Research statement

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One of the main questions in heliophysics definitely concerns the relation between solar magnetic activities and the space weather. Sunspots and active regions are one of the manifestation of the solar magnetic field and their role in triggering phenomena like CMEs, flares, and coronal heating is known. Therefore, it is important to study the origin of sunspots and active regions and determine the underlying mechanism which creates them. It is believed that rising flux tubes from the bottom of the convection zone creates the sunspots. So far, this theory was not confirmed by numerical nor observational studies (Guerrero & Käpylä, 2011; Käpylä et al., 2014; Fan , 2009). Furthermore, the flux tubes are expected to expand as they rise, hence their strength weakens and some sort of reamplification mechanism must complement this model to match the observational properties of sunspots. In the following I briefly present my past research, which mainly has focused on the numerical studies of the different mechanisms for the formation of sunspots and active regions.

1 Past and current research activities

1.1 Sunspot formation: negative effective magnetic pressure instability

In the last few years, there has been significant development in a new model of magnetic field concentration using the negative effective magnetic pressure instability (NEMPI) in a highly stratified turbulent plasma. In fact, the suppression of the total turbulence pressure by a large-scale magnetic field leads to a negative term in total pressure, which causes the instability (Kleeorin et al., 1989, 1990; Brandenburg et al., 2012).

Recently, for the first time, we studied NEMPI in spherical geometry and in the presence of a dynamo-generated magnetic field. The purpose of this study was to see how NEMPI interacts with a dynamo-generated magnetic field. In this model plasma is highly stratified and an adiabatic equation of state was applied. The results of mean-field simulations (MFS) showed that NEMPI and dynamo act together very well but the resulting system behaves in a complicated manner. The reason is that in such model we deal with a coupled system which both NEMPI and dynamo effect simultaneously (Jabbari et al., 2013). This also showed that the coupled system of NEMPI and dynamo needs to be studied in more detail. Losada et al. (2013) found in direct numerical simulations (DNS) that in the presence of high Coriolis number, Co the growth rate of NEMPI increases, which was not consistent with the fact that the rotation suppresses NEMPI. This implies that there is another source which provides growth. This mechanism acts at the same time with NEMPI or even after NEMPI was suppressed. One explanation -which later was proved by MFS- was that for higher Co, an α dynamo is activated and causes this observed growth rate. In other words, for large values of Co we again deal with the known coupled system of NEMPI and dynamo. Also, it was important to check if the α dynamo parameter we use for our simulation is a correct approximation. For this aim, we also performed simulations using the test-field method. Brandenburg et al. (2013) showed that in the presence of a vertical magnetic field, NEMPI results in a magnetic field concentration of equipartition field strength due to a converging flow. Such case leads to the formation of a magnetic spot, which was suggested to be based on flux tube modeling. This motivated us to study field concentration driven by a vertical field and properties of the resulting flux tube in more detail. MFS was used to consider the effect of aspect ratio and scale separation on NEMPI. The dependence on magnetic field, magnetic Prandtl number and magnetic Reynolds number, was studied by DNS (Brandenburg et al., 2014).

1.2 Sunspot formation: bi-layer model

Mitra et al. (2014) suggested a bi-layer model to study the formation of magnetic structures in the presence of a dynamo-generated field. In this model, the turbulence is forced in the entire domain, but the forcing is made helical in the lower part of the box, and non-helical in the rest of the domain. They showed that such bi-layer model could lead to the formation of bipolar structures with a super-equipartition strength. This motivated us to study the same system in spherical geometry. Our results showed that when the stratification is high enough, intense bipolar regions form and as time passes, they expand, merge and create giant structures (see Figure 1). We studied two different helicity profile and showed that the case of a simple cos profile leads to the formation of spots near the pole which is similar to the spots on a fast rotating star Jabbari et al. (2015). To understand the underling mechanism for the formation of such intense, long lived bipolar structures with sharp boundary we performed a new series of simulations in plane geometry and investigated this model in more detail Jabbari et al. (2016). We performed a systematic numerical study of this model by varying magnetic Reynolds number, the scale separation ratio, and Co. We further investigated the formation of a current sheet between bipolar regions and reconnection of the opposite magnetic field lines (see Figure 2). We determined the reconnection rate by both, measuring the inflow velocity in the vicinity of the current sheet and measuring the electric field in the reconnection region. We demonstrated that for small Lundquist number, $S < 1000$, the reconnection rate follows standard Sweet-Parker theory but for much larger S, the reconnection rate is nearly independent of S in agreement with results of recent numerical simulations performed by other groups in a simpler set-ups (Jabbari et al., 2016).

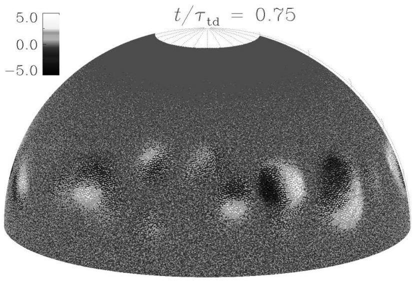

Figure 1: $B_{\rm r}/B_{\rm eq}$ at $r/R = 0.98$ for a simulation with density contrast of 450.

1.3 Sunspot formation: SST data analysis

One important way to improve our understanding of the origin of sunspots and active regions is to use observational data. Nowadays we have access to data of different ground and space-based telescopes from different layers of the solar atmosphere and its surface. Below the surface, however, it is local helioseismology that can give information about the flow properties. One can use these properties to investigate the underlying mechanism of sunspot formation and even use it to predict these phenomena. Recent work by Singh et al. (2016) suggested that magnetic flux concentrations affect the surface modes and can be detected prior to its appearance on the surface. They use data from Helioseismic and Magnetic Imager, HMI, aboard Solar Dynamics Observatory, SDO, and studied the f-modes of three active regions. In our work, we are going to use data of Swedish Solar Telescope, SST, from different wavelength and perform a similar study of the modes for the sunspot AR12325. We will also repeat our analysis with the HMI data of the exact same spot.

1.4 Coronal heating

One of the existing mysteries about the Sun is related to its hot atmosphere and the relation between this phenomenon and solar magnetic activities. Heating of the corona has been subject of many studies and different mechanisms have been proposed to explain the observed properties of corona, e.g., damping magnetohydrodynamic waves, nanoflares, and reconnection. During my master project, I studied the structure of the coronal loop and the effect of damping waves on the heating of the corona. We suggested a model to drive the wave equation for slow mode oscillations of stratified loops with non-adiabatic damping profile. This equation extents the Klein Gordon equation to cover the non-adiabatic process by including the heating and radiation in the energy equation. Then we solved this equation analytically and investigated the effect of stratification on the frequency and profile of the oscillations and compared it with the homogenous system.

2 Future research plans

Recent DNS simulations of bi-layer models in spherical geometry have already demonstrated the possibility of formation of bipolar regions with a dynamo-generated magnetic field. So it is of interest to study this model in more detail and investigate the effect of rotation, shear, and a coronal envelop on the formation of bipolar structures in a spherical shell. I also plan to improve this model by including differential rotation. All pervious studies of bi-layer models solved an isothermal equation of state, so another improvement can be to solve energy equation by including more physics e.g., adding a cooling boundary, solving radiative transfer equation in the entire domain, and taking into account the ionization.

As I already mentioned, right now I am involved also in a project related to helioseismology of the sunspots using both SST and SDO data. I am planning to continue the analyzing of the data of more active regions and from different lines (right now we are looking at $H\alpha$ data of SST). The result of this study will improve our understanding of the effect of flux concentration on the different modes. This can be used as a tool to predict the flux concentration prior to its emergence.

Regarding my other interests, I would like to investigate the coronal heating problem using both simulations and observations. For this purpose, I will focus on the role of coronal waves in the heating of the corona. One first step will be to simulate a convective box with corona at the top and study the flux emergence from the convective layer to the corona and investigate the properties of the resulted loops. The second step is to evaluate our result using observational data to improve the model.

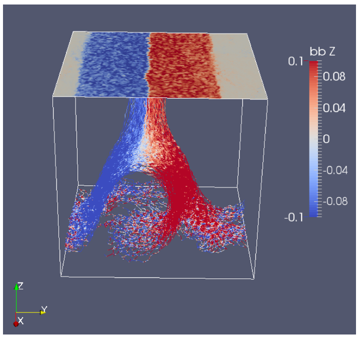

Figure 2: Three-dimensional visualization of vertical magnetic field, B_z at the surface (color-coded) together with magnetic field vectors.

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