# Chapter 7

# Conclusions and Future Plans

***This chapter provides a concise summary and conclusions of the scientific studies presented in this thesis. We also present future research directions aimed at exploring the broader implications of the scientific work discussed.***

## 7.1 Summary and Conclusions

Using extensive XMM-Newton satellite observations, this thesis examines the coronal flaring activity of two highly active Sun-like stars: AB Dor, a rapidly rotating young main-sequence star, and HR 1099, an evolved active binary system. The primary focus was on understanding the quiescent coronal properties, flare characteristics, and their relation to magnetic field geometry through detailed temporal and spectral analyses. We detected a total of 24 flares from these two stars, with 16 highly energetic flares analyzed in detail. Further, to investigate the elemental abundances in the coronal plasma during both quiescent and flaring states of these two stars, high-resolution X-ray spectroscopy was performed. We have explored the possibility of coronal mass ejections, given their association with flaring events.

The quiescent state light curves of AB Dor exhibit rotational modulation, which is indicative of large active regions distributed across its corona. However, no such modulation is observed in HR 1099, likely due to the limited dataset, although previous studies have reported similar signatures. Furthermore, we modeled the X-ray light curves of both stars using a burst model, which revealed a characteristic flare morphology marked by a rapid rise followed by a slower decay phase in both stars. The flare durations ranged from 0.7 to 5.8 hours, with rise times spanning 5 minutes to 1.4 hours and decay times between 12 minutes and 2.4 hours.

A total of 21 flares from six observations of AB Dor are detected with a flare-to-quiescent state count rate ratio of 1.5 - 34. The most powerful flare observed in AB Dor has flare-to-quiescent state count rate ratios of 34. This most powerful flare occurred in 2016 and emerged as the third most powerful flare following the two strongest flares documented during the BeppoSAX observations in 1997. The quiescent state spectra of AB Dor show a consistent three-temperature plasma with an average values of the temperatures the corresponding emission measures of 3.4 MK and 4.8 $10^{52}$ cm$^{-3}$ , 11.0 MK and 6 $10^{52}$ cm$^{-3}$ , and 22.1 MK and 3 $10^{52}$ cm$^{-3}$ , respectively; whereas the abundances is found to be 0.2 $Z_{\odot}$. The quiescent state luminosity of AB Dor is not found to be constant over the 19 years of observations, supporting the presence of long-term variations. The total X-ray energy of these flares was found to be in the range of $10^{34-36}$ erg. The most intense flare, F15, exhibits a peak temperature of 89 MK, unlike the other flares, which all have peak temperatures below 50 MK. In most flares, we observe an increase in abundance and density, suggesting chromospheric evaporation. The heights of the loops in these flares were found to be in the range $10^{9.9-10.7}$ cm, which do not extend beyond 50% of the stellar radius. Additionally, the erupted mass of CMEs appears to be 10 to 100 times higher than the most massive solar CME.

In the case of HR 1099, the quiescent corona is best described by a three-temperature plasma structure with temperatures 3.02, 6.96, and 12.53 MK. TRS analysis of these flares confirms elevated temperatures (up to 39 MK), high emission measures ($10^{53.8-54.9}$ $cm^{-3}$), and enhanced elemental abundances. The derived flare loop lengths in the range $10^{10.8-10.9}$ cm and magnetic field strengths in the range 350–450 G and the flare energetics ($10^{35.83-37.03}$ erg) are similar to those found in the flares detected earlier in HR 1099. The estimated CME masses ($10^{19-20}$ g) significantly exceed those of the most powerful solar flares.

Based on the high-resolution X-ray spectroscopic analysis of AB Dor and HR 1099, we confirm the presence of the inverse FIP (i-FIP) effect in both stars, which is consistent with earlier findings using different data sets. In AB Dor, the coronal abundances during quiescent phases show general underabundance relative to solar photospheric values, except for Ne, which remains enhanced, likely due to uncertainties in its solar reference value. The Fe/O abundance ratio, a reliable indicator of FIP bias, remained low (0.02–0.03) during quiescence and increased slightly during flares (up to 0.04), suggesting a weaker i-FIP effect during flaring episodes. This trend implies that increased heating during flares may reduce the efficiency of the fractionation process. The i-FIP effect in AB Dor appeared stable over a 19-year period, seemingly independent of its photospheric activity cycle. Similarly, HR 1099 exhibited a consistent i-FIP effect in both quiescent and flaring states, with Fe/O ratios of 0.36±0.02 and 0.35±0.05, respectively, aligning well with values reported in earlier studies. These results support the idea that the i-FIP effect is a persistent feature in highly active stars and may be governed by underlying processes such as wave-driven ponderomotive forces, which vary with stellar type, age, and magnetic activity levels.

The observed variations in hydrogen column density ($N_H$) during multiple flares on AB Dor suggest the likely presence of coronal mass ejections (CMEs), particularly given the enhanced $N_H$ during flare peaks and post-flare phases, along with dimming signatures in the X-ray light curves. The significant variation in $N_H$ values points to local absorption, likely from CME-related plasma. Consistency between $N_H$ estimates from spectral fitting and the ice-cream cone model further supports this scenario. These results show that looking at the effect of rotational modulation, variations in $N_H$ , and dimming in the light curve can help us identify CMEs on active stars.

## 7.2 Future Plans

During the course of my Ph.D. journey, I came across several new ideas and scientific directions that hold potential for further exploration. While this thesis has addressed many important aspects of stellar flaring activity and coronal dynamics, there are still areas that remain open and require more detailed investigation. These gaps present valuable opportunities for extending the current work. I intend to pursue these research directions in the near future, with the aim of gaining deeper insights into the physical processes governing magnetically active stars. My future research plans are outlined below.

- In this thesis, our study focused on flaring activities in two magnetically active stars, AB Dor and HR 1099; further investigation with a larger flare sample from these stars is essential to improve the statistical significance of the findings. Long-term monitoring of these stars would enable us to explore trends in stellar magnetic activity cycles and flare frequency distributions. Further, I would like to expand the sample size to include more K-type flaring stars, which would enhance and deepen our understanding of stellar flare dynamics. Additionally, obtaining more resolved data and adopting a multiwavelength perspective could provide a more comprehensive understanding of coronal geometry and the physical processes occurring during the flares on such stars.

- Additionally, I would like to explore detailed photometric mapping of these active stars to investigate starspot morphology, their temporal evolution, and spatial correlation with flare sites. Also, linking photospheric activity, observable in optical light, with coronal activity seen in X-rays could illuminate the connection between magnetic surface features and high-energy phenomena such as flares and CMEs. Studying rotational modulation in a larger sample of active stars will also help in identifying long-term variations in starspot distributions and overall activity levels.

- AB Dor continues to attract attention from researchers because of its strong magnetic activity, frequent flares, and the potential for coronal mass ejections (CMEs). With the help of recent advancements, by analyzing stellar light curves, it's now possible to link certain features, like sudden dimming, to possible CME events. In this study, detecting flare-related CMEs was difficult due to limitations in the available instruments and the lack of simultaneous observations across different wavelengths. In the future, using multi-wavelength high-resolution data, I would like to explore stellar CMEs more accurately and in greater detail.

- I would like to further investigate into the FIP and inverse-FIP effects observed during both quiescent and flaring states, which can lead to a better understanding of the fractionation processes in stellar coronae.

- In this study, we used a hydrodynamic loop model to analyze flare characteristics. However, incorporating more advanced models in future work could provide deeper insights, and comparing different flare modeling approaches may lead to a more accurate understanding of loop geometries and flare energetics.

This thesis lays the groundwork for understanding high-energy flares in Sun-like stars and highlights the need to study magnetic activity in a wider range of stellar environments. The ultimate goal is to uncover the physical processes behind the various features we observe. With better observations and improved theoretical models, we will be able to explore these phenomena in much greater detail. This approach will help guide and shape future research in the field.