Chapter 8

Conclusions

This thesis uses detailed dynamo modeling to enhance the understanding of how magnetic fields are generated and vary in the Sun and other solar-like stars. The Sun and stars are inherently magnetic, and their fields hint at their stellar evolution and how they influence the habitability of nearby exoplanets. The variability of these magnetic fields—manifested in cycles, irregularities, and grand minima—provides valuable insights into the dynamo mechanisms that generate them. However, many aspects of stellar dynamos remain less understood, partly due to the limited observations caused by their vast distances from us.

The findings from the various works done in this thesis collectively enhance our grasp of the processes driving stellar magnetic cycles and provide significant insights into the variability observed in stars of different rotational and internal dynamics. Chapter 2 introduces the basics of magnetic field generation in solar-like stars and explores the possible operation of a dynamo below the critical dynamo number (Vashishth et al., 2021). **Through axisymmetric kinematic dynamo modeling with Babcock-Leighton processes, this work confirms the existence of subcritical dynamo branches and hysteresis behavior. The results demonstrate that both stable, large-scale oscillatory magnetic fields and weak, decaying fields can coexist depending on initial conditions**. These results remain robust even when the magnetic field-dependent nonlinearities in $\alpha_{\rm BL}$ and η_T are connected to the local toroidal magnetic field or the toroidal field at the base of the convection zone. The stability of these subcritical branches under stochastic fluctuations confirms the robustness of these findings, even when magnetic field-dependent nonlinearities are connected to the local toroidal magnetic field. Thus, this study supports the possibility of subcritical dynamos driving large-scale magnetic cycles in Sun-like stars. After that, I move to Chapter 3, which examines the coexistence of large- and small-scale dynamos in stars and investigates hysteresis behavior (Vashishth, 2024b). **Using simulations with the** Pencil Code**, this study demonstrates that the features observed in large-scale global dynamos—such as the presence of subcritical dynamos and hysteresis—are preserved even with the inclusion of turbulent small-scale dynamos**. This further validates the robustness of dynamo operation in the subcritical regime, providing a more comprehensive understanding of dynamo behavior in both large and small scales.

Now, since meridional flow emerges as a critical factor in shaping the polar and toroidal magnetic fields in solar and stellar dynamos. **Chapter 4 looks at the role of meridional circulation in magnetic field generation and how changes in flow speed impact the strength and duration of magnetic cycles (Vashishth & Karak, 2024b).** In this study, we use the 3D STABLE (Surface flux Transport And Babcock–Leighton) dynamo model, which realistically captures the magnetic cycle and processes of the sun by generating a poloidal field through the emergence and dispersal of the tilted bipolar magnetic regions. **We observe that the polar field strength increases with a moderate increase in meridional flow speed but decreases once the flow exceeds a certain value.** In solar-like stars, the meridional flow speed is expected to vary with the rotation rate of the stars. Rapid rotators typically exhibit higher velocities near the surface but lower flow in the bulk of the convection zone, whereas slow rotators possess stronger flows in the bulk. In this work, we incorporate meridional flow from a mean-field hydrodynamics model for stars of different rotation periods and show that the strength of the magnetic field first increases with the stellar rotation rate and then declines at rapid rotation. The increasing trend suggests that the meridional flow is one of the contributors to the enhancement of magnetic activity with the increase of the rotation rate of solar-like stars. **The decline of the magnetic field strength at rapid rotation can help to compensate for the increase of field due to the**

enrichment of dynamo efficiency at rapid rotators and thus explains the saturation of magnetic activity in rapid rotators.

In rapidly rotating stars, BMRs are expected to emerge at high latitudes, which are less efficient in generating the poloidal field due to poor cross-equatorial cancellation. Therefore, chapter 5 focuses on the operation of the Babcock–Leighton dynamo in rapidly rotating stars. In this model, we extend Chapter 4 and incorporate meridional flow and differential rotation from a mean-field hydrodynamics model for stars of different rotation periods and explore the operation of Babcock-Leighton dynamo in various cases. We show that magnetic strength largely increases with the rotation period in rapidly rotating sun-like stars. When we raise the flux tube parallel to the rotation axis, the polarity shifts to quadrupolar. We also verified the operation of Babcock–Leighton process by changing the dependency of the rotation rate on the amplitude of Joy's law. Finally, we analyze the relationship between the cycle period and the rotation rate. Meanwhile, slowly rating stars shows a somewhat opposite trend that is yet to be explored.

In Chapter 6, through extensive simulations of the kinematic flux transport dynamo model with stochastically forced Babcock–Leighton source for the stars of $1M_\odot$ mass with rotation periods of 1, 3, 7, 10, 15, 20, 25.38 (solar value), and 30 days, **I study how rapidly rotating stars exhibit more irregular and stronger magnetic activity than slower rotating stars, with fewer occurrences of grand minima Vashishth et al. (2023). Grand minima are predominantly observed in slowly rotating stars, with their frequency and duration increasing as rotation slows. The results align closely with observations of the Sun and other solar-like stars because the observed Maunder minima candidates are slow rotators. Our results of the trend of the cycle variability and the grand minima are not expected to change with many details of the model (e.g., type of nonlinearity, stochastic fluctuations, turbulent transport) because they depend on the amount of supercriticality of the model.** It is obvious to accept that the dynamo supercriticality decreases with the decrease of the rotation rate of the star (mainly due to the decrease of α). Extended grand minima are easy to produce when the dynamo is near critical. Also, observations hint that the solar dynamo (which produces grand minima) is operating near the critical transition. **Furthermore, observing robust results (mainly the increase of the number and duration of grand minima with the increase of rotation period) in all the models having different parameters, I can have confidence that my results will be validated in the more realistic stellar dynamo models and observations.**

Transitioning from this, I move toward Chapter 7. In this study, using a mean-field kinematic dynamo model, we have explored the possible operation of a dynamo in stars that rotate ever slower than the Sun and exhibit anti-solar differential rotation (the equator rotates slower than the poles) (Karak et al., 2020). **A sudden increase in magnetic field strength is observed at the transition from solar-like to anti-solar DR, driven by constructive reinforcement of the toroidal field.** The study also demonstrates that polarity reversals are possible in these stars under specific conditions, offering new perspectives on their magnetic field evolution. These findings support global MHD simulations and suggest the potential for cycles and superflares in slowly rotating stars with anti-solar DR.