Abstract

The observable universe contains approximately 200 million trillion stars, each unique in their nature, though many may exhibit similarities. Among them, the Sun stands as our closest and most extensively studied star. Understanding the mechanisms that sustain the Sun's magnetic activity can provide valuable insights into the behavior of solar-like stars. Especially how the study of the solar interior will help to understand the internal dynamics of Solar-like stars. On the other hand, studying solar-like stars can enhance our understanding of the solar interior and magnetic processes.

In recent years, there has been significant progress in observing late-type stars, which include Sun-like stars with varying masses, rotation rates, convection patterns, and magnetic field strengths. Stellar magnetic cycles exhibit irregularities, with stars of rapid rotation showing stronger and more irregular magnetic activity compared to slowly rotating stars. Some stars also experience extended grand minima, similar to the Maunder minima observed in the Sun. It is now well established that global rotation plays a vital role in determining various features of stellar magnetic activity. Hence, the primary goal of this thesis is to make detailed dynamo models for the stars with different rotation rates and explain these observational trends of the magnetic activity as a function of their rotation. One of the major questions that I address by conducting extensive dynamo simulations is how the stellar cycle variability and grand minima depends on stellar rotation rate.

The large-scale magnetic activity in solar-like stars is sustained by the hydromagnetic dynamo process, a cyclic mechanism responsible for the generation and maintenance of the two primary components of the magnetic field: the azimuthally directed toroidal com-

ponent and the poloidal component, aligned with the stellar poles. Through differential rotation, the poloidal field is largely transformed into the toroidal field (Ω effect). Subsequently, the toroidal field regenerates the poloidal component via helical convective turbulence (α effect) and/or the Babcock-Leighton process. In this type of α-Ω dynamo model, the governing parameter is the dynamo number D, which depends on the measure of α-effect, the variation in the angular velocity in the sun/star, the star's radius, and the turbulent magnetic diffusivity. There is a critical dynamo number (D_c) below which the dynamo is not possible, and the initial magnetic field decay. The regime below D_c is known as the subcritical regime, and above D_c is called the supercritical regime.

Since the rotation rate of a star decreases with age, the dynamo number D is expected to decrease as the star spins down. Therefore, one might think that the dynamo ceases immediately when $D < D_c$. In Chapter 2, I explored the possible operation of the dynamo working in the subcritical regime. Through axisymmetric kinematic dynamo modeling with Babcock-Leighton processes, this work confirms the existence of subcritical dynamo branches and hysteresis behavior which says that both stable, large-scale oscillatory magnetic fields and weak, decaying fields can coexist depending on initial conditions. Now, for Sun, many observations suggest that the large-scale field co-exists with the small-scale field at the same time and location. In Chapter 3, using simulations with the Pencil Code, I further validate the robustness of dynamo operation in the subcritical regime. 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.

Now, since meridional flow emerges as a critical factor in shaping the polar magnetic fields in solar and stellar dynamos. Studies indicate that meridional circulation changes with stellar rotation rate, suggesting that this flow influences the properties of stellar magnetic cycles. Chapter 4 looks at the role of meridional circulation in magnetic field generation, how changes in flow speed impact the strength and duration of magnetic cycles. In this study, I 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. I observe that the polar field strength increases with a moderate increase in meridional flow speed but decreases once the flow exceeds a certain value. The study further explores how negligible meridional flow results in poor cross-equatorial cancellation, while increased flow speeds enhance the transport of trailing polarity flux, thereby strengthening the polar field. A further increase in flow leads to both leading and trailing polarity fluxes moving towards the poles, which diminishes the polar field. Similarly, the toroidal field also exhibits a dependency on meridional flow, increasing at moderate speeds before decreasing due to the competing effects of shearing and diffusion. In this work, I also incorporate meridional flow from a mean-field hydrodynamics model for stars of different rotation periods. The study highlights the connection between flow speed, magnetic cycle strength, and cycle duration, and offers an explanation for the observed saturation of magnetic activity in rapidly rotating stars.

However, in rapidly rotating stars, starspots are expected to emerge at high latitudes, which are less efficient in generating the poloidal field due to poor cross-equatorial cancellation. Chapter 5 focuses on the possibility of the operation of the Babcock–Leighton dynamo in rapidly rotating stars. In this model, I extend Chapter 4 and incorporate meridional flow and differential rotation from a mean-field hydrodynamics model for stars of different rotation periods and validate the working of Babcock-Leighton process in fast rotators. Aditionally, when I made starspots to appear in the high latitudes by raising the flux tube parallel to the rotation axis, then the polarity shifts to quadrupolar. I also verified the results by varying the dependency of the rotation rate on the amplitude of Joy's law.

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 different rotation periods. I study how rapidly rotating stars exhibit more irregular and stronger magnetic activity than slower rotating stars, with fewer occurrences of grand minima. Grand minima are predominantly observed in slowly rotating stars, with their frequency and duration increasing as a star spins down. The results align closely with observations of the Sun and other solar-like stars because the observed Maunder minima candidates (HD

166620, HD 217014, HD 20807, and Sun) are slow rotators. Our results of the trend of the cycle variability and the grand minima remain robust and 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. Furthermore, I have confidence that my results will be validated in the more realistic stellar dynamo models and observations.

Transitioning from this, Chapter 7 addresses slowly rotating stars exhibiting anti-solar differential rotation, where the equator rotates slower than the poles. In this study, using a mean-field kinematic dynamo model, I have explored the possible operation of a dynamo in stars that rotate ever slower than the Sun and exhibit anti-solar differential rotation. A sudden increase in magnetic field strength is observed at the transition from solar-like to anti-solar differential rotation, driven by constructive reinforcement of the toroidal field. The study also demonstrates that the polarity reversals are possible in these stars under specific conditions, offering new perspectives on their magnetic field evolution. These findings give hint about the superflares in slowly rotating stars.

Finally, in Chapter 8, I provide the comprehensive summary and the conclusions of the research and findings presented in my thesis.

In summary, this thesis contributes to our understanding of stellar magnetic activity by developing comprehensive dynamo models to explain observed trends in magnetic cycles, variability, and grand minima across stars with different rotation rates. The findings highlight the critical role of rotation and large-scale flows in shaping magnetic field behavior. The variability of stellar magnetic cycles presented in this thesis has important implications for understanding "space weather" around stars, driven by their variable magnetic fields. This knowledge is also crucial for identifying the habitability of exoplanets orbiting around host stars, whose numbers are rapidly increasing. Additionally, variable magnetic fields influence stellar evolution through magnetic braking. These results provide a strong foundation for future research on stellar dynamos and magnetic phenomena across a wide range of stars, contributing to a deeper understanding of solar and stellar physics.