Magnetic flux emergence on the Sun and Sun-like stars

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Abstract

For our understanding of stellar magnetic activity across the Hertzsprung Russel diagram it is essential to study how dynamo generated magnetic field in stellar convection zones is transported toward the stellar surface, reorganized in the near surface layers to form star spots, and expands into the stellar coronae. For a detailed study of the process of flux emergence, the sun plays a central role, since only here the relevant processes can be studied in sufficient resolution and also detailed subsurface information can be derived through means of local helioseismology. Major advancements in this field in the near future are possible due to a combination of high resolution multi-wavelength observations, numerical simulations, and advancement in local helioseismic techniques.

1 Introduction

It is believed that magnetic activity on main sequence stars with outer convection zones is driven by a dynamo operating within the convective envelope. To understand how this magnetic field leads to the observable magnetic activity, it is essential to understand the flux emergence process, which encompasses the transport of magnetic field toward the stellar surface, the formation of starspots, and the expansion of the magnetic field into the stellar corona. While global properties of surface magnetism can be studied in a variety of stars (e.g. Haisch et al., 1991; Schrijver , 1993; Strassmeier , 1996), only the sun allows us to study these processes with sufficient detail to elucidate the underlying magneto-convection processes in the interior and the magnetic field reconfiguration in the solar corona.

Despite the much finer resolution available through solar observations, the physical understanding of sunspot structure has been hampered for decades by 1) insufficient resolution of the fine structure by observations, 2) lack of information about the layers below the visible surface, and 3) insufficient computational power to perform ab-initio 3D MHD simulation of a full sunspot including the surrounding granulation. Recently, we have seen considerable progress on all three of these fronts: 1) adaptive optics, image selection and reconstruction at ground-based telescopes and the advent of spectro-polarimetry in the visible from space with the *Hinode* satellite have led to a wealth of new information about the fine structure of sunspot umbrae and penumbrae (e.g. Bharti et al., 2007; Langhans et al., 2007; Ichimoto et al., 2007; Riethmüller et al., 2008; Rimmele & Marino, 2006) 2) local helioseismology

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has started to probe the sub-surface structure of sunspots (e.g., Gizon and Birch , 2005; Cameron et al., 2008), and 3) the ever-increasing computational power of parallel computers has enabled us to performs ab-initio simulations of full sunspots.

Recent multi-wavelength observations of emerging active regions with high temporal and spatial resolution from both ground based and space based instruments have also revealed signatures indicative of the transport of twisted magnetic flux from the interior into the solar atmosphere and corona. These include sunspot rotations, highly sheared transverse magnetic fields at the polarity inversion lines (PILs), and in some cases the rotation of the transverse magnetic fields into an inverse configuration at the PILs (e.g. Lites et al., 1995; Brown et al., 2003; Okamoto et al. , 2008; Zhang et al., 2008). Very often these signatures are found to be associated with the brightening of X-ray sigmoid loops and the onset of eruptive flares in the corona. These observations provide important clues to the physical processes responsible for the build-up of twisted coronal magnetic structures containing free magnetic energy, capable of driving solar eruptions. MHD simulations of the emergence of a twisted magnetic flux tube from the solar interior into the solar atmosphere and corona have begun to reproduce qualitatively many of the above observed signatures in emerging active regions (e.g. Magara and Longcope , 2001, 2003; Magara , 2004; Manchester et al. , 2004; Archontis et al. , 2004; Murray et al. , 2006; Magara , 2006; Archontis and Toëroëk , 2008; Fan , 2009)

2 Sunspot fine structure, detailed magneto convection

Over the past few years there has been a tremendous progress leading to a new realism in theoretical modeling of sunspot structure and a unified understanding of magneto-convection in strong field regions (Stein and Nordlund , 2000; Schüssler & Vögler, 2006; Heinemann et al., 2007; Rempel et al., 2009). While Schüssler & Vögler (2006) focused on understanding magneto-convection in strong field regions using a simulation localized in the center of the umbra of a sunspot, Heinemann et al. (2007) were the first to perform a simulation encompassing the transition from almost field free granulation toward the umbra of a sunspot. Rempel et al. (2009) expanded this work by performing a simulation of a 20 Mm wide sunspot, showing for the first time the transition from umbral dots to filaments in the inner penumbra of a sunspot. All these simulations showed the common magneto-convective origin of sunspot fine-structure. Work currently in progress expands upon this even further by simulating an entire active region (100Mm $\times$ 50Mm), showing for the first time also the origin and depth structure of the Evershed flow. The big numerical challenge of detailed modeling of sunspots and active regions comes from the combination of large domain sizes required to get the global field structure right and the high resolution needed to resolve the relevant scales of magneto-convection. The coming decade will likely lead to fundamental break throughs, since advances in computing power will allow simulations on scales of active regions with grid resolutions of less than 10 km required to fully resolve the relevant magneto-convection. At the same time new large aperture telescopes such as ATST will allow to observe details of the magneto-convection process, which are currently still near the resolution limit of current ground and space based instrumentation.

3 Sunspot formation and large-scale structure

Unsolved problems of the large-scale sunspot structure are primarily related to the formation of sunspots, subsurface structure and connectivity, as well as large scale flows (moat flows) surrounding spots. While it is generally accepted that sunspots form from magnetic field rising from the base of the convection zone to the surface (see reviews by Moreno-Insertis, 1997; Fisher et al., 2000; Fan, 2004, and further references therein), the last stages of the emergence process are not well understood. The latter is primarily due to the fact that the numerical approximations (thin-flux tube, anelastic) used to describe the rise through the bulk of the convection zone break down near the surface and radiative MHD simulations used to describe very accurately the surface layers cannot (yet) be extended sufficiently downward to allow for a sufficient overlap and coupling with the former.

The coming decade promises significant discoveries in this field, since on the one hand advances in computing power will allow us to address the subsurface structure and formation of sunspots in realistic MHD simulations; on the other hand significant progress can be also made by combining simulations with helioseismic inversions through forward modeling. While recent work by (Cameron et al., 2008) focuses on modeling the wave propagation through a given magneto-hydrostatic sunspot model, simulations can push this effort further by self-consistently coupling the excitation and propagation of waves with the dynamical evolution of the sunspot as well as moat flows in its periphery. The benefits from this interaction with helioseismology are twofold. On the one hand, numerical simulations can help to improve inversion methods to accurately separate thermal, magnetic, and flow effects; on the other hand helioseismic constraints on the subsurface structure can help to improve sunspot simulation by providing a more realistic initial state.

4 Emergence of active region flux into the solar atmosphere and the corona

Understanding how twisted magnetic fields emerge from the dense, convectively unstable solar convection zone into the stably stratified, rarefied solar atmosphere and corona is fundamentally important for understanding the formation of solar active regions and the development of precursor structures for solar eruptions such as flares and CMEs. In recent years, a large body of 3D MHD simulations have been carried out to study the dynamic emergence of a twisted flux tube from the top layer of the solar interior into the solar atmosphere and the corona (e.g. Fan , 2001; Magara and Longcope , 2001, 2003; Magara , 2004; Manchester et al. , 2004; Archontis et al. , 2004; Murray et al. , 2006; Magara , 2006; Archontis and Toëroëk , 2008; Fan , 2009). It has been shown that magnetic flux reaching the photosphere can undergo a dynamic expansion into the atmosphere as a result of the non-linear growth of the magnetic buoyancy instability.

These simulations also suggest that a twisted subsurface flux tube does not rise bodily into the corona as a whole due to the heavy plasma that is trapped at the bottom concave portions of the helical field lines. It is found that shear and rotational flows on the photosphere driven by the Lorentz force of the twisted flux tube during flux emergence are the crucial means whereby twist is transported from the interior into the solar corona, driving the formation of a coronal flux rope with sigmoid-shaped, dipped core fields (e.g. Magara and Longcope , 2003; Manchester et al. , 2004; Magara , 2006; Manchester , 2007; Fan , 2009). The models suggest that sunspot rotations are a manifestation of nonlinear torsional Alfvén waves propagating along the emerging flux tube, transporting twist from the tube's interior portion, where the rate of twist is high, towards its expanded coronal portion, where the rate of twist is much lower (Longcope and Welsch , 2000; Fan , 2009). The rotational motions of the two polarities are found to twist up the inner field lines of the emerged fields such that they change their orientation into an inverse configuration (i.e. pointing from the negative polarity to the positive polarity over the neutral line), leading to the formation of the sigmoid-shaped core field of a coronal flux rope (Fan , 2009).

Due to the need to resolve the photospheric pressure scale height ($\sim$ 150 km) and the short dynamic time scale in the low plasma β region in the corona which severely limit the numerical time step, most of the above simulations were done on domain sizes a few times smaller than active region size scales. With the advance of massively parallel super-computing, simulations of active region scale flux emergence with significantly increased horizontal and vertical domain size scales are becoming feasible.

5 Conclusion

Recent advancement in computing power has enabled ab-initio numerical simulations of magneto-convection in the top layer of the solar convection zone and the photospheric layers, on scales of sunspots and active regions including the surrounding moat region with sufficient resolution to show penumbral fine structure as well as umbral dots. While the simulations capture the basic properties of penumbral filaments (weaker almost horizontal field, outflows along filaments, central dark lanes), the overall appearance of the penumbra in terms of width and filament density are not (yet) fully reproduced. These simulations clearly indicate that the underlying magneto-convection processes happen on scales which are currently at the resolution limit of large scale simulations as well as current ground and space based telescopes. Significant progress is likely through a combination of high resolution simulations of entire active regions and new large aperture ground-based instrumentation such as ATST. Apart from still insufficient numerical resolution to resolve the photospheric layers in detail, the lower boundary condition as well as the initial magnetic field configuration are currently the major uncertainties and shortcomings in our ability to numerically model the process of sunspot formation. Further advancement in computing power in the next decade is likely to enable a full numerical model of solar active region formation, encompassing both realistic magneto-convection modeling of the formation of sunspots from rising flux tubes and the emergence of the active region flux into the stably stratified solar atmosphere and the corona. Prototypes of such full numerical model are already being developed but have only been run on cases with domain sizes significantly below active region scales, e.g. Abbett (2007) and Martínez-Sykora et al. (2008). In the meantime a combination of local helioseismic inversions with MHD simulations as forward modeling tool is the most promising way to understand the subsurface sunspot structure in detail. Furthermore, coordinated multi-wavelength observations of emerging active regions at high temporal and spatial resolutions, combined with MHD simulations of flux emergence into the atmosphere at active region scales, will advance our understanding of how twisted coronal structure capable of driving eruptive flares are formed through active region flux emergence.

For the possibility of detecting subsurface rising flux tubes and inferring the subsurface structure of emerged active regions with local helioseismology, continuous observations of solar oscillations on the surface are required. The helioseismic signatures of subsurface emerging active regions are thought to be very subtle; there has not yet been a definitive detection of a rising flux concentration much below the photosphere (for some very recent results see Kosovichev , 2008). As a result, it may be necessary to study rising flux in a statistical sense (rather than on a case-by-case basis). The GONG network currently provides high quality continuous data for helioseismic studies of emerging and evolving active regions. We emphasize that GONG is by no means redundant or made obsolete by existing or planned spacecraft observations. Independent data sets provide the opportunity to detect systematic artifacts. In addition, the GONG network provides a unique (and relatively cost-efficient) source of continuous data over the long term (spanning multiple solar cycles) for studying the subsurface properties of emerging and evolving active regions on the Sun.

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