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I, Ritika Solanki, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of Dr. Abhishek K. Srivastava and co-supervision of Prof. Bhola N. Dwivedi from July 2015 to September 2020 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 wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, 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 Honour of My Sister

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(Ritika Solanki)

Preface

For millennia, the Sun (and the universe) has been viewed in the visual light. As the bestower of light and life, the ancients made God out of the Sun. With the Babylonians, or with the multiple origins with the Chinese, Egyptians and Indians, quoting the Rig Veda: “All that exists was born from Sūrya, the God of god”, we have come a long way to understanding the Sun. In the early seventeenth century, however, Galileo showed that the Sun was not an immaculate object. Thus began our scientific interests in our nearest stellar neighbour, the Sun, with its sunspots and the related solar activity. The observations of the Sun and their interpretations are of universal importance for at least two reasons: First, the Sun is the source of energy for the entire planetary system and all aspects of our life have direct impact on what happens on the Sun; and second, the Sun’s proximity makes it unique among the billions of stars in the sky of which we can resolve its surface features and study physical processes at work.

Observations of the solar atmosphere led to the development of the theory of radiative transfer in stellar atmospheres and the discovery of the element helium. Moreover, the Sun is the principal magnetohydrodynamic (MHD) laboratory for large magnetic Reynolds numbers, exhibiting the totally unexpected phenomena of magnetic fibrils, sunspots, prominences, flares, coronal loops, coronal mass ejections (CMEs), the solar wind, the X-ray corona, and irradiance variations etc. It is the physics of these exotic phenomena, collectively making up variations of solar activity, with which we are confronted today. The activity affects the terrestrial environment, from occasionally knocking out power grids to space weather and most probably general climate.

Beginning with the first solar ultraviolet light from space in 1946, X-rays in 1948, hard X-rays and γ-rays in 1958; many experiments have been conducted or being conducted using balloons, rockets and satellites (e.g., OSOs, Skylab, SMM, Yohkoh, SOHO, TRACE, RHESSI, Hinode, STEREO, SDO, IRIS, Solar Orbiter etc.). Artificial satellites have provided the unique opportunity to have uninterrupted observations of the Sun from the vantage points, such as the Sun-Earth Lagrangian point L1 (e.g., SOHO), or from outside the ecliptic plane (e.g., Ulysses), or in stereoscopic modes using different orbits (e.g., STEREO). All these have provided a rich source of data, unlocking the secrets of the Sun and addressing some of its outstanding riddles (e.g., coronal heating, solar wind acceleration etc.).

Ground-based observations suffer from the effects of the Earth's atmosphere such as atmospheric extinction resulting in the limited radiative spectrum of the Sun, and turbulence resulting in image distortions. None the less, making use of adaptive optics system, solar images with resolution of about $0.13''$ (90 km on the Sun), or even smaller structures down to 60 km, have been obtained by the Swedish 1-meter Solar Telescope (SST) on La Palma. Further, the resolution of $\leq$ 30 km has been achieved after the first-light from the 4-m Daniel K. Inouye Solar Telescope (DKIST) at Hawaii, revealing new science above the solar surface. Similarly, the Solar Orbiter from space has recently imaged the EUV corona with a fine resolution of about 100 km, providing a host of enormous small-scale solar flares going into the solar corona and most likely acting as potential candidates for generating energy. Apart from the observations of the solar atmosphere, the neutrino detectors have provided a unique tool for probing the Sun's interior by comparing the emitted flux with the predictions of the standard solar models. Helioseismology from space and from the ground (e.g., GONG) have revolutionised our understanding of the workings of the Sun.

As pointed out above, the solar studies inform us of nature operating on the enormous scales encountered across the Universe. It exhibits remarkable phenomena, such as sunspots, the corona, flares, the solar wind, and CMEs. The Sun is a machine that converts a small but important fraction of its benign power into variable energetic radiation, magnetism and particles. Today the biggest problems in solar physics concern the dynamical interactions between solar plasma and its magnetic fields. While passing through the Earth, solar outbursts disturb Earth's protective magnetic field, causing problems for electrical infrastructure, though leading to beautiful aurorae. Our increasing technology-dependence makes our way of life vulnerable to sustaining damage as a result of the poorly-understood workings of the Sun.

As noted in above paragraphs, the interplay of the complex magnetic field and plasma generates a variety of dynamical plasma processes in the solar atmosphere. A major development has taken place since the SOHO era in the form of the observations of the localized giant plasma eruptions in the solar corona, which exhibit the properties of the jet-like guided motion along the magnetic field lines, and termed as "The Coronal Jets". These massive ejecta signify as ubiquitous solar transients that are triggered more often in the solar corona locally, and may transport significant mass and energy into the overlying solar atmosphere and the solar wind. Although the energy budget of these jets is less compared to the typical solar flares and CMEs, yet these ejecta are also considered as an explosive magnetically driven transients. The study of the coronal jets, therefore, may provide critical and significant knowledge about the bigger and more complex drivers of the solar activity, and their inherent energetics.

Coronal jets are typically seen very clearly erupting along the open field lines of the coronal holes as well as in polar caps as the background radiation is less there because of the darker background. In the typical X-ray and Extreme Ultraviolet Emissions, these jets are observed as collimated, beam-like structures, which are anchored on the bright small-scale loop-like base revealing their reconnection-generated origin. The signature of these collimated jets can be seen up to several tens of mega-meter in the EUV and X-ray images in the inner corona. Sometimes, the traces of these coronal jets can also be seen up to several solar radii in white-light coronagraphic images, supporting the fact that these jets could be an efficient means of structuring the plasma in the extended corona also that may further lead to mass transport. The unprecedented development in the spatial and temporal resolution of imaging observations in the last over three decades from various space missions and their imagers (e.g., Yohkoh, SOHO, STEREO, Hinode, SDO, IRIS, Solar Orbiter) provide further details of the origin and evolution of the coronal jets, and their capability to couple the solar atmosphere by the means of energy and mass transport processes. The fine details of the morphology, kinematics and dynamics, and their connection and interaction with other coronal structures are unveiled recently by the high-resolution recent imaging and spectroscopic observations that have yielded unique scientific information about these important coronal transients.

Apart from typical scenario of the magnetic reconnection between the emerging twisted fluxtubes with the pre-existing ambient fields in the formation of coronal jets, the remarkable advancement has taken place during the last decade, regarding understanding the details of the role of mini-filaments and magnetic (e.g., kink) as well as gravity-driven (e.g., Kelvin-Helmholtz) instabilities. Moreover, the improved observational manifestation has also revealed the fine structure dynamics (e.g., motion of the helical magnetic skeleton and tornadoe-like motions), wave motions (e.g., kink and Alfvén waves) in the jets, as well as revealed a variety of the information about the inter-relationship of these jets with other coronal structures and transients, e.g., plumes, sigmoids, solar wind, narrow-CMEs, energetic particles, etc.

The connection between coronal jets and narrow-CME is a front-line research topic in the field of solar physics. A CME is described in terms of the significant release of magnetized plasma and associated flux-rope/magnetic field from the solar corona. They are usually accompanied by the onset of solar flares and are typically evolved during a solar prominence eruption. However, CMEs may also occur without the occurrence of the solar flare and prominence eruption also. In the outer solar atmosphere, the CMEs may slide or dragged by the solar wind plasma once they are injected into its stream. The CMEs are most often triggered above flaring active regions on the Sun's surface, and they consist of three part structure namely the core, cavity, and shock-front. These CMEs, propagating towards the Earth, may cause severe geo-magnetic storm and can cause the space-weather. If a CME reaches the Earth's outer atmosphere, it may produce a geomagnetic storm causing anomalies and disruptions to the modern conveniences upon which the humanity depends. In a quantitative measure, the fluctuating magnetic fields associated with these geo-magnetic storms may induce currents in power-grids causing a wide-spread blackouts, disruption in the telecommunication and air-aviation, space-hazard to the satellites and astronauts, and many more. Therefore, the study of the solar eruptions and CMEs and their forecast in causing space-weather is at the forefront of the solar and heliospheric research.

As stated above, the study of the origin, evolution, and kinematical properties of CMEs are important for the space-weather research and its real-time forecast. Their origin in the inner corona and linkage with the upper atmospheric response as well as directivity towards the Earth must be understood together to make a real-time space-weather forecast tool and to inhibit the potential space-weather related damages to the mankind. Apart from the typical CMEs, there are unique CMEs discovered in the recent era, which are generated due to the eruption of the coronal jets and termed as narrow-CMEs. These CMEs possess different morphology, kinematics, and energetics, but put on similar effects in the heliosphere and Earth's outer atmosphere. A recent study has revealed that narrow CMEs which are originated due to coronal jets, in turn can generate low-energy particles in the vicinity of the Earth without commencement of the other large-scale solar eruptions on the Sun. This scenario adds a fascinating development in the space-weather forecast that in addition to the classical solar eruptions (e.g., solar flares, CMEs) the atypical silent players (e.g., coronal jets and associated narrow CMEs) could also be given attention. Their origin in the solar atmosphere, and their imprints in the heliosphere must also be included in the study of the solar transients that may also be useful for the space weather studies and related predictions. The present thesis aims to reveal the multi-wavelength origin of the coronal jets and underlying physical processes, and their connection with the CMEs. As stated above, the scientific objectives and derived new results in the present thesis will make an advancement in understanding the inter-relationship between coronal jets and CMEs, and also provide the clues to their potential future use in space weather studies and related forecast. The present thesis therefore, uniquely deals with the one of the front-line scientific themes in the field of the solar physics, which is related to understanding the physics of coronal jets and associated CMEs. This will further provide a platform to study such transients in greater details using multi-wavelength and multi-instrument observations to explore their physical behaviour starting from the solar atmosphere up to the inter-planetary space, and their role in causing the space weather. Against this brief background and significance of my works, more precisely we have focused on describing the observational works of coronal jets in order to understand the role of mini-filaments in the eruption of coronal jets. We have explored the relation and association of coronal jets with CMEs, and also the conditions when a coronal jet becomes CME-productive and non-productive. This thesis is organized as follows:

Chapter 1:- Introduction

This chapter gives a brief introduction of the Sun's structure and its atmosphere. The magnetic field behavior and its relation with the solar activity are discussed. Different transient phenomena e.g., flares, filaments and prominence, coronal jets and CMEs are presented. The detailed observational view and numerical models of solar coronal jets are also described. At the end, this chapter briefly outlines the new scientific results derived in Chapter 3-5.

Chapter 2:- Observations and Data Analysis Techniques: Space and Ground-based Instruments

This chapter describes a brief overview of different observational data and related instruments used to study the transient phenomena (e.g., flares, coronal jets, and CMEs), and the techniques used to analyze them.

Chapter 3:- Quiet Sun Coronal Jets and Twin CMEs

This chapter is devoted to the observational study of a blowout jet which was observed on 16 May 2014 in the internetwork region of the quiet-Sun using SDO/AIA observations. The twin CMEs as jet-like and bubble-like CMEs observed by LASCO-C2 onboard the SOHO and STEREO-A and STEREO-B/COR2. These CMEs are associated with the eruption of northern and southern sections of the filament. The circular filament is rooted at the base of blowout jet. The continuous magnetic flux cancellation is observed by SDO/HMI line-of-sight (LOS) magnetograms at the northern end of the filament, which makes this filament unstable and further makes it to erupt in two different stages. In the first stage, the northern section of circular filament is ejected and drives the evolution of northern part of blowout jet. The Kelvin-Helmholtz (K-H) unstable plasma blobs are detected in the northern twisted magneto-plasma spire of blowout jet. The northern part of the blowout jet is further extended in the form of jet-like CME. In the second stage, the southern section of circular filament erupts in the form of twisted magnetic flux rope and forms the southern part of the blowout jet. The eruption of the southern section of filament most likely is due to the eruption of the northern section of filament, which removes the confined overlying magnetic field. The eruption of the southern section of filament further drags a bubble-like CME. To the best of our knowledge, this provides first detailed observations and inter-relationship between quiet-Sun network-flare, eruption of multiple segments of filaments, episodic formation of coronal jets, and evolution and propagation of two CMEs in the outer corona.

Chapter 4:- Origin of CME Productive and Non-productive Coronal Jets

This chapter deals with the observational study of recurring jets near active region AR11176 during the period 31 March 2011 17:00 UT to 01 April 2011 05:00 UT using observations from SDO/AIA. Two Mini-filaments are found at the base of these recurring jets where mini-filament1 is found at the base of first three jets shows partial eruption and mini-filament2 at the base of fourth jet shows complete eruption and drives evolution of a full blow-out jet. Second mini-filament triggers C-class (GOES C-3.1) flare and full blow-out jet. This blow-out jet further triggers a CME. The plane-of-sky velocities of recurring jets are $160\,\mathrm{km\,s^{-1}}$, $106\,\mathrm{km\,s^{-1}}$, $151\,\mathrm{km\,s^{-1}}$ and $369\,\mathrm{km\,s^{-1}}$. The estimated velocity of CME is $636\,\mathrm{km\,s^{-1}}$. The plasma blobs are detected during the eruption of first jet. The continuous magnetic flux cancellation is found at the base of jet productive region which is the reason of eruption of mini-filaments and recurring jets. In the former case when mini-filament1 is partially erupted and first three jets are produced the rate of cancellation was low. In the latter case, when mini-filament2 is fully erupted and triggered C-class flare and CME-productive blow-out jet the flux cancellation rate is high. The partial eruption of mini-filament1 is pushed the overlying dynamic complex thin loops and made them to reconnect and drive first three jets. The present chapter provides new scientific information on the linkage of mini-filament eruptions with the multiple coronal jets, and differentiate about the CME-productive and non-productive jets above the eruption site.

Chapter 5:- Study of Two-Stage Coronal Jet Associated with a C1.4 Class Solar Flare

This chapter is devoted to observational study of a complex active region jet which evolved from southward of a major sunspot of NOAA AR12178 on 04 October 2014. This complex jet is associated with a GOES C-1.4 flare and a cool surge. Different observational data e.g., SDO/AIA, SDO/HMI, GONG Hα and GOES are used to analyse the observed event. We have termed this jet as a two-stage confined eruption. In first stage of jet, some plasma erupts above the compact flaring region and in second stage eruptive jet plasma and associated magnetic fields interact with another set of magnetic fields in south-east direction. At the interaction point of these two different magnetic fields a null point (Xpoint) is created, where second stage of jet deflected along curvilinear path into overlying corona. The magnetic flux cancellation at the base of jet causes a C-class flare and the flare energy energizes first stage of coronal jet. The lower part of jet is followed by a cool surge visible only in Hα emissions. This two-stage jet observation imposes some rigid constraints on existing jet models. The new scientific results in this chapter put a rigid constraint on the existing coronal jet models, and advocate in their refinements as the real observed jet in the present case is very complex and display multiple physical processes during its evolution.

Chapter 6:- Conclusions and Future Plans

This chapter briefly presents conclusions and summary of thesis work and also describes some future plans in the direction of this area of research.

The main new results of Chapters 3 to 5 of this thesis have already been published in the reputed international journals, e.g., Solar Physics, Astrophysics & Space Science, and presented in the national and international conferences (e.g., IAU Symposium) during the Ph.D. programme.

List of Acronyms

AIA	Atmospheric Imaging Assembly
DKIST	Daniel K. Inouye Solar Telescope
EUVI	Extreme Ultraviolet Imager
EVE	Extreme Ultraviolet Variability Experiment
GOES	Geostationary Orbiting Environmental Satellites
GONG	Global Oscillation Network Group
HMI	Helioseismic and Magnetic Imager
IRIS	Interface Region Imaging Spectrograph
LASCO	Large Angle Spectroscopic Coronagraph
MDI	Michelson Doppler Imager
NRL	Naval Research Laboratory
OSO	Orbiting Solar Observatory
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
SDO	Solar Dynamics Observatory
SECCHI	Sun-Earth Connection Coronal and Heliospheric Investigation
SMM	Solar Maximum Mission
SOHO	Solar and Heliospheric Observatory
SOT	Solar Optical Telescope
SST	Swedish Solar Telescope
STEREO	Solar TErrestrial RElations Observatory
SXT	Soft X-ray Telescope
TRACE	Transition Region and Coronal Explorer
XRT	X-ray Telescope

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