthly Notices of the Royal Astronomical Society (2017).

Chapter 7: Conclusions and Future Plan

We discuss the summary and scientific conclusions. The future prospects of these works are also briefly outlined.

Main new results of this thesis, reported in Chapters 3 to 6, are already published in the reputed journals, e.g., The Astrophysical Journal, Monthly Notices of the Royal Astronomical Society, Annales Geophysicae etc., and presented in the National and International Symposia/Conferences during the PhD programme.