

Preface

The stars are massive spheres of plasma, born from clouds of gas and dust, known as nebulae. In these clouds, gravity causes material to collapse and ignite nuclear fusion at their cores. Among numerous stars, one holds special significance to us, and it is our parental star: The Sun. Our nearest and only spatially resolved star is not only a source of light but also the foundation of life on our planet Earth. The Sun is a dynamic star comprise with several layers, like the core where nuclear fusion occurs; the radiative and convective zones, transporting energy outward; and the outer atmospheric layers, comprising the photosphere, chromosphere, and corona. Each layer of the solar atmosphere plays a crucial role in the Sun's magnetic activity, energy transport, and interaction with the solar system. The corona is the outermost layer of the atmosphere, and it is a highly active region where magnetic fields dominate the dynamics of the hot plasma (plasma beta (β) < 1), driving eruptive phenomena like flares, Coronal Mass Ejections (CMEs), solar wind, etc.. The direct impact of these activities on Earth and interplanetary space makes their study important. The magnetic field configuration plays a crucial role in the occurrence of such activities on the Sun.

The magnetic field generated by the dynamo process creates dark and cool sunspots on the visible surface of the Sun. These spots occur due to the interaction of the plasma flows with the differential rotation and convection process. The Sun undergoes an 11-year activity cycle, which is marked by fluctuations in these sunspot numbers, as depicted by the famous butterfly diagram. These spots are regions of the strong magnetic field, which are responsible for enhanced activity during the solar maxima. Studying the magnetic properties of the Sun is crucial for understanding the origin of such activities. For instance, Solar flares are sudden explosions of magnetic energy stored in coronal loops; such bursts of plasma in outer space can disrupt the communication system and affect satellite operations.

But why should we focus only on the Sun? Other stars, particularly those having similar properties to the Sun, provide more information that holds the key to understanding the broader universe. By studying them, we can understand how stars evolve, how their magnetic activity influences surrounding planets, and how our own Sun can be compared with the stars present across galaxies. Sun-like stars hold a special place in our understanding of stellar evolution. These are defined as stars with masses and compositions similar to our Sun. They serve as a critical benchmark for studying the processes that occur in stellar coronae and their effects on exoplanets. Although they share many features with the Sun, such as their core hydrogen fusion and relatively stable lifespans, the variations in activity, magnetic fields, and environments often reveal their distinct behaviors.

The flares on these stars are of special interest. These explosive events confirm the presence of strong magnetic regions on the surface of the star. Sometimes these flares are accompanied by coronal mass ejections (CMEs), which are the massive bursts of plasma into outer space, and also highlight the underlying physical mechanisms responsible for such events. The stars are spatially unresolved, making the Sun an invaluable reference star for studying such magnetically active stars and their atmosphere. Stellar flares are analyzed across a broad range of wavelengths, from radio to X-rays and gamma rays, as different features of a flare become evident at different wavelengths. To study such events, multiple space-based satellites are utilized, including XMM-Newton, Swift, eROSITA, and Chandra for X-ray observations; Kepler and TESS for optical data; and various instruments like EUVE, HST, VLA, etc. for UV and radio emissions. These tools provide a comprehensive view of flare dynamics, helping to understand their mechanisms and effects on diverse stellar environments.

In this work, we have studied the properties of energetic X-ray flares in Sun-like stars. We addressed paramount of questions e.g. (i) how do different coronal parameters (e.g.,

temperature, plasma density, emission measure, luminosity) vary during the flare evolution with respect to the quiescent parameters?; (ii) how do the flare characteristics vary among Sun-like stars?; (iii) can we draw certain linkage between stellar flares and solar flares?; (iv) how do the coronal plasma compositions vary among different stars?; (v) and how variation in hydrogen column density is related to the possible signature of some failed eruptions or coronal mass ejections? We have studied the temporal as well as the spectral variability in stellar flares to address these questions.

The study of coronal loop geometry, particularly through the measurement of loop length, has been a key aspect of research in understanding stellar and solar flares. Early observations of solar flares, particularly with the advancement of high-resolution X-ray and UV telescopes, provided initial insights into the complex structure of the solar corona and its dynamic behavior during flare events. Using the solar analogy and solar flare models, researchers tried to do similar analogical studies in the case of other magnetically active flaring stars. Different techniques for studying temporal and spectral variations in flare emissions have been developed in the past, which have played a significant role in mapping the geometry of coronal loops. In this work, we have used time-resolved spectroscopy and the hydrodynamic loop model to determine the physical parameters of coronal loops by analyzing the properties of the emitting plasma. It has been especially important in understanding the responsible physical processes, such as magnetic reconnection, heat conduction inside the loop, evaporation of plasma, and cooling mechanisms during a flare.

Complementing loop geometry, the investigation of coronal elemental abundances provides invaluable insights into a star's corona. Such studies have a long history rooted in the early observations of solar and stellar coronae, which revealed that the elemental composition of the outer layers of stars differs significantly from their photospheric abundances. Initially, solar observations suggested that the Sun's corona is enriched in elements such as iron and other high-temperature elements, while being depleted in lighter elements like

hydrogen and helium. This unexpected difference led researchers to investigate whether similar patterns existed in other stars. As a result, analogous abundance anomalies were identified, with the Sun showing what is known as the First Ionization Potential (FIP) effect, and some stars exhibiting the opposite trend, termed the inverse FIP effect. Examining the elemental composition of stellar coronal plasma, especially during flares, helps us better understand the physical mechanisms behind such events and broader issues like coronal heating. In this thesis, we investigate the presence of FIP and inverse FIP effects in Sun-like stars.

Alongside flares, the detection of mass ejections and plasma eruptions associated with flares has evolved significantly over the years, beginning with early optical observations of solar and stellar flares. As instrumentation advanced, the study of these events expanded to the ultraviolet (UV) and X-ray regimes, revealing the high-energy aspects of these eruptions. Such observations have been crucial in identifying the energetic nature of these events, providing insights into the heating and dynamics of stellar coronae. However, the detection of such eruptions in the X-ray regime through variations in the hydrogen column density is a relatively new approach. This method offers a novel way to probe the dense regions of the corona during flare events. Our study utilizes the X-ray observations for capturing subtle variations in the interstellar medium caused by plasma released from such events. Now, we outline briefly the structure of this Ph.D. thesis:

Chapter 1: Introduction

In this chapter, we provide an overview of the Sun and Sun-like stars and briefly discuss their internal structure, atmospheric layers, and activity cycles driven by the dynamo process. We then explore the various magnetic activities occurring in these atmospheric layers, focusing mainly on coronal activities, such as flares and coronal mass ejections (CMEs). Further, we discussed these events in detail, using both observations

and theoretical models, highlighting the solar and stellar connection. We also provide an overview of flare-associated eruptions and the flare-CME relationship. This chapter covers important diagnostics derived from stellar light curves and high-resolution spectra, such as the presence of rotational modulation and coronal abundance anomalies in different flaring regions. In conclusion, this thesis aims to characterize the coronal loop geometry and magnetic field properties of flaring regions on Sun-like stars in the X-ray regime.

Chapter 2: X-ray Observations, Data Reduction, and Analysis Techniques

In this chapter, we discuss the working principle of the X-ray telescopes and the detectors onboard the spacecraft. We present the list of X-ray observations obtained from the XMM-Newton satellite for two Sun-like stars, AB Doradus and V711 Tau. Further, the chapter outlines the standard data reduction procedure followed to generate calibrated science products such as light curves and spectra from multiple detectors. We also provide a brief overview of the software tools and analysis packages used in processing the data. Additionally, the plasma emission models APEC and VAPEC used for spectral modeling and various analysis techniques are briefly discussed. These techniques have been essential for deriving key physical parameters from the X-ray flares, offering valuable insights into the magnetic structure and the dynamics of stellar coronae during flaring epochs.

Chapter 3: Diagnostics of Super-flares Observed on Active Fast Rotator AB Doradus

In this chapter, we present the analysis of intense X-ray flares detected on the active fast rotator AB Doradus using observations from the XMM-Newton spacecraft. A total of 21 flares were identified, of which 13 flares were analyzed in detail. These flares exhibit total X-ray energies in the range of 10^{34-36} erg, classifying them as superflares. The flares display a characteristic rapid rise followed by a slower decay, attributed to the dominance

of cooling mechanisms during the decay phase. Notably, we report the second and third most energetic flares observed on AB Doradus till date. Additionally, the X-ray light curves exhibit clear rotational modulation, indicative of active regions rotating with the star. The semi-loop lengths of the flaring events were derived to be in the range of $10^{9.9-10.7}$ cm, providing valuable insights into the coronal magnetic geometry and energy release mechanisms of this highly active star. The detailed plasma diagnostics were made using the X-ray observational data, and physical conditions were inferred.

Chapter 4: Characterizing Super-flares in V711 Tau using Time-resolved Spectroscopy (TRS)

In this chapter, we analyze three energetic X-ray flares from the active RS CVn binary system V711 Tau using data obtained from XMM-Newton. The flare light curves exhibit a rapid rise and a slower decay. The flare frequency on V711 Tau was found to be approximately one flare per rotation period. We derived key coronal loop parameters, including loop length, temperature, emission measure, plasma density, and magnetic field strength, using the time-resolved spectroscopy (TRS) analysis technique. The derived flare semi-loop lengths, ranging from 6 to 8.9×10^{10} cm, and the estimated flare energies, ranging from $10^{35.83-37.03}$ erg, are indicative of extreme energetic processes occurring in the corona of this highly active binary system. Notably, the magnetic field strengths of these flaring loops were found to be significantly higher than those typically observed in the solar corona. The detailed diagnostics of these superflares were made using X-ray observations.

Chapter 5: Coronal Elemental Abundance Analysis: FIP and Inverse-FIP effect

In this chapter, we have studied the variations in coronal elemental abundances during the flare epochs with respect to the solar photospheric values for AB Doradus and V711

Tau. Our analysis revealed the presence of an inverse-FIP (First Ionization Potential) effect in both stars. This is a phenomenon where low-FIP elements are depleted, and high-FIP elements are enhanced in the corona, which is the opposite of the effect observed on the Sun. These findings connect such anomalies to the magnetic activity of the star and highlight intriguing differences in the fractionation process operating in the chromosphere of these stars.

Chapter 6: Possible Evidence of CMEs Associated with Flares by Inferring Variations in Hydrogen Column Density

In this chapter, we have studied the flares observed in the active fast rotator AB Doradus, focusing on the temporal variations in the hydrogen column density during these events. Our analysis revealed a significant increase in the column density during the peak phase of multiple overlapping flares, while single flares did not exhibit such variations. These findings confirm the presence of cool plasma between the source and observer, localized precisely around the time of flare occurrence, establishing its association with the flares. This provides compelling evidence for the presence of failed eruptions or coronal mass ejections (CMEs) linked to the flaring events. This novel approach of detecting plasma eruptions through X-ray observations adds a significant dimension to the understanding of stellar magnetic activity and flare-related dynamics.

Chapter 7: Conclusions and Future Plans

In this chapter, we summarize briefly the key scientific findings presented in this Ph.D. thesis, highlighting the major contributions and insights gained from our research. The conclusions are drawn in a systematic and scientific manner, providing glimpses of a comprehensive analysis of the results obtained during the entire Ph.D. work. Furthermore, we outline the broader implications of these works and discuss how they contribute to addressing the research problem. Finally, we propose future directions to extend this study,

emphasizing unexplored scientific aspects, advancements in methodology, and the wider applicability of the findings to the related research, creating a way for continued progress in this domain and enhancing the existing.