Interaction of convective plasma and small-scale magnetic fields in the lower solar atmosphere

Santiago Vargas Domínguez1 · Dominik Utz2,3

Received: 2 May 2022 / Accepted: 27 September 2022 © The Author(s) 2022

Abstract
In the following short review we will outline some of the possible interaction processes of lower solar atmospheric plasma with the embedded small-scale solar magnetic fields. After introducing the topic, important types of small-scale solar magnetic field elements are outlined to then focus on their creation and evolution, and finally end up describing foremost processes these magnetic fields are involved in, such as the reconnection of magnetic field lines and the creation of magneto-hydrodynamic waves. The occurrence and global coverage in the solar atmosphere of such small-scale phenomena surpass on average those of the more explosive and intense events, mainly related to solar active regions and, therefore, their key role as building blocks of solar activity even during the weaker phases of the 11-year solar cycle. In particular, understanding the finest ingredients of solar activity from the lower to the upper solar atmosphere could be determinant to fully understand the heating of the solar corona, which stands out as one of the most intriguing problems in astrophysics nowadays.

Keywords Solar atmosphere · Magnetic fields · Convective plasma · High-resolution

Santiago Vargas Domínguez
svargasd@unal.edu.co

Dominik Utz
Dominik.Utz@Kepleruniklinikum.at

1 Observatorio Astronómico Nacional, Universidad Nacional de Colombia, Bogota, Colombia
2 Institute of Physics, Faculty of Science, University of South Bohemia, České Budějovice, Czech Republic
3 Neuroimaging Science and Support Center-NISSC, Institute of Neuroradiology, Kepler University Hospital, Linz, Austria

Published online: 20 October 2022
1 Introduction

The surface of the Sun, known as photosphere, displays a plethora of features at several spatial and temporal scales, mostly related to the existence of convective flows, which in turn transport plasma and magnetic fields from the solar interior. Sunspots are the most prominent and best studied manifestation of the emergence of the most intense magnetic flux, and their appearance/disappearance in the photosphere is directly related to high/low activity of the Sun, being the basis for the discovery and characterization of the solar cycle.

From the visible sunspots or groups of them, to the finest magnetic elements, studying the evolution of magnetic fields embedded in the photospheric plasma is essential to understand multiple other processes occurring from the lower to the upper solar atmospheric layers, which are responsible for phenomena involving energy release and ultimately have implication on space weather.

Concerning the solar plasma, the photospheric one can be described theoretically well by a single fluid magnetohydrodynamic (MHD) approach due to the comparatively large density and strong collisional coupling between ions and neutrals. This allows for full fledged computer simulations due to the still manageable computational power needed for such simulations (e.g., Vögler et al. 2005). Contrary to the photosphere, the corona can be described by a fully ionized plasma changing the theoretical description dramatically (e.g., usage of kinetic approaches during flare events to describe particle acceleration processes Bárta et al. 2011; Zhao et al. 2021). The layer in between—chromosphere—is the most complicated one to theoretically describe in full detail, as the transition from a weakly ionized plasma to a fully ionized one is occurring in this region. Due to the lower density in the chromosphere, compared to the photosphere, the non-ideal (multi-fluid) effects are more pronounced. Thus the approach of multi-fluid MHD is heavily utilized nowadays for this layer (Martínez-Sykora et al. 2012), although the pure ideal MHD theory has been very successful in explaining lots of observational phenomena in the solar corona and especially the photosphere.

From the observational point of view, the photosphere is characterized by the presence of flow convective patterns at multiple spatial and temporal scales, being the so-called granulation, mesogranulation, and supergranulation, the more studied ones, from lower to greater scales. Granular cells are characterized by diameters of 100 km, vertical flows of 1 km s\(^{-1}\) and lifetimes of 0.2 h. Mesogranular cells have diameters of 5000 km, vertical flows of 60 m s\(^{-1}\) and lifetimes of 3 h. Supergranular cells exhibits diameters of 32,000 km, horizontal flows of 400 m s\(^{-1}\) and lifetimes of 20 h. While granulation and supergranulation are definitely present, well known and confirmed numerous times, the origin and existence of mesogranulation, also known as family of granules, is still under debate, as summarized in (Rast 2003, and references therein).

Correlation tracking techniques have been extensively used since the 80s to study the evolution of such patterns (November and Simon 1988; Title et al. 1989; Palacios et al. 2012, and references therein). In particular, the evolution of granules, with their typical expansion and fragmentation, and interaction with
embedded small-scale magnetic fields, have been studied to characterize the disturbance of the granulation pattern and the accumulation of magnetic fields in intergranular regions (Domínguez Cerdeña et al. 2003; Ishikawa and Tsuneta 2011). The grouping of magnetic fields at different sizes, from small-scales, such as Magnetic Bright Points (MBPs; Dunn and Zirker 1973; Berger et al. 2004), to large-scale magnetic concentrations such as sunspots or active regions can be detected in the photosphere, and have been matter of observational and theoretical studies. While sunspots have been widely observed for centuries, small-scale magnetic features were elusive until the advent of high-resolution solar instrumentation. Such compact and minuscule magnetic fluxes are thought to constitute building blocks of solar activity (see, e.g., Zwaan 1987), considering that they are, for instance, more ubiquitously distributed in the Sun (see, e.g., Utz et al. 2013) and the fact that exist even during the weakest phases of the solar cycle (Utz et al. 2016), therefore, playing an important role in the overall layout of the star (for detailed analysis of the solar cyclic behaviour as well as latitudinal distribution of small scale fields as observed by the Solar and Heliospheric Observatory (SoHO) with the Michelson Doppler Imager (MDI), see, Jin and Wang 2012).

2 Small-scale solar magnetic fields

The solar surface is spreckled with small-scale solar magnetic field elements which are more or less organised. We can differentiate between the regions of occurrence in network magnetic field elements and intranetwork fields. Network regions comprise generally the larger and stronger small-scale elements being characterized by their vertical magnetic field often reaching kG. Intranetwork fields are found inside the magnetic network roughly corresponding to the boundary of the supergranular cells and being, contrary to the network fields, frequently orientated horizontally and weaker, with field strengths of about 100 G. In the following sections, some of the important types of small-scale solar magnetic field elements are introduced.

2.1 Pores

Pores are visible structures in the photosphere, characterized by purely dark areas, as “naked” sunspots without a penumbra (García-Rivas et al. 2021), as displayed in Fig. 1. The generation of pores is a consequence of the inhibition of convection once magnetic field emerges from the boundary between radiative and convective zones (tachocline) due to buoyancy driven instabilities, and crosses the photosphere, thus reducing the transfer of heat from lower layers, making them look dark. Pores exhibit diameters in the range from 1000 to 6000 km (for detailed statistics, see, e.g., Cho et al. 2015), and can harbour smaller structures produced by the convection not being fully suppressed by the emerging magnetic field, such as umbral dots (e.g., Schüssler and Vögler 2006) and light bridges (Sobotka et al. 2013) commonly known and found in larger sunspots. For many years solar pores were the
finest coherent magnetic structures that were able to be studied rigorously in the photosphere, while even smaller magnetic field concentrations have been, to a major fraction, characterised only phenomenologically via photometric observations (e.g., bright filigree observations). However, solar pores are, for the current high-resolution solar physicists, just the starting point for going into much smaller spatial scales to discover new exciting phenomena.

Fig. 1 Sequence of evolutionary stages of a pore during its lifetime as presented by García-Rivas et al. (2021). Images show intensity maps with white contours for $I = 0.55I_{\text{QuietSun}}$, and magnetic field strength contours in blue for $B = 1921$ G (top row), vertical magnetic field contour of $1731$ G in orange (second row). Maps of magnetic field strength are shown in the last two rows, using the same contours code as in first and second rows, respectively

Pores seem like a perfect laboratory to study the interaction and evolution of almost vertical emerging magnetic fields with the convective pattern around, considering that, different from sunspots, pores do not exhibit a formal penumbra (see, Bray and Loughhead 1964; Cameron et al. 2007), which is generated by more inclined magnetic fields. Pores can be, therefore, regarded as the first step prior to the evolution of a sunspot although not all pores will eventually evolve into sunspots but rather disintegrate and vanish (Muller et al. 1992; Sobotka et al. 1997). The relatively simple configuration of the magnetic field in pores represents an appropriate scenario to probe the interaction between the magnetic field and the moving plasma.

There are multiple studies dealing with the fine structures in and around pores, which reveal a complex interplay between the emerging magnetic flux and the convective plasma motions (Sobotka et al. 1999; Domínguez et al. 2010; Ermolli et al. 2017; Xu et al. 2022). In some cases, a transitory penumbra can be formed extending outwards from some regions of the pore. A number of bright dots can also be evidenced inside the pore, resembling the umbral dots (UD) detected in sunspots’ umbra but being more dynamic, brighter and with longer lifetimes, mainly due to
the pore’s weaker magnetic field that inhibits convection less efficiently (Sobotka et al. 1993). The immediate photosphere around pores is characterized by flows toward them, which can make small granules penetrate the pore’s border similar to UD, with average lifetimes of ~ 6 min, as studied in Wang and Zirin (1992) and more recently in chapter 6 of Dominguez (2009). In general, the elongated small-scale features are signatures of more inclined magnetic fields at the border of the pore García-Rivas et al. (2021).

2.2 Single flux magnetic fibrils

Detecting and understanding the behaviour of small-scale magnetic elements needs the combination of both, detailed observations and advanced numerical simulations. For nearly 3 decades, since the first pioneering observational work of Lites et al. (1996) and several following works (Centeno et al. 2007; Gömöry et al. 2010; González and Rubio 2009) using spectropolarimetric data at very small spatial scales of less than 2 arcsec (Fig. 2), it is now well-established the presence and overall action of small-scale individual magnetic loops emerging through the quiet solar atmosphere. The magnetic $\Omega$-loops, which emerge from beneath the photosphere, leave an imprint in the spectropolarimetric maps. While rising up, the more horizontal segment of the loops (apex) is the first part detected by linear polarization signals, subsequently followed by the more vertical field, which is evidenced by a pair of opposite-polarity circular polarization signals, as displayed in the sequence of frames in the lower panel in Fig. 2. Recent observations (Centeno et al. 2017) and

---

**Fig. 2** Observational evidence of small-scale magnetic loops emerging in the solar photosphere. Top row: Images taken from Centeno et al. (2007) with frames separated by 125 s displaying the solar granulation pattern with overlying contours in red, green, orange for positive circular, negative circular, and linear net polarization signals, respectively. The frames evidence the spatial correlation between the emerging magnetic flux and the location of the granule. Bottom row: Images of the solar quiet granulation pattern taken from González and Rubio (2009), with red contours representing linear polarization signals, and black and white contours for circular polarization ones. Axes are in arcsec.
numerical simulations (Moreno-Insertis et al. 2018) have evidenced the appearance of magnetic field patches, composed of bunches of fibrils, which cover single granules, exhibiting mainly aligned and horizontal magnetic fields, with the corresponding footpoints rooted close to the granular border. Some of them are low-lying loops which can rapidly submerge and disappear without any detectable action above a few hundred kilometers, but others rising further up can produce brightenings in the lower and upper chromosphere, meaning they are interacting with plasma and background fields at those heights, as will be commented in Sect. 5.1. It is now clear that a significant fraction of the quiet Sun is populated by magnetic fields. By increasing the integration time of the spectro-polarimeter of the Hinode mission (Kosugi et al. 2007), to larger and larger values, it was shown that the fraction of the photosphere occupied by magnetic fields increases until the point that one can detect magnetic fields practically over the whole field of view (Rubio and Suárez 2012). Weak intranetwork fields were found to be mostly horizontally orientated (e.g., Lites et al. 1996), and therefore, our understanding of the quiet Sun changed dramatically over the course of the last decades. From a magnetic atmosphere organized in active regions, a magnetic network, and magnetic void regions in between, the picture evolve into a more complex magnetic atmosphere full of small-scale highly dynamic field elements. This new way of conceiving the solar atmosphere highlights the importance of the small-scale solar magnetic fields for implications on the overall magnetic configuration of the Sun as well as for further implications on the overall solar activity.

### 2.3 Magnetic bright points

Magnetic bright points (MBPs) have been investigated since the 1970s (Dunn and Zirker 1973) when they were discovered in the intergranular lanes between the photospheric granules. Later their shapes were described in more detail as some MBPs form chain or ribbon-like structures, a kind of magnetic sheet, while others are situated roundish around granules looking like a flower pattern (see, Berger et al. 2004), as shown in Fig. 3.

In the recent years, it has become more and more common to study the magnetic nature and topology by means of spectro-polarimetric investigations and inversions (Viticchié et al. 2010; Riethmüller et al. 2014; Kuckein 2019; Keys et al. 2020; Hao et al. 2020). MBPs are features in the lower solar atmosphere with an increased brightness compared to their surrounding. Their relative brightness increase is due to the hot wall effect in combination with the possibility to increase the optical depth into the solar atmosphere. After the formation of MBPs, via the most commonly assumed convective collapse process (to be discussed in full detail in a following chapter), MBPs exist as very strong and partly evacuated magnetic field concentrations. To keep the structure evacuated the horizontal inward pressure of the surrounding plasma is balanced by the magnetic pressure of the contained strong magnetic field itself. However, strong vertical upflows might happen in MBPs leading to their destruction (Rubio et al. 2001). The mentioned evacuation of MBPs leads to a lower line formation height compared to its surrounding which now comprises...
deeper and hotter parts of the photosphere causing an increase in intensity. In addition, the hot walls of the magnetic “bore hole” can contribute (especially when observations are taken closer to the solar limb, Carlsson et al. 2004; Keller et al. 2004; Thaler and Spruit 2014).

MBPs are mostly studied in the photosphere with the help of the G-band filter. The G-band is a spectral region containing a vast number of CH molecular lines. Thus, using a filter centered at 430.5 nm containing these lines is advantageous as the contrast of small scale magnetic features is increased. This is due to a heat-dissociation effect (e.g., Almeida et al. 2001). As the light emitted within a magnetic structure originates from deeper atmospheric layers due to a local evacuation caused by the magnetic pressure, more of the absorbing CH molecules are dissociated and hence the absorption becomes weaker increasing the intensity of the structure further when compared to normal continuum (all the details can be found in, Steiner et al. 2001; Schüssler et al. 2003). Besides of the G-band, also shorter wavelength filters are partly employed, such as the CN band head filter at 388.35 nm, showing the features with an even higher contrast and slightly improved resolution under perfect conditions (low straylight contribution, good seeing conditions) (Zakharov et al. 2005; Riethmüller et al. 2014). In addition to the photosphere, MBPs can also be identified in the chromosphere (for a recent work, see, e.g., Xiong et al. 2017, 2017), and a special focus is given here on the connection between the two layers and wave phenomena (Jafarzadeh et al. 2013; Stangalini et al. 2017).

MBPs can be seen as the visible bright cross section of strong small-scale vertical magnetic flux tubes. Their magnetic field strength is generally thought to be in the range of kG, often reaching values of about 1.3 kG (see Beck et al. 2007; Keys et al. 2019), although, in the observations the inverted magnetic field depends a lot on the inversion routine. These are generally not too stable and lead to significant
ambiguity in the magnetic field measurements. Nevertheless, Schüssler et al. (2003) suggest that the Stokes Inversion based on Response functions (SIR) inversions show the magnetic field up to 1.9 kG. Furthermore, in the simulations, which are not suffering from inversion ambiguities and resolution effects, the magnetic field in MBPs can be even higher than that (e.g., Riethmüller et al. 2014).

The size of MBPs are observationally found in the range of a few hundred km (< 300 km; Muller and Keil 1983; Wiehr et al. 2004; Utz et al. 2009; Yang et al. 2014; Xu et al. 2021) down to the resolution limit of the most modern telescopes of 40–70 km (Abramenko et al. 2010). The actual shape of the size distribution of MBPs is still under debate (e.g., Utz et al. 2009; Abramenko et al. 2010) with an ever broader range of evidence pointing to log-normal distributed size distributions (e.g., Crockett et al. 2010; Saavedra et al. 2022).

MBPs have generally a very short lifetime in the range of a few minutes (e.g., Utz et al. 2010; Liu et al. 2018) as indicated by recent research. Older papers give values also in the range of 10–20 min (e.g., Muller 1983; de Wijn et al. 2008). This can be due to manifold reasons of which the most likely one are different instrumentation and methods to extract the features on the one hand and different selected features on the other hand, e.g., by manual pre-selection of the data sets (active/quiet Sun) and/or, especially in older studies, by a biased visual inspection and selection of the scientist. In former studies, and with lower cadence data, authors most likely biased their analysis to longer features as they were easier to observe, while on the contrary in modern studies, with high resolution telescopes, authors tend to prefer isolated MBPs belonging most likely on intranetwork fields which just might live shorter compared to MBPs related to stronger network magnetic fields. Another problem arises in the definition of lifetime as MBPs are highly dynamic and can split and merge on a regular basis. This fact brings up to the researcher the problem of finding the best considerations for the definition of lifetime for such ever changing features. Finally, the higher cadence in the data means also that the quality of an automated detection algorithm needs to be sufficiently good not to terminate prematurely a time sequence of an evolving MBP by missing one time instance and breaking a sequence into two shorter sequences. Overall, the findings can still be seen as an indication that there might be two populations of MBP features. This speculation is now even more backed up by similar findings in the magnetic field strength distribution (Utz et al. 2013; Keys et al. 2019) as well as in the size distribution (Saavedra et al. 2022). The distributions of both defining characteristics of MBPs show a bimodal behaviour with two distinct characterising values for the size as well as the magnetic field strength. Such a bimodal parametrization might be related to the occurrence of MBPs which can be found in the network as well as in the intranetwork region possibly giving rise to two populations of MBPs.

They are very dynamic, often undergoing splitting and merging events, especially when they are part of an enhanced magnetic network. Their horizontal velocities are around 1 km s\(^{-1}\) (e.g., Nisenson et al. 2003) sometimes reaching velocities as high as 4–6 km s\(^{-1}\) (Keys et al. 2011), which is important for the generation of MHD waves (Choudhuri et al. 1993). Their movement can be overall described by a random walk and they play a role in the diffusion of magnetic fields at the surface of the Sun (Hagenaar et al. 1999; Stanislavsky and Weron 2007).
Another interesting topic is the relationship between MBPs and granules. This subject caused more scientific interest some time ago with works like (Muller et al. 1989; Muller and Roudier 1992), where the authors studied the location of MBPs and the dynamic caused by the granular flows surrounding them as well as the idea of magnetic compression and granular buffeting. Recent works on this topic nowadays focus less on MBPs as tracers of strong magnetic fields but go more directly into high resolution magnetograms from high cadence magnetographs. An example is the work of Requerey et al. (2014) who follow in detail the evolution of a magnetic field patch from the emergence within a granule, the expulsion out of the granule, the agglomeration in a downdraft centre, and finally convective collapse events forming a kG strong MBP signature. Recent research to the interplay of granulation, intergranular lanes, and flux tubes can be found, also in Solov’ev et al. (2019).

While MBPs are tremendously important for small-scale processes and dynamics, as we will see in the next sections, they also play a fundamental role in the structuring of the larger magnetic field topology as can be seen in Hofmeister et al. (2019). In this work, the authors showed that the footpoints of coronal holes are anchored indeed in small-scale magnetic field concentrations often seen as MBPs.

3 Generation of small-scale magnetic fields

To generate magnetic fields one needs an operational magnetic field dynamo. On the global scale this is done in the Sun via an alpha/omega ($\alpha/\Omega$) dynamo which can be well simulated nowadays and creates the typical pattern of the sunspot distribution (e.g., Charbonneau 2020). On smaller scales evidence is mounting for an acting second local dynamo (Thaler and Spruit 2015; Borrero et al. 2017; Käpylä et al. 2018). However, magnetic field could be also injected via turbulence from larger scales (sunspots) down to smaller scales during the break up of sunspots at the end of their lifetime. A possible mechanism for this cascading flux injection would be Moving Magnetic Features (MMFs, Li et al. 2019). MMFs are small-scale magnetic elements which move radially away from decaying sunspots. Finally there are indications that the dynamo process should be even without significant scales as can be seen by a continuous magnetic flux spectrum (Parnell et al. 2009).

Recently, there are also first suggestions of a chromospheric small-scale dynamo (Martínez-Sykora et al. 2019). As the authors of the aforementioned work found in their computer simulations that the inflow of magnetic flux from the photosphere into the chromosphere is not sufficient to explain the rapid formation of chromospheric magnetic fields, they suggest that there must be a working mechanism to generate and amplify magnetic fields directly in the chromosphere (see Fig. 4). In their work they outline also ideas for such mechanisms. To summarize for the photosphere, magnetic flux can be injected from subsurface via flux emergence either by the working global dynamo and possibly on smaller scales by a more shallow secondary small scale dynamo or by shredding from large scale structures.

Flux emergence and the forming of magnetic field elements are well observed for both cases large active regions (e.g, on larger scales Rozo et al. 2019) as well as single magnetic loops (e.g., Gömöry et al. 2010). Sometimes also the emergence
happens in the form of magnetic bubbles (Ortiz et al. 2014) usually starting within the centre of granules. In a next step, the magnetic field gets expelled from the centre of the granule and starts to accumulate in the inter-granular lanes. Here the magnetic field can agglomerate and amplify up to roughly 400 G. This limit is given due to the build up of magnetic pressure which starts to resist in letting the magnetic field be further compressed by convective motion. From an energetic point of

Fig. 4 Simulations of the solar photosphere and lower chromosphere presented by Martínez-Sykora et al. (2019). Upper row: Emerging flux tubes (in red) in the photosphere (left panel), flux sheets (middle panel) and flux tube canopies (right). The horizontal map is vertical velocity cut at the photosphere with white/black for $2/-2$ km s$^{-1}$, respectively. Middle and lower rows: Magnetic field structures in the lower chromosphere, with vertical flux tube concentrations formed at the chromospheric shock fronts (top panels), and flux sheets of up to 64 G (bottom panels). The colorbar shows the field strength in Gauss

 Springer
view, the energy stored in the static magnetic field becomes larger than the energy
contained in the kinetic movement and thus the corresponding magnetic pressure
withstands further compression by the gas pressure (see also Solanki et al. 2006).
Investigations have revealed that the magnetic fields can travel within the intergranu-
lar lanes and are slowly, but steadily, advected into downdraft centres, where further
magnetic field amplification can happen (Requerey et al. 2014). On larger scales the
flux transport is dominated by the supergranular flows, and ultimately by meridional
flows bringing the magnetic flux to the poles of the Sun and causing there the polar
reversals, as part of the global solar magnetic field cycle (see also, Jiang et al. 2014).

4 Magnetic field amplification and the formation of the magnetic
network

On the individual magnetic field element level, one can observe magnetic field
amplification, which occurs once sufficient field has agglomerated at a downdraft
center and an instability, called “convective collapse”, sets in amplifying the several
100 G strong magnetic field further up into the region of 1 kG and beyond. On larger
scales the magnetic network is formed via magnetic flux transport to the boundaries
of supergranular cells, where the weak intranetwork fields merge to form stronger
network magnetic elements.

4.1 Convective collapse

The convective collapse scenario describes the magnetic field amplification in a
magnetic flux tube due to a thermodynamic driven instability and evacuation of the
flux tube. The basic scenario states that a sufficient strong magnetic field concentra-
tion in the form of a flux tube can start to inhibit the convective influx of new energy
in the form of heat from the subsurface layers. Thus, as there is a radiation loss
of energy and thus heat from the plasma confined in the magnetic field configura-
tion, the plasma starts to cool down and consequently these now denser and heavier
plasma starts to flow down and out of the flux tube. Due to the small-size of the
magnetic fields under investigation, e.g., MBPs, this process is very rapid leading
to the process named convective collapse as the evacuated flux tube now has not
sufficient inside pressure to prevent the magnetic field from compression/collapse.
The collapse leads to a strong amplification of the magnetic field, e.g., in the case
of MBPs from sub kG fields to kG fields. The process was theoretical described
by Parker (1978) and Spruit (1979) and later impressively shown by observations
from the Hinode mission in a case study Nagata et al. (2008), (see Fig. 5). Here the
observables (line-of-sight velocity, brightness, and magnetic field strength) followed
the theoreticized temporal evolution, namely, that a strong downflow is followed by
an evacuation of the flux (increase in brightness) and collapse of the magnetic field
(strengthening of the magnetic field strength). This result was verified and set on
more robust statistical foundations by Fischer et al. (2009). Early first indications for
the convective collapse process causing the magnetic field amplification are dating
back to at least the 90s (Solanki et al. 1996). Besides, researchers were searching for the effect of the convective collapse in simulations and comparing the magnetic field intensification as observed in the simulations with real observations. This means that they were comparing the typical time-scales (a few minutes), downflow velocities (4–10 km $s^{-1}$) and magnetic field amplification (from a few hundred G to above a kG) and found good agreement between observations and simulations (e.g., Danilovic et al. 2010).

Nowadays, the convective collapse scenario is considered the process being responsible for the creation of e.g., MBPs. While not only indicating the convective collapse as a fundamental process for the creation of MBPs Rubio et al. (2001) also gave an idea about the weakening and dispersion of MBPs by a back-propagating shock wave created by the impact of the evacuated plasma on the lower denser atmospheric plasma. These back-propagating shock waves increase the diameters of the flux tube, decrease thus the field strength and are probably a cause for the destruction and short lifetime of intense MBPs undergoing very strong convective collapse processes. Very recently, evidence is showing up for further processes leading to higher magnetic field strengths and thus amplifications in MBPs regardless of the convective collapse process (see, Utz et al. 2014; Keys et al. 2020). In the following subsection we will see how on larger scales, and statistically, magnetic flux merging can lead to strong magnetic elements forming the magnetic network pattern.

### 4.2 Network magnetic flux

Network magnetic flux can be lost due to submergence or cancellation with opposite polarity elements (as we will see in the last section) and thus needs to be to be continuously replenished. The research points to the idea that practically the whole amount of magnetic flux in the network needs to be recreated within 24 h. However, where is all the magnetic flux coming from? Several different hypothesis were
stated, among them that the flux is coming from ephemeral regions (see, e.g., the introduction of Hagenaar 2001, and references therein). Recent studies with Hinode, however, show that the small-scale flux emergence within the intranetwork regions seem to be sufficient to create enough magnetic net flux to stabilize the network (see, Gošić et al. 2014, 2016). The authors of the aforementioned papers investigated an exceptional long time series of the Hinode/SOT instrument and tracked the evolution of appearing small-scale intranetwork fields. These magnetic elements drift slowly from the inside of the supergranular structure to its boundary and join there the persistent magnetic network. The estimated rates of newly added flux are comparable to believed disappearance rates and thus seems to be sufficient to explain the appearance and maintenance of the magnetic network.

Figure 6, taken from Borrero et al. (2015), shows an example of recent numerical simulations dealing with the analysis of the small scale dynamo. Moreover, the classical salt (positive polarity; white) and pepper (negative polarity; black) spotted image is created. This happens due to the visible prevalence of stronger vertical network magnetic fields, especially in earliest magnetograms with lower resolution.

5 Plasma—magnetic field interaction

Multiple processes involving the interaction of plasma and magnetic fields are present in the solar atmosphere. Among the main ones are the buffeting of magnetic fields by the granular motions (e.g., Muller and Roudier 1992), the creation of vortex flows (Bonet et al. 2008; Giagkiozis et al. 2018), and the convective transport of magnetic fields (e.g., on small-scales from the centre of granules to the intergranular lanes and on larger scales from the inside of supergranules to the magnetic network). Except from them, the most important processes are driven by magnetic field reconnection leading to explosive phenomena, such as jets, spicules, fibrils, mottles and other outflow phenomena as well as the driving of magneto-hydrodynamic waves.

5.1 Magnetic reconnection

In plasma physics, it is well known that magnetic field lines are “frozen-in” to an infinitely conductive plasma. Magnetic reconnection happens when the frozen-in concept breaks down and magnetic field lines shatter and reorganize, to form a new magnetic topology (see, e.g., Snow et al. 2018). In this process huge amounts of energy can be released (i.e., magnetic energy gets converted into heat, and kinetic energy) and particles accelerated (Zhou et al. 2016). In the case of small-scale magnetic fields magnetic reconnection might lead to phenomena such as jets (Nelson et al. 2019) and spicules (Heggland et al. 2009, ), as well as explosive events, such as Ellerman Bombs (Reid et al. 2016). In the recent paper of (Samanta et al. 2019), the authors report on the observation of small-scale strong magnetic field elements with the Goode Solar Telescope, formerly New Solar Telescope (NST; Goode et al. 2010) at Big Bear Observatory, which is among the leading and highest resolving solar telescopes under operation only outpassed by the recent first light of the Daniel
K. Inouye Solar Telescope (DKIST) facility at Mauna Loa Observatory (Rast et al. 2021). The authors observed a weak intranetwork magnetic field element approaching a strong opposite network field element. Once the weak element practically touched the stronger network element it started to disappear, while simultaneously a spicule was launched to the upper atmosphere. The spicule was subsequently heated to coronal temperatures as observed by the Atmospheric Imaging Assembly instrument onboard the Solar Dynamics Observatory (SDO; Lemen et al. 2012; Pesnell et al. 2012).

The authors concluded that they observed magnetic reconnection happening on small-scale magnetic fields in the lower atmosphere which can explain the triggering of spicules and subsequent heating of the quiet Sun upper atmospheric layers.
5.2 Plasma brightenings, jets and surges

The magnetic field emerging to the solar photosphere (Emerging flux regions, EFR) can shape the structure of solar atmospheric layers, in particular due to the interaction of the emerging fields and the pre-existing (ambient) fields (Zwaan et al. 1985; Magara 2001; Stein et al. 2011). Magnetic reconnection is the mechanism responsible for most of the small-scale explosive phenomena releasing energy, and mainly visible as brightenings and jets, among others. These phenomena have been proved to be a source of energy and mass injection into higher layers of the solar atmosphere, according to numerical simulations (Archontis et al. 2005; Isobe et al. 2007; Pariat et al. 2010), and observationally revealed by high-resolution solar telescopes (Guo et al. 2013; Domínguez et al. 2012). The complexity of the real 3D scenario, in which a large population of small-scale magnetic fields with different orientations rise up from the photosphere to the lower chromosphere, and subsequently interact with background fields, can generate a wide variety of jets that contribute to the energy budget and mass of the upper chromosphere and beyond.

Figure 7, adapted from (Domínguez et al. 2014), shows multi-wavelength high-resolution observations of a small-scale emerging magnetic flux event acquired with the ground-based NST and space-borne solar telescopes; SDO, Interface Region Imaging Spectrograph (IRIS; De pontieu et al. 2014) and the Hinode mission, detailing the response of different solar atmospheric layers. The interaction of

![Figure 7](image-url)

*Fig. 7 Multi-wavelength observations of the solar atmosphere presented in Domínguez et al. (2014) using data from ground-based (NST) with the instruments Visible Imaging Spectrometer (VIS) and InfraRed Imaging Magnetograph (IRIM), and space telescopes (SDO, IRIS and Hinode). Panels show images of NOAA 11810 on Aug 7, 2013. Upper row: NST/IRIM/HeI image (left panel) displaying a dark-absorbing feature (surge), NST/TiO photospheric image (middle panel), and NST/VIS/Hα images in the blue/red wing, as labeled (right panels). Lower row: Chromospheric and coronal images of the region framed by large white boxes in the upper panels, highlighting the localized brightenings in transition region and coronal heights. All units are in arcsec.*
the emerging fields with the overlying field causes high-temperature emission, evidenced as localized brightenings, UV bursts due to plasma heating, as well as the generation of cool surges and hot plasma jets, as shown in the figure.

Explosive small-scale transient episodes, including the so-called Ellerman Bombs (observed in the wings of Hα) and UV bursts, are now commonly reported through detailed high-resolution observations of the solar chromosphere and transition region (e.g., de la Cruz Rodríguez et al. 2015; Guglielmino et al. 2018; Ortiz et al. 2020) and in numerical simulations (e.g., Cheung et al. 2008; Nóbrega-Siverio et al. 2016; Hansteen et al. 2019) dealing with complex 3D scenarios, demonstrating how the reconnection process can provide the energy to heat, and accelerate particles within the plasma.

In a recent observational study van der Voort et al. (2017), the authors furnish compelling evidence for the existence of plasmoids (magnetic islands), revealed by very dynamic brightenings at sub-arcsec scales, providing support for the interpretation of intermittent magnetic reconnection driven by the plasmoid instability, previously studied through MHD numerical simulations (e.g., Yang et al. 2013; Nóbrega-Siverio et al. 2016).

Further studies should be carried out to establish, and fully understand, the dominant modes of reconnection and the physical conditions responsible for the generation of the wide variety of chromospheric small-scale phenomena, and their implications on the heating of the transition region and corona.

5.3 Waves

A hot topic in solar physics is the one related to the generation, propagation, and absorption of waves within the solar atmosphere (e.g., Erdélyi and Ballai 1999; Terra-Homem et al. 2003; Cranmer and van Ballegooijen 2005; Mathioudakis et al. 2013; Jess et al. 2015; Nakariakov et al. 2022). The community investigated early on if episodic acoustic waves (Biermann 1948) could be a possible contributor to the coronal heating problem (under which the maintenance of the million degree Kelvin hot outer atmosphere is summarized) and was able to rule out that possibility as such waves could not penetrate into the higher atmosphere (characterized by the so called cutoff frequency, see, e.g., Wiśniewska et al. 2016). It also appears that pure acoustical waves would not suffice to heat the quiet chromosphere (Carlsson et al. 2007). Thus, as the solar atmosphere is permeated by magnetic fields, it is self-evident to look for magnetic waves opening the field of magnetohydrodynamic wave investigations.

One of the important recent topics aims at probing solar pores as magnetic wave guides. The umbral regions of pores typically exhibit 3 mHz oscillations, as consequence of p-modes penetrating the magnetic region, though 5 mHz oscillations have recently been detected in a solar pore Stangalini et al. (2021). There are already some observational signatures of resonant MHD oscillations confined within the pore umbra and evidence of propagating MHD-wave activity above pores Gilchrist-Millar et al. (2021). Wavelet and Fourier techniques, for instance, have been used to
detect oscillations in the intensity and the cross-sectional area in pores Grant et al. (2015).

Considering more compact magnetic fields, due to their vast amount, small-scale magnetic flux tubes, e.g., as seen by MBPs, would represent perfect wave guides to explain the heating of the quiet Sun upper atmospheric layers, if sufficient wave energy can be created, injected, propagated, and finally absorbed in the higher atmosphere (Kayshap et al. 2020). Thus the community started already in the 70s and 80s with efforts to model magnetic flux tubes which are nowadays essential as input elements for advanced numerical simulations (e.g., Gent et al. 2013; Murawski et al. 2018).

The problem of the wave propagation then was tackled from the theoretical, observational (see, e.g., the review Mathioudakis et al. 2013; Chitta et al. 2012), as well as computational (Vigeesh et al. 2009; Fedun et al. 2011) side, with various studies claiming that small-scale magnetic field elements and the waves which propagate in them, would be sufficient to maintain the quiet Sun’s temperature at higher atmospheric heights. An important part is to understand how the waves ultimately are damped and absorbed, and how the energy can be added to the local atmosphere (e.g., Gilchrist-Millar et al. 2021; Riedl et al. 2021). Some recent modelling works study the role of “non-classical” ambipolar diffusion on absorption of waves in the small-scale magnetic field concentrations, with variable success (see, e.g., Arber et al. 2016; Shelyag et al. 2016; Cally and Khomenko 2019, and references therein.).

Besides of this “classical” wave studies, the recent discovery of so-called magnetic field line switchbacks within the solar wind by the NASA’s Parker Solar Probe (PSP; Fox et al. 2016) mission, further increased the interest also in small-scale magnetic fields as possible source region for such switchbacks. First simulations were not totally conclusive as they have shown that in principle driving of small-scale flux tubes in the lower solar atmosphere can cause the formation of magnetic field line switchbacks; however, they seem not to survive a propagation through the higher solar atmosphere to ultimately join the outstreaming solar wind, as presented in (see Magyar et al. 2021, 2021). In the latter work, the authors simulate an oscillating vortex extending upwards from the photosphere, as shown in Fig. 8. In the recent years, plasma and magnetic vortices have been of special interest and were tackled by both observing and simulation approaches (Bonet et al. 2008; Shelyag et al. 2011; Domínguez et al. 2011; Silva et al. 2021; Aljohani et al. 2022, and references therein). The interest in the magnetic vortices arises as they are involved in manifold interesting processes such as the breading of magnetic field lines that could stimulate magnetic reconnection, producing plasma heating, jets, and eruptive phenomena. Besides, they can also be sources of upwards wave propagation. The relationship between vorticity generation, magnetic fields and Alfvén waves has been shown using simulations in Shelyag et al. (2011), Wedemeyer-Böhm et al. (2012), Shelyag et al. (2013), Battaglia et al. (2021).

Another direction of wave research is aimed to the understanding of torsional Alfvén modes and waves (Luo et al. 2002; Morton et al. 2011; Fedun et al. 2011) as they are possible further agents to heat the higher atmosphere (Soler et al. 2021). Such oscillations were observed at the solar limb in higher atmospheric layers (De Pontieu et al. 2012). This is due to the fact that the oscillation would
cause, perpendicular to the rotation axis of the plasma column, counter-rotating plasma (Tian et al. 2012). Such a plasma would yield a common observable signature of a split plasma column, where one side would move to the observer and one side away from the observer. However, for small-scale magnetic fields on the disk such observations would be tricky as the structures are way too small to directly detect the caused motions. Thus, researchers employed up to now mostly indirect methods such as measuring line width oscillations caused by the torsional oscillation (Jess et al. 2009). However, in the recent past now more works are published about the detection of torsional oscillations in the lower solar atmosphere. In the following case the oscillations were detected in observational data within a magnetic pore (Stangalini et al. 2021), with a kink mode plausible to be an excitation mechanism of the generated Alfvén waves, and are proposed to be a significant contribution to the energy transport in the atmosphere and, moreover, in the acceleration of the solar wind.

From the viewpoint of observations, one can differentiate between studies trying to shed light on waves in magnetic structures by direct evidence of the waves, such as a translation or deformation of the wave guide (such as oscillating coronal loops), as well as changes in intensity, and more subtle indirect evidences, such as e.g., a change in the spectral line width. This method was successfully applied to MBPs to show the possibility of torsional Alfvén waves in MBPs (Jess et al. 2009), while kink and sausage magneto-acoustic waves are often detected via displacements, intensity variations or size variations (Moreels and Van Doorselaere 2013; Moreels et al. 2013; Stangalini et al. 2017; Jafarzadeh et al. 2017) of the wave guiding magnetic field element. Figure 9, extracted from Morton et al. (2011), shows an observational detection of sausage modes in magnetic pores. Recently, the degree of understanding the observations goes as far as detailed mode identification (even in non-circular
shaped flux tubes Aldhafeeri et al. (2021)) and differentiation between body and surface type modes (Moreels et al. 2015; Keys et al. 2018).

Finally, MHD waves are also helpful in revealing physical information about the magnetic field in higher atmospheric layers. Due to the weaker magnetic field the Zeeman effect becomes too difficult to be applied successfully to detect magnetic fields in the higher solar atmosphere. An alternative window is opened by magnetoseismology, the art to understand MHD waves in such detail as to decipher physical quantities (generally, magnetic field strength, density, temperature) of the wave guide (e.g., Morton et al. 2012).

From the viewpoint of theory (Edwin and Roberts 1983), the focus is shifting more and more to understand partly ionized wave guides (e.g., Ballai et al. 2019; Alharbi et al. 2022) as this will open new avenues in better understanding and addressing waves in the chromosphere. In addition, there is still development going on to fully understand how waves get damped and energy absorbed (Van Doorsselaere et al. 2020). Properties of sausage waves and their propagation are address from numerical simulations, e.g., initiated at the base of the photosphere in a gravitationally stratified and viscous plasma (Ballai et al. 2006), along a wide flux tube expanding with height Pardi et al. (2014), among many others.

Finally, we wish to mention that in the recent years the boundary between jets, spicules, fibrils and other mass flow phenomena and waves are starting to dissolve, as there is more and more work contributing to the coupling of the two phenomena. This means, on the one hand, to understand how jets can create waves. Here we wish to mention exemplarily the work of Dover et al. (2021). In this work the authors were reporting on wavelike substructures which were forming within a jet. Thus, it is an example of a jet causing a wave phenomenon. On the other hand, we mentioned that there are waves causing jet phenomena. In this case we wish to mention as an example the recent work of Scalisi et al. (2021), where the creation of jets and outflow phenomena due to waves are discussed.
6 Removal of magnetic field

As mentioned earlier, magnetic field is constantly removed from the solar surface and replenished by the creation of new magnetic field visible via the flux emergence on the solar surface. It is believed that magnetic fields from large scales, such as sunspots, are broken up and shredded by turbulent motions also called turbulent diffusion. Important observational constraints are the moat flow region around a sunspot (a region of out-flowing plasma) leading to the phenomenon of so-called moving magnetic features [(MMFs, e.g., Ryutova (2018)], which transport magnetic field away from the sunspot. Another characteristic sign for a breaking up of a sunspot is the formation of light-bridges (Berger and Berdyugina 2003) which are regions of non suppressed convective flows within sunspots. The shredding process happens until the magnetic energy comes down into sufficient small scales to annihilate with opposite polarity elements (e.g., Rubio et al. 2005). On these small scales various processes are observed, such as splitting and further dispersal leading ultimately to in-situ disappearance in the case no clear counterpart of the disappearing opposite flux can be seen. However, more often it can be evidenced that the opposite magnetic field polarity approaches a flux element, in a process kind of opposite to the emergence, until the two opposite polarities meet and start to cancel out; first weakening the strong magnetic field elements until they completely disappear (Gošić et al. 2018). In the meeting process obviously magnetic reconnection happens on the one or other height, reconnecting the field lines and leading to a new magnetic field topology. Figure 10, taken from Rubio and Suárez (2019), shows three different

![Fig. 10](image_url)

**Fig. 10** Observational evidences for cancellation, disappearance, and fragmentation of magnetic flux features as presented by Rubio and Suárez (2019) through sequence of images (with a cadence of 100 s). White/black represent positive/negative polarity. The magnetograms are saturated to ± 30 Mx cm.$^{-1}$ to highlight the evolution of the magnetic flux. Tickmarks are separated by 1 arcsec. The sketch on the right represents possible cancellation scenarios proposed by Zwaan (1987), including the submergence (retraction) of existing field lines forming an $\Omega$-loop (a), and prior reconnection of unrelated field lines below (b) of above (c) the photosphere.
scenarios: cancellation, disappearance, and fragmentation of magnetic flux features. Depending on the height of the reconnection site (see right panel in Fig. 10) two U-shaped loops are formed with the lower one being pushed down into the convection zone and the upper one being lifted in the higher atmosphere. During such reconnection events, jets and fibrils can be formed, shooting plasma further up. Such reconnection processes also play a fundamental role in the disappearance of magnetic pores as witnessed in Xue et al. (2021). These authors observe an active region with forming and decaying pores, where the decaying of the pores is due to approaching counter polarities which lead to 2 magnetic reconnection events and a strong change in the magnetic field line topology as indicated by non-linear force free magnetic field (NLFFF) extrapolations during the evolution of the pores, as shown in Fig. 11.

7 Outlook

New facilities and instrument suites that have recently become available, or are currently in development, will hopefully shed new insights on plasma processes in the lower solar atmosphere. The recent first light by DKIST will be followed by the planned 4-m European Solar Telescope (Schlichenmaier et al. 2019; Matthews et al. 2016), the 8-m Chinese Giant Solar Telescope (Deng 2011), and the 2-m National Large Solar Telescope of India (Hasan 2011). Each of these facilities will offer varying instrument suites with the possibility of high temporal and spatial resolutions which will give us unprecedented detail and, thus, improve our understanding of dynamics and small-scale magnetic fields in the solar of the lower solar atmosphere. It is hoped that these facilities and instruments will give more insights on MBPs, umbral dots, jets and fibrils.

Fig. 11 Evolution of decaying of pores driven by small-scale magnetic reconnection, as shown by Xue et al. (2021) in data from SDO on 2020 October 26. Left panels show sequence of continuum images, LOS magnetograms, and Bx, as labeled, displaying the evolution of positive/negative white/black magnetic kernels (N1, P1, and P2). Right panels (k, l, m, n) are snapshots of a numerical simulation showing 3D NLFFF configurations during the magnetic reconnection events, with loops before reconnection takes place (pink), and shorter/longer (yellow/green) loops formed during the reconnection process.
With the latest instruments the community is about to reach spatial resolution levels comparable to the photon mean free path in the photosphere. Thus, beyond this point in spatial size, it becomes difficult for features to create enough imprint to evidence observable changes. However, for spectro-polarimetric observations still larger facilities will be sought after, as one needs to distribute the available photons on a four dimensional space (two spatial dimensions, temporal and spectral) and divide them by at least four for the four polarization states to accurately estimate the magnetic field. However, in practice even more photons are needed as the polarization signals are rather weak and often only leading to signals of a few percent of the total intensity even for strong magnetic fields and circular polarization states. For linear polarization (measurement of the horizontal fields) and hG and below fields it becomes an art to detect enough photons in a sufficiently short time period. Thus, even though the 4-m class telescopes open new pathways and insights, from the spectro-polarimetric viewpoint we have not yet reached the end of the story, and from the perspective of open science we are still missing the connection between the atmospheric layers as well as simple fundamental questions such as how the field is created on small-scales and how it eventually disappears. In addition, one has to consider the need for inputs from privileged locations in space on the high-resolution front. This is of great importance to address fundamentally important questions regarding the polar magnetic fields in the Sun. Those magnetic field regions are not, or only very limited, accessible from the ecliptic plane due to foreshortening effects. Hence the community still does not understand sufficiently well the magnetic fields of this mysterious region and only with the help of space missions, going considerably out of the ecliptic plane to acquire clear images from the solar poles, those enigmatic regions on the Sun could be fully understood. Assisting us in finally understanding the whole solar cycle as well as to verify the magnetic field dynamo as currently theorized. At present, we have a decent understanding of various aspects of the solar atmosphere; however, there are still many open questions that need to be addressed in the future. The interested reader might like to have a look into the Critical Science Plan of DKIST (Rast et al. 2021) or the Science Requirement Document of EST (Schlichenmaier et al. 2019), where many of the to-be-addressed problems are outlined in detail.

Furthermore, a very relevant topic, only limited covered in this short review, is the simulation of the full lower solar atmosphere from the upper convection zone all the way up to the photosphere and chromosphere. However, going into more details of these simulations is beyond the scope of this work and we refer the interested reader to recent works, such as (Abbett 2007; Leenaarts 2020; Skirvin et al. 2022, and references therein).

**Funding** Open Access funding provided by Colombia Consortium.

**Declarations**

**Conflict of interest** The authors state that there is no conflict of interest. We express our gratitude to the anonymous referees for their comments that significantly helped to improve the presentation of some of the ideas.
References

W.P. Abbett, The magnetic connection between the convection zone and corona in the quiet sun. ApJ 665(2), 1469–1488 (2007). https://doi.org/10.1088/519788

V. Abramenko, V. Yurchyshyn, P. Goode, A. Kilcik, Statistical distribution of size and lifetime of bright points observed with the new solar telescope. ApJ 725, 101–105 (2010). https://doi.org/10.1088/2041-8205/725/1/L101. arXiv:1012.1584 [astro-ph.SR]

A.A. Aldhafeeri, G. Verth, W. Brevis, D.B. Jess, M. McMurdo, V. Fedun, Magnetohydrodynamic wave modes of solar magnetic flux tubes with an elliptical cross section. ApJ 912(1), 50 (2021). https://doi.org/10.3847/1538-4357/abec7a

A. Alharbi, I. Ballai, V. Fedun, G. Verth, Waves in weakly ionized solar plasmas. MNRAS 511(4), 5274–5286 (2022). https://doi.org/10.1093/mnras/stab1044. arXiv:2112.13305 [astro-ph.SR]

Y. Aljohani, V. Fedun, I. Ballai, S.S.A. Silva, S. Shelyag, G. Verth, New approach for analyzing dynamical processes on the surface of photospheric vortex tubes. ApJ 928(1), 3 (2022). https://doi.org/10.3847/1538-4357/ac56db. arXiv:2202.09332 [physics.flu-dyn]

J.S. Almeida, A.A. Ramos, J.T. Bueno, J. Cernicharo, G-band spectral synthesis in solar magnetic concentrations. ApJ 555(2), 978–989 (2001). https://doi.org/10.1086/321521. arXiv:astro-ph/0103006 [astro-ph]

T.D. Arber, C.S. Brady, S. Shelyag, Alfvén wave heating of the solar chromosphere: 1.5D models. ApJ 817(2), 94 (2016). https://doi.org/10.3847/0004-637X/817/2/94. arXiv:1512.05816 [astro-ph.SR]

V. Archontis, F. Moreno-Insertis, K. Galsgaard, A.W. Hood, The three-dimensional interaction between emerging magnetic flux and a large-scale coronal field: reconnection, current sheets, and jets. ApJ 635(2), 1299–1318 (2005). https://doi.org/10.1086/497533

I. Ballai, R. Erdélyi, J. Hargreaves, Slow magnetohydrodynamic waves in stratified and viscous plasmas. Phys. Plasmas 13(4), 042108 (2006). https://doi.org/10.1063/1.2194847

I. Ballai, E. Forgács-Dajka, A. Marcu, Dispersive shock waves in partially ionised plasmas. Adv. Space Res. 63(4), 1472–1482 (2019). https://doi.org/10.1016/j.asr.2018.10.024. arXiv:1810.07948 [astro-ph.SR]

M. Bárá, J. Büchner, M. Karlický, J. Skála, Spontaneous current-layer fragmentation and cascading reconnection in solar flares. I. Model and analysis. ApJ 737(1), 24 (2011) arXiv:1011.4035 [astro-ph.SR]. https://doi.org/10.1088/0004-637X/737/1/24

A.F. Battaglia, J.R.C. Cuisia, F. Calvo, A.A. Bossart, O. Steiner, The Alfvénic nature of chromospheric swirls. A &A 649, 121 (2021). https://doi.org/10.1051/0004-6361/202040110. arXiv:2103.07366 [astro-ph.SR]

C. Beck, L.R.B. Rubio, R. Schlichenmaier, P. Sütterlin, Magnetic properties of G-band bright points in a sunspot moat. A &A 472, 607–622 (2007). https://doi.org/10.1051/0004-6361:20065620. arXiv:0707.1232

T.E. Berger, S.V. Berdyugina, The observation of sunspot light-bridge structure and dynamics. ApJ 589(2), 117–121 (2003). https://doi.org/10.1086/376494

T.E. Berger, L.H.M.R. van der Voort, M.G. Löfdahl, M. Carlsson, A. Fossum, V.H. Hansteen, E. Marthinsussen, A. Title, G. Scharmer, Solar magnetic elements at 0.1 arcsec resolution General appearance and magnetic structure. A &A 428, 613–628 (2004). https://doi.org/10.1051/0004-6361:20040346

L. Biermann, Über die Ursache der chromosphärischen Turbulenz und des UV-Exzesses der Sonnenstrahlung. ZAp 25, 161 (1948)
J.A. Bonet, I. Márquez, J.S. Almeida, I. Cabello, V. Domingo, Convectively driven vortex flows in the sun. ApJ 687, 131–134 (2008). https://doi.org/10.1086/593329. arXiv:0809.3885

J.M. Borrero, S. Jafarzadeh, M. Schüssler, S.K. Solanki, Solar magnetoconvection and small-scale dynamo—recent developments in observation and simulation. Space Sci. Rev. (2015). https://doi.org/10.1007/s11214-015-0204-5. arXiv:1511.04214 [astro-ph.SR]

J.M. Borrero, S. Jafarzadeh, M. Schüssler, S.K. Solanki, Solar magnetoconvection and small-scale dynamo. recent developments in observation and simulation. Space Sci. Rev. 210(1–4), 275–316 (2017). https://doi.org/10.1007/s11214-015-0204-5. arXiv:1511.04214 [astro-ph.SR]

R.J. Bray, R.E. Loughhead, Sunspots, (1964)

P.S. Cally, E. Khomenko, Fast-to-Alfvén mode conversion and ambipolar heating in structured media. I. Simplified cold plasma model. ApJ 885(1), 58 (2019). https://doi.org/10.3847/1538-4357/ab3bce

R. Cameron, M. Schüssler, A. Vogler, V. Zakharov, Radiative magnetohydrodynamic simulations of solar pores. A&A 474(1), 261–272 (2007). https://doi.org/10.1051/0004-6361:20078140

M. Carlsson, R.F. Stein, A. Nordlund, G.B. Scharmer, Observational manifestations of solar magnetoconvection: center-to-limb variation. ApJ 610(2), 137–140 (2004). https://doi.org/10.1086/423305. arXiv:astro-ph/0406160 [astro-ph]

M. Carlsson, V.H. Hansteen, B. de Pontieu, S. McIntosh, T.D. Tarbell, D. Shine, S. Tsuneta, Y. Katsumata, K. Ichimoto, Y. Suematsu, T. Shimizu, S. Nagata, Can high frequency acoustic waves heat the quiet sun chromosphere? PASJ 59, 663 (2007). https://doi.org/10.1093/pasj/59.sp3.S663. arXiv:0709.3462 [astro-ph]

R. Centeno, H. Socas-Navarro, B. Lites, M. Kubo, Z. Frank, R. Shine, T. Tarbell, A. Title, K. Ichimoto, S. Tsuneta, Y. Katsumata, Y. Suematsu, T. Shimizu, S. Nagata, Emergence of small-scale magnetic loops in the quiet-sun internetwork. ApJ 666(2), 137–140 (2007). https://doi.org/10.1086/521726

R. Centeno, J. B. Rodríguez, J.C. Del Toro Iniesta, S.K. Solanki, P. Barthol, A. Gondorfer, L. Gizon, J. Hirzberger, T.L. Rehmhüller, M. van Noort, D. O. Suárez, T. Berkfeld, W. Schmidt, V. M. Pillet, M. Knölker, A tale of two emergences: sunrise II observations of emergence sites in a solar active region. ApJS, 229(1), 3 (2017). https://doi.org/10.3847/1538-4365/229/1/3. arXiv:1610.03531 [astro-ph.SR]

P. Charbonneau, Dynamo models of the solar cycle. Living Rev. Solar Phys. 17(1), 4 (2020). https://doi.org/10.1007/s41116-020-00025-6

M.C.M. Cheung, M. Schüssler, T.D. Tarbell, A.M. Title, Solar surface emerging flux regions: a comparative study of radiative mhd modeling and Hinode SOT observations. ApJ 687(2), 1373–1387 (2008). https://doi.org/10.1086/591245. arXiv:0810.5723 [astro-ph]

L.P. Chitta, R. Jain, R. Kariyappa, S.M. Jefferies, Observations of the interaction of acoustic waves and small-scale magnetic fields in a quiet sun. ApJ 744, 98 (2012). https://doi.org/10.1088/0004-637X/744/2/98

I.-H. Cho, K.-S. Cho, S.-C. Bong, E.-K. Lim, R.-S. Kim, S. Choi, Y.-H. Kim, V. Yurchyshyn, Statistical comparison between pores and sunspots by using SDO/HMI. ApJ 811(1), 49 (2015). https://doi.org/10.1088/0004-637X/811/1/49

A.R. Choudhuri, H. Auffret, E.R. Priest, Implications of rapid footpoint motions of photospheric flux tubes for coronal heating. Sol. Phys. 143, 49–68 (1993)

S.R. Cranmer, A.A. van Ballegooijen, On the generation, propagation, and reflection of Alfvén waves from the solar photosphere to the distant heliosphere. ApJ 156, 265–293 (2005). https://doi.org/10.1086/426507. arXiv:astro-ph:0410639

P.J. Crockett, M. Mathioudakis, D.B. Jess, S. Shelyag, F.P. Keenan, D.J. Christian, The area distribution of solar magnetic bright points. ApJ 722, 188–193 (2010). https://doi.org/10.1088/2041-8205/722/2/L188. arXiv:1009.2410 [astro-ph.SR]

S. Danilovic, M. Schüssler, S.K. Solanki, Magnetic field intensification: comparison of 3D MHD simulations with Hinode/SP results. A&A 509, 76 (2010). https://doi.org/10.1051/0004-6361/200912283. arXiv:0910.1211 [astro-ph.SR]

J. de la Cruz Rodríguez, V. Hansteen, L. Bellot-Rubio, A. Ortiz, Emergence of granular-sized magnetic bubbles through the solar atmosphere II non-LTE chromospheric diagnostics and inversions. ApJ 810(2), 145 (2015). https://doi.org/10.1088/0004-637X/810/2/145. arXiv:1503.03846 [astro-ph.SR]

B. De Pontieu, M. Carlsson, L.H.M.R. van der Voort, R.J. Rutten, V.H. Hansteen, H. Watanabe, Ubiquitous torsional motions in type II spicules. ApJ 752(1), 12 (2012). https://doi.org/10.1088/2041-8205/752/1/L12. arXiv:1205.5006 [astro-ph.SR]
A.G. de Wijn, B.W. Lites, T.E. Berger, Z.A. Frank, T.D. Tarbell, R. Ishikawa, Hinode observations of magnetic elements in internetwork areas. ApJ 684, 1469–1476 (2008). https://doi.org/10.1086/590237

I. Domínguez, Study of horizontal flows in solar active regions based on high-resolution image reconstruction techniques. PhD thesis, (2009). https://doi.org/10.48550/arXiv.0906.0336

S.V. Domínguez, J. Sánchez Almeida, F. Kneer, Inter-network magnetic fields observed with sub-arcsec resolution. A &A 407, 741–757 (2003). https://doi.org/10.1051/0004-6361:20030892. arXiv:astro-ph/0306329 [astro-ph]

S.V. Domínguez, A. de Vicente, J.A. Bonet, V.M. Pillet, Characterization of horizontal flows around solar pores from high-resolution time series of images. A &A 516, 91 (2010). https://doi.org/10.1051/0004-6361/200913264

S.V. Domínguez, L. van Driel-Gesztelyi, L.R.B. Rubio, Granular-scale elementary flux emergence episodes in a solar active region. Sol. Phys. 278(1), 99–120 (2012). https://doi.org/10.1007/s11127-012-9968-x. arXiv:1203.6428 [astro-ph]

F.M. Dover, R. Sharma, R. Erdélyi, Magnetohydrodynamic simulations of spicula jet propagation applied to lower solar atmosphere model. ApJ 913(1), 19 (2021). https://doi.org/10.3847/1538-4357/abed1
C.E. Fischer, A.G. de Wijn, R. Centeno, B.W. Lites, C.U. Keller, Statistics of convective collapse events in the photosphere and chromosphere observed with the Hinode SOT. A & A 504, 583–588 (2009). https://doi.org/10.1051/0004-6361/200912445. arXiv:0906.2308 [astro-ph.SR]

N.J. Fox, M.C. Velli, S.D. Bale, R. Decker, A. Driesman, R.A. Howard, J.C. Kasper, J. Kinnison, M. Kusterer, D. Lario, M.K. Lockwood, D.J. McComas, N.E. Raouafi, A. Szabo, The solar probe plus mission: humanity’s first visit to our star. Space Sci. Rev. 204(1–4), 7–48 (2016). https://doi.org/10.1007/s11214-015-0211-6

M. García-Rivas, J. Jurčák, N.B. González, Magnetic properties on the boundary of an evolving pore. A & A 649, 129 (2021). https://doi.org/10.1051/0004-6361/202039661. arXiv:2102.08459 [astro-ph.SR]

F.A. Gent, V. Fedun, S.J. Mumford, R. Erdélyi, Magnetohydrostatic equilibrium—I. Three-dimensional open magnetic flux tube in the stratified solar atmosphere. MNRAS 435(1), 689–697 (2013). https://doi.org/10.1093/mnras/stt1328. arXiv:1305.4788 [astro-ph.SR]

I. Giagkiozis, V. Fedun, E. Scullion, D.B. Jess, G. Verth, Vortex flows in the solar atmosphere: automated identification and statistical analysis. ApJ 869(2), 169 (2018). https://doi.org/10.3847/1538-4357/aaf797

C.A. Gilchrist-Millar, D.B. Jess, S.D.T. Grant, P.H. Keys, C. Beck, S. Jafarzadeh, J.M. Riedl, T. Van Doorsselaere, B.R. Cobo, Magnetooacoustic wave energy dissipation in the atmosphere of solar pores. Philos. Trans. R. Soc. Lond. Ser. A 379(2190), 20200172 (2021). https://doi.org/10.1098/rsta.2020.0172. arXiv:2007.11594 [astro-ph.SR]
S.S. Hasan, National Large Solar Telescope of India. In: Astronomical Society of India Conference Series. Astronomical Society of India Conference Series, vol. 2, pp. 37–45 (2011)

L. Heggland, B. De Pontieu, V.H. Hansteen, Observational signatures of simulated reconnection events in the solar chromosphere and transition region. ApJ 702, 1–18 (2009). https://doi.org/10.1088/0004-637X/702/1/1

S.J. Hofmeister, D. Ulz, S.G. Heinemann, A. Veronig, M. Temmer, Photospheric magnetic structure of coronal holes. A&A 629, 22 (2019). https://doi.org/10.1051/0004-6361/201935918

R. Ishikawa, S. Tsuneta, The relationship between vertical and horizontal magnetic fields in the quiet sun. ApJ 735(2), 74 (2011). https://doi.org/10.1088/0004-637X/735/2/74

H. Isobe, D. Tripathi, V. Archontis, Ellerman bombs and jets associated with resistive flux emergence. ApJ 657(1), 53–56 (2007). https://doi.org/10.1086/512969

S. Jafarzadeh, S.K. Solanki, A. Feller, A. Lagg, A. Pietarila, S. Danilovic, T.L. Riehmüller, V.M. Pillet, Structure and dynamics of isolated internetwork Ca II H bright points observed by SUNRISE. A&A 549, 116 (2013). https://doi.org/10.1051/0004-6361/201220089

D.B. Jess, M. Mathioudakis, R. Erdélyi, P.J. Crockett, F.P. Keenan, D.J. Christian, Alfven waves in the lower solar atmosphere. Science 323, 1582 (2009). https://doi.org/10.1126/science.1168680

D.B. Jess, R.J. Morton, G. Verth, V. Fedun, S.D.T. Grant, I. Giagkiozis, Multiwavelength studies of MHD waves in the solar chromosphere. An overview of recent results. Space Sci. Rev. 190(1–4), 103–161 (2015). https://doi.org/10.1007/s11214-015-0141-3

J. Jiang, D.H. Hathaway, R.H. Cameron, S.K. Solanki, L. Gizon, L. Upton, Magnetic flux transport at the solar surface. Space Sci. Rev. 186(1–4), 491–523 (2014). https://doi.org/10.1007/s11214-014-0083-1

C.L. Jin, J.X. Wang, The latitude distribution of small-scale magnetic elements in solar cycle 23. ApJ 745, 39 (2012). https://doi.org/10.1088/0004-637X/745/1/39

P.J. Käpylä, M.J. Käpylä, A. Brandenburg, Small-scale dynamos in simulations of stratified turbulent convection. Astronomische Nachrichten 339(127), 127–133 (2018). https://doi.org/10.1002/asna.201813477

P. Kayshap, A.K. Srivastava, S.K. Tiwari, P. Jelinek, M. Mathioudakis, Propagation of waves above a plage as observed by IRIS and SDO. A&A 634, 63 (2020). https://doi.org/10.1051/0004-6361/201936070

C.U. Keller, M. Schüssler, A. Vogler, V. Zakharov, On the origin of solar faculae. ApJ 607(1), 59–62 (2004). https://doi.org/10.1086/421553

P.H. Keys, M. Mathioudakis, D.B. Jess, S. Shelyag, P.J. Crockett, D.J. Christian, F.P. Keenan, The velocity distribution of solar photospheric magnetic bright points. ApJ 740, 40 (2011). https://doi.org/10.1088/2041-8205/740/2/L40

P.H. Keys, R.J. Morton, D.B. Jess, G. Verth, S.D.T. Grant, M. Mathioudakis, D.H. Mackay, J.G. Doyle, D.J. Christian, F.P. Keenan, R. Erdélyi, Photospheric observations of surface and body modes in solar magnetic pores. ApJ 857(1), 28 (2018). https://doi.org/10.3847/1538-4357/aab432

P.H. Keys, A. Reid, M. Mathioudakis, S. Shelyag, V.M.J. Henriques, R.L. Hewitt, D. Del Moro, S. Jafarzadeh, D.B. Jess, M. Stangalini, The magnetic properties of photospheric magnetic bright points with high-resolution spectropolarimetry. MNRAS 488(1), 53–58 (2019). https://doi.org/10.1093/mnrasl/slz097

P.H. Keys, A. Reid, M. Mathioudakis, S. Shelyag, V.M.J. Henriques, R.L. Hewitt, D. Del Moro, S. Jafarzadeh, D.B. Jess, M. Stangalini, High-resolution spectropolarimetric observations of the temporal evolution of magnetic fields in photospheric bright points. A&A 633, 60 (2020). https://doi.org/10.1051/0004-6361/201936545

T. Kosugi, K. Matsuzaki, T. Sakao, T. Shimizu, Y. Sone, T. Tachikawa, T. Hashimoto, K. Minesugi, A. Ohnishi, T. Yamada, S. Tsuneta, H. Harra, K. Ichimoto, Y. Suematsu, M. Shimizu, T. Watanabe, S. Shimada, J.M. Davis, L.D. Hill, J.K. Owens, A.M. Title, J.L. Culhane, L.K. Harra, G.A. Doschek, L. Golub, The Hinode (solar-B) mission: an overview. Sol. Phys. 243, 3–17 (2007). https://doi.org/10.1007/s11207-007-9014-6
C. Kuckein, Height variation of magnetic field and plasma flows in isolated bright points. A &A 630, 139 (2019). https://doi.org/10.1051/0004-6361/201935856. arXiv:1909.05550 [astro-ph.SR]

J. Leenaarts, Radiation hydrodynamics in simulations of the solar atmosphere. Living Rev. Solar Phys. 17(1), 3 (2020). https://doi.org/10.1007/s41116-020-00204-x. arXiv:2002.03623 [astro-ph.SR]

J.R. Lemen, A.M. Title, D.J. Akin, P.F. Boerner, C. Chou, J.F. Drake, D.W. Duncan, C.G. Edwards, F.M. Friedlaender, G.F. Heyman, N.E. Hurlburt, N.L. Katz, G.D. Kushner, M. Levay, R.W. Lindgren, D.P. Mathur, E.L. McFeaters, S. Mitchell, R.A. Rehse, C.J. Schrijver, L.A. Springer, R.A. Stern, T.D. Tarbell, J.-P. Wuelser, C.J. Wolfson, C. Yanari, J.A. Bookbinder, P.N. Cheimets, D. Caldwell, E.E. Deluca, R. Gates, L. Golub, S. Park, W.A. Podgorski, R.I. Bush, P.H. Scherrer, M.A. Gunmin, P. Smith, G. Auker, P. Jerram, P. Pool, R. Soufli, D.L. Windt, S. Beardsley, M. Clapp, J. Lang, N. Waltham, The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). Sol. Phys. 275(1–2), 17–40 (2012). https://doi.org/10.1007/s11207-011-0177-6

Q. Li, N. Deng, J. Jing, C. Liu, H. Wang, High-resolution observation of moving magnetic features. ApJ 876(2), 129 (2019). https://doi.org/10.3847/1538-4357/ab10aa

B.W. Lites, K.D. Leka, A. Skumanich, V.M. Pillet, T. Shimizu, Small-scale horizontal magnetic fields in the solar photosphere. ApJ 460, 1019 (1996). https://doi.org/10.1086/177028

Y. Liu, Y. Xiang, R. Erdélyi, Z. Liu, D. Li, Z. Ning, Y. Bi, N. Wu, J. Lin, Studies of isolated and non-isolated photospheric bright points in an active region observed by the new vacuum solar telescope. ApJ 856(1), 17 (2018). https://doi.org/10.3847/1538-4357/aab150

Q.Y. Luo, F.S. Wei, X.S. Feng, Excitation and dissipation of torsional modes in solar photospheric magnetic flux tubes. A &A 395, 669–675 (2002). https://doi.org/10.1051/0004-6361:20021292

T. Magara, Dynamics of emerging flux tubes in the sun. ApJ 549(1), 608–628 (2001). https://doi.org/10.1086/319073

N. Magyar, D. Utz, R. Erdélyi, V.M. Nakariakov, Could switchbacks originate in the lower solar atmosphere? I. Formation mechanisms of switchbacks. ApJ 911(2), 75 (2021). https://doi.org/10.3847/1538-4357/abec49. arXiv:2103.03726 [astro-ph.SR]

N. Magyar, D. Utz, R. Erdélyi, V.M. Nakariakov, Could switchbacks originate in the lower solar atmosphere? II. Propagation of switchbacks in the solar corona. ApJ 914(1), 8 (2021). https://doi.org/10.3847/1538-4357/abfa98. arXiv:2104.10126 [astro-ph.SR]

J. Martínez-Sykora, B. De Pontieu, V. Hansteen, Two-dimensional radiative magnetohydrodynamic simulations of the importance of partial ionization in the chromosphere. ApJ 753(2), 161–161 (2012) arXiv:1204.5991 [astro-ph.SR]. https://doi.org/10.1088/0004-637X/753/2/161

J. Martínez-Sykora, V.H. Hansteen, B. Gudiksen, M. Carlsson, B. De Pontieu, M. Gošić, On the origin of the magnetic energy in the quiet solar chromosphere. ApJ 878(1), 40 (2019). https://doi.org/10.3847/1538-4357/abfa98. arXiv:1904.04464 [astro-ph.SR]

M. Mathioudakis, D.B. Jess, R. Erdélyi, Alfvén waves in the solar atmosphere. From theory to observations. Space Sci. Rev. 175, 1–27 (2013). https://doi.org/10.1007/s11214-012-9944-7. arXiv:1210.3625 [astro-ph.SR]

S.A. Matthews, M. Collados, M. Mathioudakis, R. Erdelyi, The European Solar Telescope (EST). In: Evans, C.J., Simard, L., Takami, H. (eds.) Proc. SPIE 9908. Ground-based and Airborne Instrumentation for Astronomy VI (International Society for Optics and Photonics), vol. 9908, pp. 47–55 (2016). https://doi.org/10.1117/12.2234145

M.G. Moreels, T. Van Doorsselaere, Phase relations for seismology of photospheric flux tubes. A &A 551, 137 (2013). https://doi.org/10.1051/0004-6361/201219568

M.G. Moreels, M. Goossens, T. Van Doorsselaere, Cross-sectional area and intensity variations of sausage modes. A &A 555, 75 (2013). https://doi.org/10.1051/0004-6361/201321545

M.G. Moreels, N. Freij, R. Erdélyi, T. Van Doorsselaere, G. Verth, Observations and mode identification of sausage waves in a magnetic pore. A &A 579, 73 (2015). https://doi.org/10.1051/0004-6361/201425096

F. Moreno-Insertis, J. Martinez-Sykora, V.H. Hansteen, D. Muñoz, Small-scale magnetic flux emergence in the quiet sun. ApJ 859(2), 26 (2018). https://doi.org/10.3847/2041-8213/aac648. arXiv:1806.00489 [astro-ph.SR]

R.J. Morton, M.S. Ruderman, R. Erdélyi, Torsional Alfvén waves: magneto-seismology in static and dynamic coronal plasmas. A &A 534, 27 (2011). https://doi.org/10.1051/0004-6361/201117020

R.J. Morton, R. Erdélyi, D.B. Jess, M. Mathioudakis, Observations of sausage modes in magnetic pores. ApJ 729(2), 18 (2011). https://doi.org/10.1088/2041-8205/729/2/L18. arXiv:1011.2375 [astro-ph.SR]
R.J. Morton, G. Verth, J.A. McLaughlin, R. Erdélyi, Determination of sub-resolution structure of a jet by solar magnetoseismology. ApJ 744(1), 5 (2012). https://doi.org/10.1088/0004-637X/744/1/5. arXiv:1109.4851 [astro-ph.SR]

R. Muller, The dynamical behavior of facular points in the quiet photosphere. Sol. Phys. 85, 113–121 (1983). https://doi.org/10.1007/BF00148262

R. Muller, S.L. Keil, The characteristic size and brightness of facular points in the quiet photosphere. Sol. Phys. 87, 243–250 (1983)

R. Muller, T. Roudier, Formation of network bright points by granule compression. Sol. Phys. 141, 27–33 (1992)

R. Muller, J.C. Hulot, T. Roudier, Perturbation of the granular pattern by the presence of magnetic flux tubes. Sol. Phys. 119, 229–243 (1989). https://doi.org/10.1007/BF00146177

R. Muller, H. Auffret, T. Roudier, J. Vigneau, G.W. Simon, Z. Frank, R.A. Shine, A.M. Title, Evolution and advection of solar mesogranulation. Nature 356(6367), 322–325 (1992). https://doi.org/10.1038/35622a0

K. Murawski, P. Kayshap, A.K. Srivastava, D.J. Pascoe, P. Jelínek, B. Kuźma, V. Fedun, Magnetic swirls and associated fast magnetoacoustic kink waves in a solar chromospheric flux tube. MNRAS 474(1), 77–87 (2018). https://doi.org/10.1093/mnras/stx2763. arXiv:1710.08179 [astro-ph.SR]

S. Nagata, S. Tsuneta, Y. Suematsu, K. Ichimoto, Y. Katsukawa, T. Shimizu, T. Yokoyama, T.D. Tarbell, B.W. Lites, R.A. Shine, T.E. Berger, A.M. Title, L.R. Bellot-Rubio, D. Orozco-Suárez, Formation of solar magnetic flux tubes with kilogauss field strength induced by convective instability. ApJ 677, 145–147 (2008). https://doi.org/10.1086/588026

V.M. Nakariakov, D. Banerjee, B. Li, T. Wang, I.V. Zimovets, M. Falanga, Editorial to the topical collection: oscillatory processes in solar and stellar coronae. Space Sci. Rev. 218(3), 13 (2022). https://doi.org/10.1007/s11214-022-00888-1

C.J. Nelson, N. Freij, S. Bennett, R. Erdélyi, M. Mathioudakis, Spatially resolved signatures of bidirectional flows observed in inverted-Y shaped jets. ApJ 883(2), 115 (2019). https://doi.org/10.3847/1538-4357/ab3a54. arXiv:1908.05132 [astro-ph.SR]

P. Nisenson, A.A. van Ballegooijen, A.G. de Wijn, P. Sütterlin, Motions of isolated G-band bright points in the solar photosphere. ApJ 587, 458–463 (2003). https://doi.org/10.1086/368067. arXiv:astro-ph/0212306

D. Nóbrega-Siverio, F. Moreno-Insertis, J. Martínez-Sykora, The cool surge following flux emergence in a radiation-MHD experiment. ApJ 822(1), 18 (2016). https://doi.org/10.3847/1538-4357/822/1/18. arXiv:1601.04074 [astro-ph.SR]

L.J. November, G.W. Simon, Precise proper-motion measurement of solar granulation. ApJ 333, 427 (1988). https://doi.org/10.1086/166758

A. Ortiz, L.R.B. Rubio, V.H. Hansteen, J. de la Cruz Rodríguez, L.R. van der Voort, Emergence of granular-sized magnetic bubbles through the solar atmosphere. I. Spectropolarimetric observations and simulations. ApJ 781(2), 126 (2014). https://doi.org/10.1088/0004-637X/781/2/126

A. Ortiz, V.H. Hansteen, D. Nóbrega-Siverio, Ellermann bombs and UV bursts: reconnection at different atmospheric layers. A &A 633(58) (2020). https://doi.org/10.1051/0004-6361/201936574. arXiv:1910.10736 [astro-ph.SR]

J. Palacios, J. Blanco Rodríguez, S. Vargas Domínguez, V. Domingo, V. Martínez Pillet, J.A. Bonet, L.R. Bellot Rubio, J.C. Del Toro Iniesta, S.K. Solanki, P. Barthol, A. Gandorfer, T. Berkefeld, W. Schmidt, M. Knölker, Magnetic field emergence in mesogranular-sized exploding granules observed with sunrise/IMaX data. A &A 537, 21 (2012). https://doi.org/10.1051/0004-6361/201117936. arXiv:1110.4555 [astro-ph.SR]

A. Pardi, I. Ballai, A. Marcu, B. Orza, Sausage mode propagation in a thick magnetic flux tube. Sol. Phys. 289(4), 1203–1214 (2014). https://doi.org/10.1007/s11207-013-0380-y. arXiv:1310.5871

E. Pariat, S.K. Antiochos, C.R. DeVore, Three-dimensional modeling of Quasi-homologous solar jets. ApJ 714(2), 1762–1778 (2010). https://doi.org/10.1088/0004-637X/714/2/1762

E.N. Parker, Hydraulic concentration of magnetic fields in the solar photosphere. VI—adiabatic cooling and concentration in downdrafts. ApJ 221, 368–377 (1978). https://doi.org/10.1086/156035

C.E. Parnell, C.E. DeForest, H.J. Hagenaar, B.A. Johnston, D.A. Lamb, B.T. Welsch, A power-law distribution of solar magnetic fields over more than five decades in flux. ApJ 698(1), 75–82 (2009). https://doi.org/10.1088/0004-637X/698/1/75

W.D. Pesnell, B.J. Thompson, P.C. Chamberlin, The Solar Dynamics Observatory (SDO). Sol. Phys. 275(1–2), 3–15 (2012). https://doi.org/10.1007/s11207-011-9841-3
M.P. Rast, The scales of granulation, mesogranulation, and supergranulation. ApJ 597(2), 1200–1210 (2003). https://doi.org/10.1086/381221

M.P. Rast, N. B. González, L. B. Rubio, W. Cao, G. Cauzzi, E. Deluca, B. de Pontieu, L. Fletcher, S.E. Gibson, P.G. Judge, Y. Katsukawa, M.D. Kazachenko, E. Khomenko, E. Landi, V. M. Pillet, G.J.D. Petrie, J. Qiu, L.A. Rachmeler, M. Rempel, W. Schmidt, E. Scullion, X. Sun, B.T. Welsch, V. Andretta, P. Antolin, T.R. Ayres, K.S. Balasubramanian, I. Ballai, T.E. Berger, S.J. Bradshaw, R.J. Campbell, M. Carlsson, R. Casini, R. Centeno, S.R. Cranmer, S. Criscuoli, C. Deforest, Y. Deng, R. Erdélyi, V. Fedun, C.E. Fischer, S.J. González Manrique, M. Hahn, L. Harra, V.M.J. Henriques, N.E. Hurlburt, S. Jaeggli, S. Jafarzadeh, R. Jain, S.M. Jefferies, P.H. Keys, A.F. Kowalski, C. Kuckein, J.R. Kuhn, D. Kuridze, J. Liu, W. Liu, D. Longcope, M. Mathioudakis, R.T.J. McAteer, S.W. McIntosh, D.E. McKenzie, M.P. Miralles, R.J. Morton, K. Muglach, C.J. Nelson, N.K. Panesar, S. Parenti, C.E. Parnell, B. Poduval, K.P. Reardon, T.A. Schad, D. Schmit, R. Sharma, H. Socrates Navarro, A.K. Srivastava, A.C. Sterling, Y. Suematsu, L.A. Tarr, S. Tiwari, A. Tritschler, G. Verth, A. Vourlidas, H. Wang, Y.-M. Wang, NSO and DKIST Project, DKIST Instrument cientists, KIST Science Working Group, DKIST Critical Science Plan Community: Critical Science Plan for the Daniel K. Inouye Solar Telescope (DKIST). Sol. Phys. 296(4), 70 (2021). https://doi.org/10.1007/s11207-021-01789-2. arXiv:2008.08203 [astro-ph.SR]

A. Reid, M. Mathioudakis, J.G. Doyle, E. Scullion, C.J. Nelson, V. Henriques, T. Ray, Magnetic flux cancellation in Ellerman bombs. ApJ 823(2), 110 (2016). https://doi.org/10.1088/0004-637X/823/2/110. arXiv:1603.07100 [astro-ph.SR]

I.S. Requerey, J.C. Del Toro Iniesta, L.R.B. Rubio, J.A. Bonet, V.M. Pillet, S.K. Solanki, W. Schmidt, The history of a quiet-sun magnetic element revealed by IMaX/SUNRISE. ApJ. 789(1), 6 (2014). https://doi.org/10.1088/0004-637X/789/1/6. arXiv:1405.2837 [astro-ph.SR]

J.M. Riedl, C.A. Gilchrist-Millar, T. Van Doorsselaere, D.B. Jess, S.D.T. Grant, Finding the mechanism of wave energy flux damping in solar pores using numerical simulations. A &A 648, 77 (2021). https://doi.org/10.1051/0004-6361/202040163. arXiv:2102.12420 [astro-ph.SR]

T.L. Riethmüller, S.K. Solanki, S.V. Berdyugina, M. Schüssler, V.M. Pillet, A. Feller, A. Gandorfer, J. Hirzberger, Comparison of solar photospheric bright points between sunrise observations and MHD simulations. A &A 568, 13 (2014). https://doi.org/10.1051/0004-6361/201423892. arXiv:1406.1387 [astro-ph.SR]

J.I.C. Rozo, D. Utz, S.V. Domínguez, A. Veronig, T. Van Doorsselaere, Photospheric plasma and magnetic field dynamics during the formation of solar AR 11190. A &A 622, 168 (2019). https://doi.org/10.1051/0004-6361/201832760. arXiv:1901.02437 [astro-ph.SR]

L.R.B. Rubio, C. Beck, Magnetic flux cancellation in the moat of sunspots: results from simultaneous vector spectropolarimetry in the visible and the infrared. ApJ 626, 125–128 (2005). https://doi.org/10.1086/431648

L.R.B. Rubio, D.O. Suárez, Pervasive linear polarization signals in the quiet sun. Astrophys. J. 757(1), 19 (2012). https://doi.org/10.1088/0004-637x/757/1/19

L.B. Rubio, D.O. Suárez, Quiet Sun magnetic fields: an observational view. Living Rev. Solar Phys. 16(1), 1 (2019). https://doi.org/10.1007/s41116-018-0017-1

L.R.B. Rubio, I.R. Hidalgo, M. Collados, E. Khomenko, B.R. Cob, Observation of convective collapse and upward-moving shocks in the quiet sun. ApJ 560, 1010–1019 (2001). https://doi.org/10.1086/323061

M. Ryutova, Moving magnetic features (MMFs), pp. 287–321. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-96361-7_11

G.B. Saavedra, D. Utz, S.V. Domínguez, J.I.C. Rozo, S.J.G. Manrique, P. Gömöry, C. Kuckein, H. Balthasar, P. Zelina, Observational evidence for two-component distributions describing solar magnetic bright points. A & A 657, 79 (2022). https://doi.org/10.1051/0004-6361/202141231. arXiv:2110.12404 [astro-ph.SR]

T. Samanta, H. Tian, V. Yurchyshyn, H. Peter, W. Cao, A. Sterling, R. Erdélyi, K. Ahn, S. Feng, D. Utz, D. Banerjee, Y. Chen, Generation of solar spicules and subsequent atmospheric heating. Science 366(6467), 890–894 (2019). https://doi.org/10.1126/science.aaw2796. arXiv:2006.02571 [astro-ph.SR]

J. Scalisi, M.S. Ruderman, R. Erdélyi, Reflection and evolution of torsional Alfvén pulses in zero-beta flux tubes. ApJ 922(2), 118 (2021). https://doi.org/10.3847/1538-4357/ac2509

R. Schlichenmaier, L.R.B. Rubio, M. Collados, R. Erdelyi, A. Feller, L. Fletcher, J. Jurcak, E. homenko, J. Leenaarts, S. Matthews, L. Belluzzi, M. Carlsson, K. Dalmasse, S. Danilovic, P. Gömöry, C. Kuckein, R.M. Sainz, M.M. Gonzalez, M. Mathioudakis, A. Ortiz, T.L. Riethmüller, L.R. van der
Voort, P.J.A. Simoes, J.T. Bueno, D. Utz, F. Zuccarello, Science Requirement Document (SRD) for the European Solar Telescope (EST) (2nd edition, December 2019). arXiv e-prints, 1912–08650 (2019) arXiv:1912.08650 [astro-ph.SR]

M. Schüssler, A. Vögler, Magnetocovection in a sunspot umbra. ApJ 641(1), 73–76 (2006). https://doi.org/10.1086/493772. arXiv:astro-ph/0603078 [astro-ph]

M. Schüssler, S. Shelyag, S. Berdyugina, A. Vögler, S.K. Solanki, Why solar magnetic flux concentrations are bright in molecular bands. ApJ 597, 173–176 (2003). https://doi.org/10.1086/379869

S. Shelyag, V. Fedun, F.P. Keenan, R. Erdélyi, M. Mathioudakis, Photospheric magnetic vortex structures. Annales Geophysicae 29(5), 883–887 (2011). https://doi.org/10.5194/angeo-29-883-2011

S. Shelyag, P. Keys, M. Mathioudakis, F.P. Keenan, Vorticity in the solar photosphere. A & A 526, 5 (2011). https://doi.org/10.1051/0004-6361/201015645. arXiv:1010.5604 [astro-ph.SR]

S. Shelyag, P.S. Cally, A. Reid, M. Mathioudakis, Alfvén waves in simulations of solar photospheric vortices. ApJ 776(1), 4 (2013). https://doi.org/10.1088/2041-8205/776/1/L4. arXiv:1309.2019 [astroph.SR]

S. Shelyag, E. Khomenko, A. de Vicente, D. Przybyski, Heating of the partially ionized solar chromosphere by waves in magnetic structures. ApJ 819(1), 11 (2016). https://doi.org/10.3847/2041-8205/819/1/L11. arXiv:1602.03373 [astro-ph.SR]

S.S.A. Silva, G. Verth, E.L. Rempel, S. Shelyag, L.A.C.A. Schiavo, V. Fedun, Solar vortex tubes. II. On the origin of magnetic vortices. ApJ 915(1), 24 (2021). https://doi.org/10.3847/1538-4357/abf62c

S. Skirvin, G. Verth, I.J. González-Avilés, S. Shelyag, R. Sharma, F.S. Guzmán, I. Ballai, E. Scullion, S.S.A. Silva, V. Fedun, Small-scale solar jet formation and their associated waves and instabilities. Adv. Space Res. (2022). https://doi.org/10.1016/j.asr.2022.05.033

B. Snow, G.J.J. Botha, J.A. McLaughlin, A. Hillier, Onset of 2D magnetic reconnection in the solar photosphere, chromosphere, and corona. A & A 609, 100 (2018). https://doi.org/10.1051/0004-6361/201731214. arXiv:1711.00683 [astro-ph.SR]

M. Sobotka, J.A. Bonet, M. Vázquez, A high-resolution study of inhomogeneities in sunspot umbrae. ApJ 415, 832 (1993). https://doi.org/10.1086/173205

M. Sobotka, P.N. Brandt, G.W. Simon, Fine structure in sunspots. I. Sizes and lifetimes of umbral dots. A & A 328, 682–688 (1997)

M. Sobotka, M. Vázquez, J.A. Bonet, A. Hanslmeier, J. Hirzberger, Temporal evolution of fine structures in and around solar pores. ApJ 511(1), 436–450 (1999). https://doi.org/10.1086/306671

M. Sobotka, M. Švanda, J. Jurčák, P. Heinzel, D. Del Moro, F. Berrilli, Dynamics of the solar atmosphere above a pore with a light bridge. A & A 560, 84 (2013). https://doi.org/10.1051/0004-6361/20132148. arXiv:1309.7790 [astro-ph.SR]

S.K. Solanki, D. Zufferey, H. Lin, I. Ruedi, J.R. Kuhn, Infrared lines as probes of solar magnetic features. XII. Magnetic flux tubes: evidence of convective collapse? A & A 310, 33–36 (1996)

S.K. Solanki, B. Inhester, M. Schüssler, The solar magnetic field. Rep. Progress Phys. 69(3), 563–668 (2006). https://doi.org/10.1088/0034-4885/69/3/R02. arXiv:1008.0771 [astro-ph.SR]

R. Soler, J. Terradas, R. Oliver, J.L. Ballester, Resonances in a coronal loop driven by torsional Alfvén waves propagating from the photosphere. ApJ 909(2), 190 (2021). https://doi.org/10.3847/1538-4357/abdec5

A.A. Solov’ev, L.D. Parfinenko, V.I. Efremov, E.A. Kirichek, O.A. Korolkova, Structure of photosphere under high resolution: granules, faculae, micropores, intergranular lanes. Ap & SS 364(12), 222 (2019). https://doi.org/10.1007/s10509-019-3710-1

H.C. Spruit, Convective collapse of flux tubes. Sol. Phys. 61, 363–378 (1979). https://doi.org/10.1007/BF00150420

M. Stangalini, F. Giannattasio, R. Erdélyi, S. Jafarzadeh, G. Consolini, S. Criscuoli, I. Ermolli, S.L. Guglielmino, F. Zuccarello, Polarized kink waves in magnetic elements: evidence for chromospheric helical waves. ApJ 840(1), 19 (2017). https://doi.org/10.3847/1538-4357/aa6c5e. arXiv:1704.02155 [astro-ph.SR]

M. Stangalini, D.B. Jess, G. Verth, V. Fedun, B. Fleck, S. Jafarzadeh, P.H. Keys, M. Murabito, D. Calcchi, A.A. Aldhafeeri, F. Berrilli, D. Del Moro, S.M. Jefferies, J. Terradas, R. Soler, A novel approach to identify resonant MHD wave modes in solar pores and sunspot umbrae: B ~ω analysis. A & A 649, 169 (2021). https://doi.org/10.1051/0004-6361/202140429. arXiv:2103.11639 [astro-ph.SR]
M. Stangalini, R. Erdélyi, C. Boocock, D. Tsiklauri, C.J. Nelson, D. Del Moro, F. Berrilli, M.B. Korsós, Torsional oscillations within a magnetic pore in the solar photosphere. Nat. Astron. 5, 691–696 (2021). https://doi.org/10.1038/s41550-021-01354-8

A.A. Stanislavsky, K. Weron, Subdiffusive transport in intergranular lanes on the Sun. The Leighton model revisited. Ap &SS 312, 343–347 (2007). https://doi.org/10.1016/j.apsusc.2007.09.007

R.F. Stein, A. Lagerjárd, A. Nordlund, D. Georgobiani, Solar flux emergence simulations. Sol. Phys. 268(2), 271–282 (2011). https://doi.org/10.1007/s11207-010-9510-y

O. Steiner, P.H. Hausschildt, J. Bruls, Radiative properties of magnetic elements. I. Why are vec G-band bright points bright? A & A 372, 13–16 (2001). https://doi.org/10.1051/0004-6361:20010540

M. Terra-Homem, R. Erdélyi, I. Ballai, Linear and non-linear MHD wave propagation in steady-state magnetic cylinders. Sol. Phys. 217(2), 199–223 (2003). https://doi.org/10.1023/B:SOLA.000006901.22169.59

I. Thaler, H.C. Spruit, Brightness of the sun's small scale magnetic field: proximity effects. A & A 566, 11 (2014). https://doi.org/10.1051/0004-6361/201322126. arXiv:1404.2871 [astro-ph.SR]

I. Thaler, H.C. Spruit, Small-scale dynamos on the solar surface: dependence on magnetic Prandtl number. A & A 578, 54 (2015). https://doi.org/10.1051/0004-6361/201423738. arXiv:1505.04575 [astro-ph.SR]

H. Tian, S.W. McIntosh, T. Wang, L. Ofman, B. De Pontieu, D.E. Innes, H. Peter, Persistent Doppler shift oscillations observed with Hinode/EIS in the solar corona: spectroscopic signatures of Alfvénic waves and recurring upflows. ApJ 759(2), 144 (2012). https://doi.org/10.1088/0004-637X/759/2/144. arXiv:1209.5286 [astro-ph.SR]

A.M. Title, T.D. Tarbell, K.P. Topka, S.H. Ferguson, R.A. Shine, SOUP Team, Statistical properties of solar granulation derived from the SOUP instrument on Spacelab 2. ApJ 336, 475–494 (1989). https://doi.org/10.1086/167026

D. Utz, A. Hanslmeier, C. Möstl, R. Muller, A. Veronig, H. Muthsam, The size distribution of magnetic bright points derived from Hinode/SOT observations. A & A 498, 289–293 (2009). https://doi.org/10.1051/0004-6361:200810867

D. Utz, A. Hanslmeier, R. Muller, A. Veronig, J. Rybáč, H. Muthsam, Dynamics of isolated magnetic bright points derived from Hinode/SOT G-band observations. A & A 511, 39 (2010). https://doi.org/10.1051/0004-6361:200913085. arXiv:0912.1965 [astro-ph.SR]

D. Utz, A. Hanslmeier, A. Veronig, O. Kühner, R. Muller, J. Jurčák, B. Lemmerer, Variations of magnetic bright point properties with longitude and latitude as observed by Hinode/SOT G-band data. Sol. Phys. 284(2), 363–378 (2013). https://doi.org/10.1007/s11207-012-0210-7. arXiv:1212.1310 [astro-ph.SR]

D. Utz, J. Jurčák, A. Hanslmeier, R. Muller, A. Veronig, O. Kühner, Magnetic field strength distribution of magnetic bright points inferred from filtergrams and spectro-polarimetric data. A & A 554, 65 (2013). https://doi.org/10.1051/0004-6361/201116894

D. Utz, J.C. del Toro Iniesta, L.R.B. Rubio, J. Jurčák, V.M. Pillet, S.K. Solanki, The formation and disintegration of magnetic bright points observed by sunrise/MAx. ApJ 796, 79 (2014). https://doi.org/10.1088/0004-637X/796/2/79. arXiv:1411.3240 [astro-ph.SR]

D. Utz, R. Muller, S. Thonhofer, A. Veronig, A. Hanslmeier, M. Bodnárová, M. Bártá, J.C. del Toro Iniesta, Long-term trends of magnetic bright points. I. Number of magnetic bright points at disc centre. A & A 585, 39 (2016). https://doi.org/10.1051/0004-6361/201525926. arXiv:1511.07767 [astro-ph.SR]

L.R. van der Voort, B. De Pontieu, G.B. Scharmer, J. de la Cruz Rodríguez, J. Martínez-Sykora, D. Nóbrega-Siverio, L.J. Guo, S. Jafarzadeh, T.M.D. Pereira, V.H. Hansteen, M. Carlsson, G. Vissers, Immertent connection and plasmoids in UV bursts in the low solar atmosphere. ApJ 851(1), 6 (2017). https://doi.org/10.3847/2041-8213/aa99dd. arXiv:1711.04581 [astro-ph.SR]

T. Van Doorsselaere, B. Li, M. Goossens, B. Hnat, N. Magyar, Wave pressure and energy cascade rate of kink waves computed with Elsässer variables. ApJ 899(2), 100 (2020). https://doi.org/10.3847/1538-4357/aba0b8. arXiv:2007.15411 [astro-ph.SR]

G. Vigeesh, S.S. Hasan, O. Steiner, Wave propagation and energy transport in the magnetic network of the Sun. A & A 508, 951–962 (2009). https://doi.org/10.1051/0004-6361/200912450. arXiv:0909.2325 [astro-ph.SR]

B. Viticchié, D. Del Moro, S. Criscuoli, F. Berrilli, Imaging spectropolarimetry with IBIS. II. On the fine structure of G-band bright features. ApJ 723, 787–796 (2010). https://doi.org/10.1088/0004-637X/723/1/787. arXiv:1009.0721 [astro-ph.SR]
A. Vögler, S. Shelyag, M. Schüssler, F. Cattaneo, T. Emonet, T. Linde, Simulations of magneto-convection in the solar photosphere. Equations, methods, and results of the MURaM code. A & A 429, 335–351 (2005). https://doi.org/10.1051/0004-6361:20041507

H. Wang, H. Zirin, Flows around sunspots and pores. Sol. Phys. 140(1), 41–54 (1992). https://doi.org/10.1007/BF00148428

S. Wedemeyer-Böhm, E. Scullion, O. Steiner, L.R. van der Voort, J. de La Cruz Rodriguez, V. Fedun, R. Erdélyi, Magnetic tornadoes as energy channels into the solar corona. Nature 486, 505–508 (2012). https://doi.org/10.1038/nature11202

E. Wiehr, B. Bovelet, J. Hirzberger, Brightness and size of small-scale solar magnetic flux concentrations. A & A 422, 63–66 (2004). https://doi.org/10.1051/0004-6361:200400019

A. Wiśniewska, Z.E. Musielak, J. Staiger, M. Roth, Observational evidence for variations of the acoustic cutoff frequency with height in the solar atmosphere. ApJ 819(2), 23 (2016). https://doi.org/10.3847/2041-8205/819/2/L23

J. Xiong, Y. Yang, C. Jin, K. Ji, S. Feng, F. Wang, H. Deng, Y. Hu, The characteristics of thin magnetic flux tubes in the lower solar atmosphere observed by Hinode/SOT in the G band and in Ca II H bright points. ApJ 851(1), 42 (2017). https://doi.org/10.3847/1538-4357/aa9a44

L. Xu, Y. Yang, Y. Yan, Y. Zhang, X. Bai, B. Liang, W. Dai, S. Feng, W. Cao, Research on multiwavelength isolated bright points based on deep learning. ApJ 911(3), 32 (2021). https://doi.org/10.3847/1538-4357/abe705

Z. Xu, H. Ji, J. Hong, K. Ji, J. Yang, Magnetic field evolution around a fast-moving pore emerging from the quiet Sun. A & A 660, 55 (2022). https://doi.org/10.1051/0004-6361/202143021

Z. Xue, X. Yan, L. Yang, J. Chen, J. Wang, Q. Li, L. Zhao, Decay of solar pores driven by small-scale magnetic reconnection episodes. ApJ 919(2), 29 (2021). https://doi.org/10.3847/2041-8213/ac2733

L. Yang, J. He, H. Peter, C. Tu, L. Zhang, X. Feng, S. Zhang, Numerical simulations of chromospheric anemone jets associated with moving magnetic features. ApJ 777(1), 16 (2013). https://doi.org/10.1088/0004-637X/777/1/16

Y.-F. Yang, J.-B. Lin, S. Feng, K.-F. Ji, H. Deng, F. Wang, Evolution of isolated G-band bright points: size, intensity and velocity. Res. Astron. Astrophys. 14, 741–752 (2014). https://doi.org/10.1088/1674-4527/14/6/012

V. Zakharov, A. Gandorfer, S.K. Solanki, M. Löfdahl, A comparative study of the contrast of solar magnetic elements in CN and CH. A & A 437, 43–46 (2005). https://doi.org/10.1051/0004-6361:20050135

X. Zhao, F. Bacchini, R. Keppens, Magnetic island merging: two-dimensional MHD simulation and test-particle modeling. Phys. Plasmas 28(9), 092113 (2021). https://doi.org/10.1063/5.0058326. arXiv:2108.13508 [astro-ph.SR]

X. Zhou, J. Büchner, M. Bártta, W. Gan, S. Liu, Electron acceleration by cascading reconnection in the solar corona. II. Resistive electric field effects. ApJ 827(2), 94 (2016). https://doi.org/10.3847/0004-637X/827/2/94

C. Zwaan, Elements and patterns in the solar magnetic field. ARA & A 25, 83–111 (1987). https://doi.org/10.1146/annurev.aa.25.090187.000503

C. Zwaan, J.J. Brants, L.E. Cram, High resolution spectroscopy of active regions—part one—observing procedures. Sol. Phys. 95(1), 3–14 (1985). https://doi.org/10.1007/BF00162632

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.