

Research Progress on Solar Supergranulation: Observations, Theories, and Numerical Simulations

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Abstract: Solar supergranulation is a large-scale convective structure on the solar surface, whose formation mechanism and dynamical properties are closely related to key physical processes such as solar magnetic field evolution, coronal heating, and solar wind acceleration. This paper reviews recent research progress on solar supergranulation, focusing on the latest achievements in high-resolution observations, theoretical models, and numerical simulations. By analyzing the flow field structure, magnetic field distribution, and their relationship with the solar activity cycle, the crucial role of supergranulation in solar physics is revealed. Studies indicate that supergranulation is not only a crucial component of the solar convection zone but also drives coronal heating and solar wind acceleration through mechanisms such as magnetic reconnection and Alfvén wave propagation. Furthermore, the interaction between supergranulation and larger-scale convective patterns (e.g., giant cells) provides new insights into the dynamics of the solar interior. Despite significant progress in recent years, the formation mechanism and dynamical nature of supergranulation remain unresolved. Future research should combine high-resolution observations, theoretical modeling, and numerical simulations to further elucidate the complex dynamical processes and the central role of supergranulation in solar physics.



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Keywords: solar supergranulation; convection; magnetic field evolution; coronal heating; solar wind; numerical simulations; high-resolution observations

1. Introduction

Solar supergranulation is a large-scale convective structure on the solar surface, whose formation mechanism and dynamical properties are closely related to key physical processes such as solar magnetic field evolution, coronal heating, and solar wind acceleration. Since Hart [1] first discovered this convective cell structure in the upper photosphere in 1954 while measuring solar rotation using spectroscopy, researchers have gradually uncovered its complex dynamical behavior through observations, theories, and numerical simulations. The typical characteristics of supergranulation include: cell diameters of approximately 20,000–60,000 km, lifetimes ranging from several hours to 1–2 days, with slow upflows ($<0.04 \text{ km s}^{-1}$) in the central regions and faster downflows ($\sim 0.1 \text{ km s}^{-1}$) at the boundaries. The horizontal flow velocities of these convective cells are typically $0.3\text{--}0.5 \text{ km s}^{-1}$, and their boundary regions often accumulate strong magnetic flux, forming the supergranular network [2,3].

Supergranulation is not only a key component of the solar convection zone but also plays an important role in the evolution of the solar magnetic field, solar wind accelera-

tion, and coronal heating. In the early 1960s, Leighton et al. [2], Simon and Leighton [3] conducted systematic studies of supergranulation using Doppler measurements and estimated its typical scales and lifetimes, which reveal its strong correlation with the network magnetic field. Subsequent studies showed that the boundary regions of supergranulation are important areas for magnetic flux concentration, which may be key drivers of coronal heating and solar wind acceleration [4–7].

Despite nearly 70 years of research, the formation mechanism and dynamical nature of supergranulation remain incompletely understood. Recent advances in high-resolution observations through the Solar and Heliospheric Observatory (SOHO), Solar Dynamics Observatory (SDO), Hinode, Solar Orbiter [8], Goode Solar Telescope (GST) [9] at Big Bear Solar Observatory (BBSO), New Vacuum Solar Telescope (NVST) [10], Daniel K. Inouye Solar Telescope (DKIST) [11], and Huairou Solar Observation Station (HSOS)/Accurate Infrared Magnetic Field Measurements of the Sun (AIMS) [12–14], together with progress in numerical simulations and theoretical studies, have provided deeper insights into the physical mechanisms of supergranulation. For example, high-resolution imaging and Doppler observations have revealed the flow field structure and magnetic field distribution of supergranulation [15–17], while numerical simulations have offered new theoretical support for its formation mechanism [18,19]. Additionally, the relationship between the dynamical properties of supergranulation and the solar activity cycle has garnered growing attention, which suggests that its scale, lifetime, and flow velocity may be influenced by solar activity levels [20–23].

This review provides a comprehensive review of the latest research progress on solar supergranulation, focusing on four key aspects: observational advancements, theoretical models, numerical simulations, and its significance in solar physics and space science. By analyzing the flow field structure, magnetic field distribution, and the relationship between supergranulation and the solar activity cycle, this paper aims to explore the critical role of supergranulation in solar physics. Furthermore, it offers insights into potential future research directions.

2. Observational Advances

2.1. High-Resolution Imaging and Doppler Observations

Recent advancements in high-resolution imaging and Doppler velocity measurements using instruments such as SOHO, SDO, Hinode, DKIST, NVST and Solar Orbiter have enabled more precise characterization of solar supergranulation. These instruments provide high spatiotemporal resolution data and reveal the relationship between supergranulation and magnetic fields, coronal heating, and other physical processes through multi-wavelength observations.

Flow Field Structure of Supergranulation

The horizontal flow field of supergranulation exhibits a typical cellular structure, with upflows in the central regions and downflows at the boundaries. This behavior is similar to that of smaller-scale granulation but differs greatly in spatial and temporal scales. Rieutord et al. [4] used the 14-M pixel CALAS camera at the Pic-du-Midi Observatory to obtain a 7.5-h high-resolution image sequence, tracking solar granules to determine the velocity field on the solar surface across scales from 2.5 Mm to 250 Mm. As shown in Figure 1, the horizontal velocity field of supergranulation displays a clear cellular structure, with upflows in the center and downflows at the boundaries.

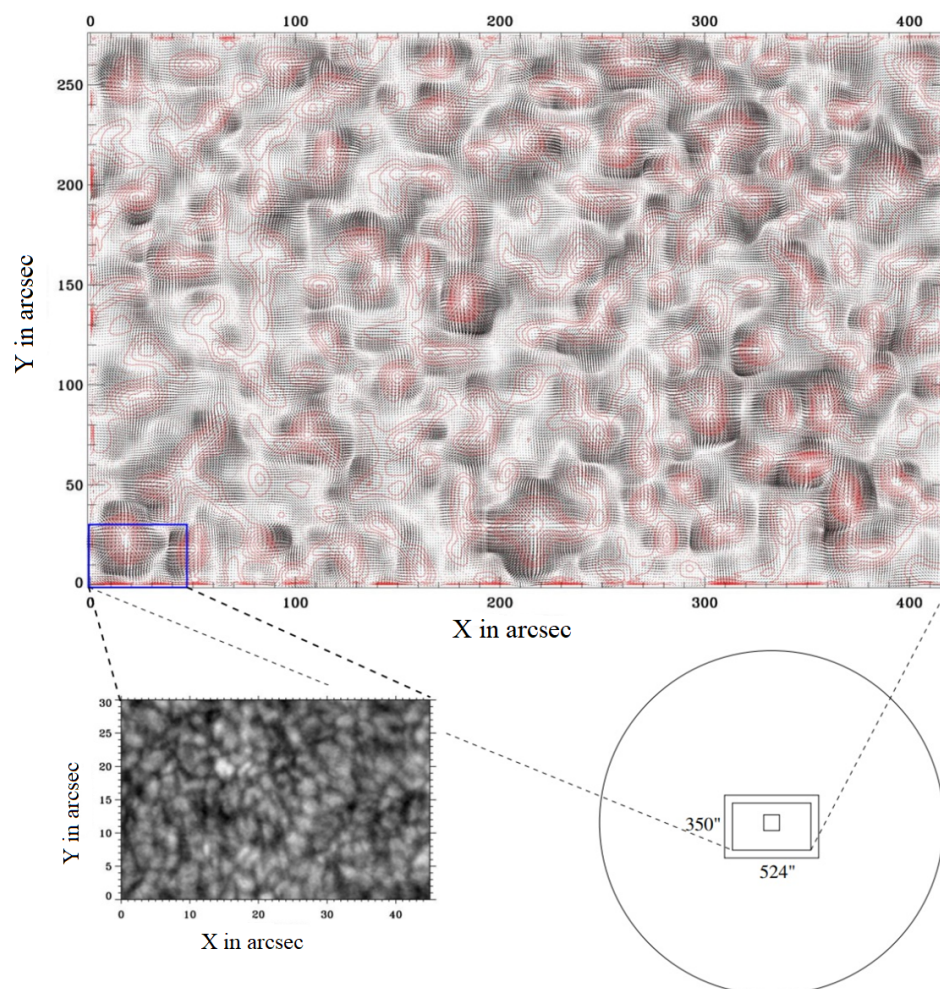


Figure 1. Horizontal velocity field of supergranulation derived from granule tracking using the CALAS camera at the Pic-du-Midi Observatory. Bottom right: CALAS field of view on the Sun. The large rectangle indicates the full image size, the smaller rectangle marks the region where velocities were computed, and the small square represents the field of view of the Hinode/SOT instrument for granule tracking. Top: Supergranulation velocity field with divergence contours overlaid. Arrows indicate the direction and magnitude of the horizontal velocity field obtained from granule tracking. Bottom left: Zoomed-in view of granulation, illustrating the relative scales of granules and supergranules [4].

Supergranulation and Network Magnetic Fields

The boundaries of supergranulation tend to accumulate strong magnetic flux concentrations, forming the supergranular network. Roudier et al. [5] studied the horizontal flow properties of supergranulation using HINODE/Solar Optical Telescope (SOT) [24] data and revealed the formation mechanism of the network magnetic field. Figure 2 illustrates the irregular distribution of magnetic fields at supergranulation boundaries.

Langfellner et al. [15] used SDO/Helioseismic and Magnetic Imager (HMI) [25,26] data and local correlation tracking (LCT) to analyze the anisotropy of network magnetic fields around average supergranular cells. The results showed that network magnetic fields at supergranulation boundaries exhibit pronounced anisotropy, closely related to the direction of the horizontal flow field. Additionally, the magnetic field strength at supergranulation boundaries is substantially enhanced, indicating that convective motions play a crucial role in the formation and evolution of network magnetic fields.

Chian et al. [27] analyzed high-resolution observations from the Hinode satellite using LCT and Lagrangian coherent structure techniques to investigate the interplay between La-

grangian chaotic saddles and persistent objective vortices in solar photospheric turbulence. By computing backward/forward finite-time Lyapunov exponents (b-FTLE/f-FTLE) and Lagrangian averaged vorticity deviation (LAVD), they identified 29 persistent objective vortices with lifetimes ranging from 28.5 to 298.3 min. These vortices were found to form predominantly in gap regions of Lagrangian chaotic saddles at supergranular junctions, driven by twisted folding motions of unstable manifolds. The study provides the first observational evidence of Lagrangian chaotic saddles in plasmas, offering a novel dynamical systems perspective on energy transport mechanisms in solar magnetic activity. In prior work, Chian et al. [28] demonstrated that attracting Lagrangian coherent structures (aLCS) identified via b-FTLE spatially coincided with high magnetic flux networks, while repelling Lagrangian structures (rLCS) revealed by f-FTLE were co-located with magnetic quasi-separatrix layers (QSLs)—a dynamic correlation further validated through numerical simulations. The study not only quantified the local contraction/expansion rates of photospheric flows but also elucidated the interaction mechanisms between turbulence-driven plasma motions and magnetic topology evolution.

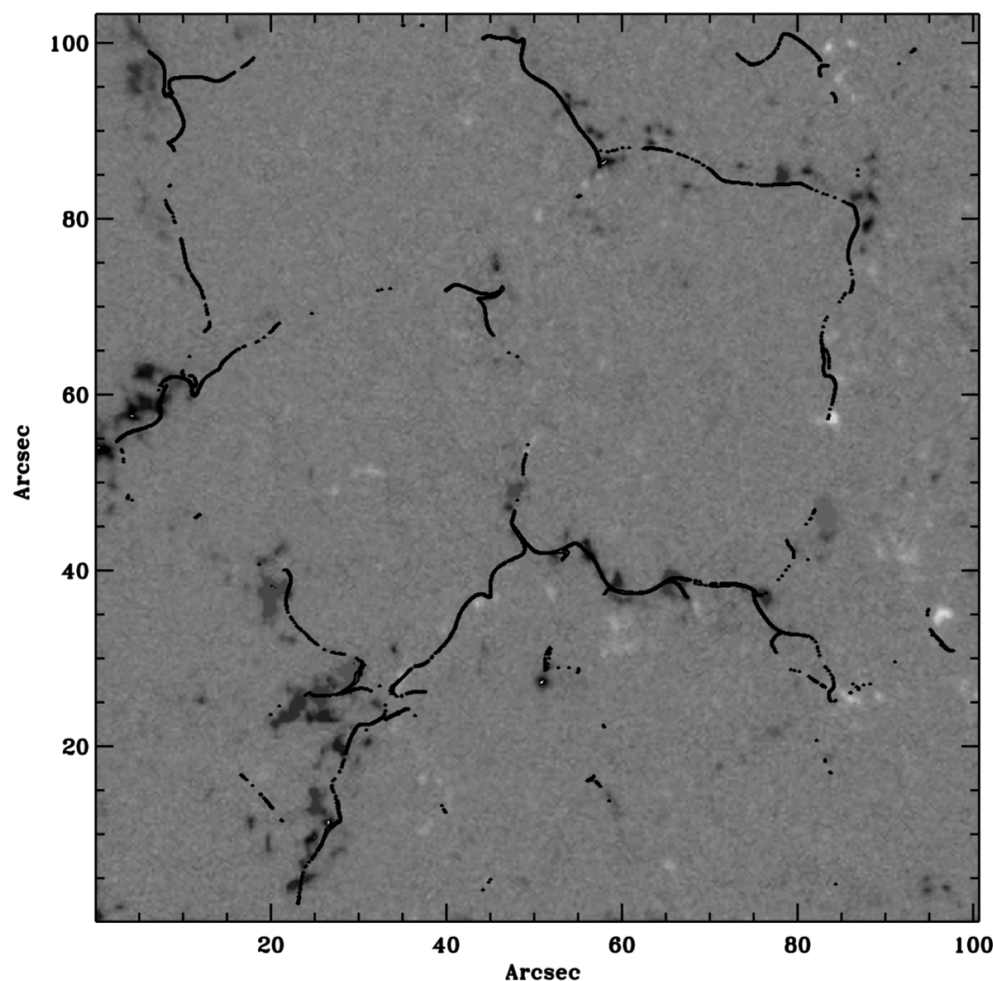


Figure 2. Irregular distribution of magnetic fields at supergranulation boundaries [5].

Robustini et al. [16] used high-resolution data from the Swedish 1-m Solar Telescope to study the magnetic configuration and dynamical properties of supergranular structures in the chromosphere. The results revealed complex magnetic topology in the chromosphere, with enhanced magnetic fields at supergranulation boundaries closely related to photospheric magnetic fields.

Suárez et al. [29] used Hinode data to investigate the relationship between internetwork magnetic elements (IMEs) and supergranular flows. The results showed that IMEs tend to drift toward supergranulation boundaries, with radial velocities consistent with supergranular flow patterns. However, Mani et al. [30] used SDO/HMI data and deep learning techniques to analyze the relationship between magnetic flux emergence and supergranular-scale surface flows. They found that magnetic flux emergence is primarily driven by subsurface dynamics, with minimal influence from surface flows.

The magnetic fields at supergranulation boundaries are considered important sources of coronal heating and solar wind acceleration. Hassler et al. [6] used SOHO observations to show that outflow velocities in coronal holes are related to chromospheric magnetic network structures as illustrated in Figure 3. This suggests that the solar wind originates from localized regions at network boundaries and intersections, providing insights into the complex structure and dynamics of the corona and the source regions of the solar wind.

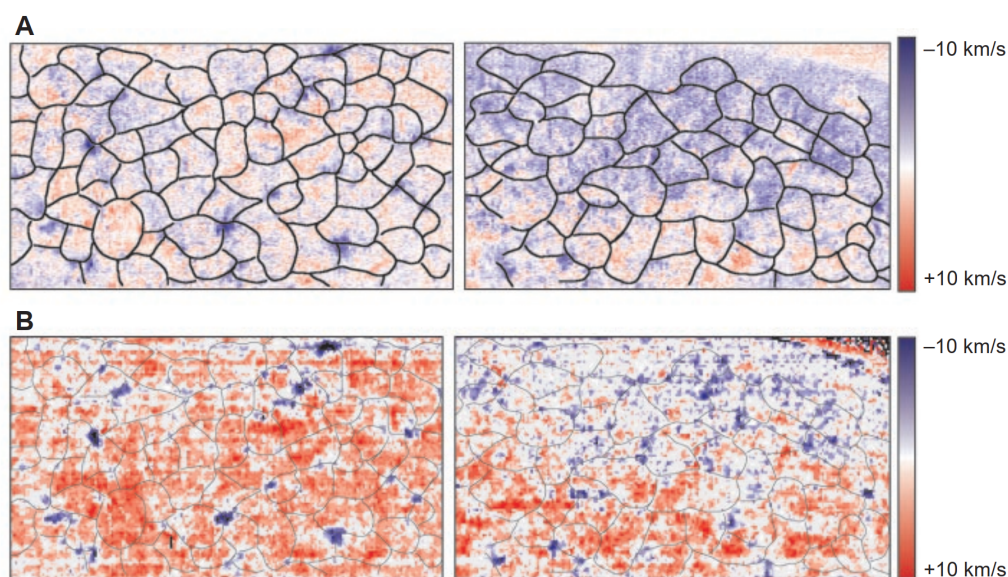


Figure 3. Supergranulation boundaries are overlaid on Doppler velocity maps for mid-latitude (left) and polar (right) regions. The top images (A) were generated using a moments technique applied to unbinned data, with off-limb solar observations serving as the “zero” velocity reference. The bottom images (B) were produced via Gaussian fitting of binned data (to enhance the signal-to-noise ratio) using the “zero velocity” wavelength reference. Blue denotes blueshifts or outflows, while red indicates redshifts or downflows. Each panel has a spatial scale of approximately $540'' \times 300''$, and the Doppler velocity maps illustrate flow patterns on the solar surface [6].

Vertical Flows and Vortex Structures

Gizon et al. [31] using time-distance helioseismology and SOHO/MDI data, they demonstrated that vertical vorticity in supergranular flows is systematically influenced by the Coriolis force, as shown in Figure 4:

- In the northern hemisphere, divergent flows exhibit clockwise vorticity, while convergent flows show counterclockwise vorticity. The pattern reverses in the southern hemisphere.
- $\langle \text{div} \cdot \text{curl} \rangle \propto \sin(\lambda) \cdot \Omega(\lambda) / \Omega_{eq}$, indicating that the dynamical effects of the Coriolis force on turbulent motions can be directly observed through local helioseismology.

These results provide the first quantitative measurement of the Coriolis force’s role in solar convection through helioseismology, offering critical constraints for understanding angular momentum transport in the solar magnetic activity cycle (e.g., meridional circulation, torsional oscillations). Additionally, the vorticity characteristics of supergranulation

are directly related to the sign of the α -effect in dynamo models, supporting the role of convective motions in generating poloidal magnetic fields.

Schmieder et al. [32] investigated horizontal photospheric flows in the filament channel of active region NOAA 11106 using SDO/HMI continuum images, AIA 304 Å EUV data, and H_α observations from the THEMIS telescope. By applying an enhanced coherent structure tracking (CST) algorithm, they analyzed photospheric velocity fields over three hours. The results revealed supergranular structures within the filament channel, with diverging flows consistent with the quiet Sun. This study demonstrated strong coupling between photospheric convection and filament dynamics, offering critical insights into filament formation and destabilization mechanisms.

Greer et al. [33] conducted a detailed analysis of the three-dimensional flow structure of supergranulation in the Sun's near-surface shear layer using helioseismic imaging techniques based on SDO/HMI data. The results revealed that supergranular flows exhibit distinct multi-scale characteristics in the near-surface shear layer, with the horizontal flow fields displaying complex spatial structures closely linked to solar rotation and deep convective processes. Furthermore, the study found that the flow fields of supergranulation also exhibit intricate depth-dependent structures, with vertical flows being stronger near the surface and gradually weakening with depth. At approximately 10 Mm depth, the vertical flows become indistinguishable from the background flows.

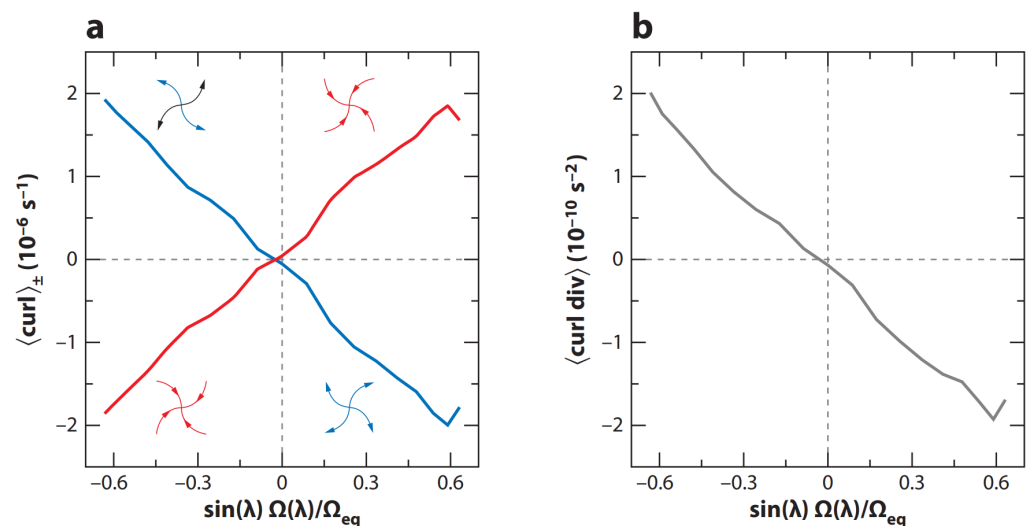


Figure 4. Influence of the Coriolis force on supergranulation flows. (a) Vertical vorticity (curl) averaged across areas with positive horizontal divergence ($\langle \text{curl} \rangle_{+}$, depicted by the blue curve) and negative horizontal divergence ($\langle \text{curl} \rangle_{-}$, shown by the red curve), plotted as functions of $\sin(\lambda)\Omega(\lambda)/\Omega_{eq}$, where λ represents the heliographic latitude and Ω/Ω_{eq} is the local surface angular velocity relative to the equator. A vorticity value of 10^{-6} s^{-1} corresponds to an angular velocity of 2.5° per day or a typical tangential velocity of 10 m s^{-1} . (b) Horizontally averaged $\langle \text{curl div} \rangle$ as a function of $\sin(\lambda)\Omega(\lambda)/\Omega_{eq}$ [31].

Langfellner et al. [34] utilized SDO/HMI Doppler velocity data combined with LCT techniques to analyze the evolution and wave-like properties of average supergranular cells. The results demonstrated that the average lifetime of supergranular cells is approximately 1.6 days, with their horizontal flow fields exhibiting pronounced wave-like behavior. The frequency of these fluctuations was found to be consistent with the solar rotation frequency. Similar to the findings of Greer et al. [33], Langfellner et al. [34] also observed that the vertical flows of supergranulation share the same characteristics, further highlighting the depth-dependent complexity of supergranular dynamics.

2.2. Dynamical and Temporal Evolution of Supergranulation

By analyzing long-term observational data from SOHO, SDO, and other instruments, researchers have extensively studied the scale variations, dynamical properties, and relationship with the solar activity cycle of supergranulation.

Dynamical Properties of Supergranulation

(1) Meunier et al. [35] applied a local correlation tracking algorithm to reconstruct the velocity field of the solar surface from SOHO/MDI intensity maps. They found a power-law relationship between the root-mean-square velocity (V_{rms}) and cell radius (R), expressed as $V_{rms} \propto R^{0.66}$, diverging from classical turbulent models. Larger supergranules exhibited stronger diverging flows, while divergence distributions displayed intermittency at supergranular scales, suggesting a turbulent origin linked to large-scale instabilities triggered by correlated upflows near the solar surface. The study critically addressed discrepancies with prior work (e.g., $V_{max} \propto R^{1/3}$ derived from Doppler data), attributing such differences to methodological limitations in resolving small-scale fluctuations. These findings provided robust observational support for supergranulation as a surface-driven turbulent phenomenon, advancing understanding of its underlying dynamics.

(2) McIntosh et al. [36] utilized long-term observational data from instruments such as the SOHO satellite and the Mount Wilson Solar Observatory, combined with network scale analysis and statistical methods, to study the evolution of supergranular network scales during solar minimum. Results revealed a reduction of approximately 0.5 Mm in the average supergranular radius during the cycle 23/24 minimum compared to the cycle 22/23 minimum, with this scale change exhibiting remarkable synchronicity with the prolonged decline in total solar irradiance. Magnetic analysis indicated reduced separations between flux elements during minima, reflecting the diffusion of magnetic flux at network vertices to smaller scales. Historical data further suggested long-term evolutionary trends in supergranular scale across multiple solar cycles, linked to magnetic field dispersal. This work highlights the regulatory role of magnetohydrodynamic processes in the quiet Sun on radiative output, providing critical observational insights into heliospheric energy transport and Earth's climatic responses during extreme minima (e.g., the Maunder Minimum).

(3) Hathaway et al. [37] investigated the dynamical properties of solar supergranules using SOHO/MDI Doppler observations and numerical simulations. They developed a spectral model with two components—supergranules (peaking at spherical wavenumber ~ 110) and granules (wavenumber ~ 4000)—and generated a 10-day series of simulated Doppler images incorporating advection by axisymmetric flows (differential rotation and meridional circulation). By comparing simulations with observations, they demonstrated that the rotational characteristics of supergranules can be explained solely by advection effects without invoking wave-like behavior. The observed “super-rotation” was attributed to projection effects, while the meridional flow measurements accurately reflected true poleward flows up to $65\text{--}70^\circ$ latitude, with equatorial countercells in polar regions. The simulations successfully reproduced observed spatial spectra, rotation rates, and temporal correlations, supporting the dominance of axisymmetric flows in the surface shear layer. These findings challenge previous wave-based interpretations and advance the understanding of magnetic flux transport on the solar surface.

(4) Getling and Kosovichev [38] analyzed the spatial spectra of subsurface convective flows using helioseismic data from the Solar Dynamics Observatory (SDO, May 2010–September 2020). By applying a spherical harmonic transform to horizontal velocity divergence fields derived via time-distance helioseismology (depths: 0–19 Mm), they revealed a depth-dependent scale transition: supergranular flows (30–60 Mm) dominate shallow layers (0.5–4 Mm), while giant-cell convection (150–300 Mm) emerges at greater depths (>6 Mm), with possible meridionally elongated (“banana-shaped”) structures in

deep layers. Notably, the total convective power anticorrelates with sunspot numbers in shallow layers but correlates positively at deeper layers, suggesting magnetic field-induced energy redistribution. These findings support a multi-scale convective superposition model, contrasting the single-scale assumption of mixing-length theory.

(5) Williams and Pesnell [39] investigated the dynamical properties of supergranulation during the 1996 and 2008 solar minima using Doppler images from SOHO/MDI and SDO/HMI. Through 60-day high-cadence time-series analyses, they identified 3–5 day periodic fluctuations in supergranule size, size range, and horizontal velocity. Cross-correlation revealed a strong positive correlation between size and size range (Pearson coefficient ≈ 0.4 – 0.5) and a moderate negative correlation between size range and velocity (≈ -0.2 – 0.3). Co-temporal MDI-HMI comparisons confirmed the solar origin of these fluctuations, ruling out instrumental artifacts. Data simulations and a stochastic cumulative growth-decay model suggested that such fluctuations likely originate from random processes in the solar convection zone. This work advances understanding of supergranule-driven magnetic field advection and evolution.

(6) Roudier et al. [40] utilized high-resolution continuum data from the SDO/HMI and the CST algorithm to investigate the structure and evolution of solar supergranulation. By tracking the motions of solar granules, they computed horizontal divergence fields and identified and tracked the evolution of supergranular cells. The results demonstrated a mean supergranule lifetime of ~ 1.5 days and an average diameter of ~ 25 Mm. The study also revealed that supergranular motions reflect solar differential rotation and a poleward meridional flow, with these large-scale flows showing no dependence on supergranule size. Additionally, the presence of magnetic fields was found to weaken diverging flows within supergranules. The study confirmed that supergranules serve as effective tracers for probing large-scale convective flows in the solar convection zone, providing critical insights into energy transport and magnetic field distribution on the solar surface. Building on this, Roudier et al. [41] employed LCT on high-resolution multi-wavelength data from the Hinode SOT to investigate Trees of Fragmenting Granules (TFGs). Over a 24-h sequence, they found that TFGs generate coherent horizontal flows (spanning 12 arcseconds, lasting 1–2 h) through successive granule explosions. These flows drive magnetic flux transport from supergranule interiors to boundaries, with diffusion exhibiting super-diffusive behavior (power-law exponent $\gamma = 1.57$). The study highlighted that strong TFGs, via cumulative expansion or displacement, form large-scale flow patterns critical for shaping the magnetic network, offering new insights into photospheric magnetic organization. Most recently, Zheng et al. [42] integrated TiO continuum and Near-Infrared Imaging Spectropolarimeter (NIRIS) data from the GST with long-term observations by SDO/HMI to conduct an in-depth investigation into the supergranulation-scale transport mechanisms of magnetic flux during sunspot decay. Through evolutionary analysis of TFGs, they revealed that TFGs drive outward magnetic diffusion via radial expansion (with velocities reaching up to 3 km s^{-1}), thereby validating their pivotal role within supergranular structures.

Relationship Between Supergranulation Scale and Solar Activity Cycle

As discussed above, numerous scholars have elucidated the dynamical properties of solar supergranulation and found that its characteristic scales are closely related to the solar activity cycle. However, the nature of this relationship remains a topic of significant debate, as illustrated in Table 1. In earlier studies, the primary method employed was autocorrelation, which revealed a positive correlation between the sizes of supergranules and the level of magnetic activity. However, with the exception of the work by Singh & Bappu, who obtained a negative correlation result. Nevertheless, an increasing number of recent studies have revealed a negative correlation between the scale of supergranulation and the level of solar activity. This emerging consensus highlights the complex interplay

between convective dynamics and magnetic activity on the Sun, providing new insights into the multi-scale processes governing solar variability.

Table 1. Variations of supergranule sizes with magnetic field from the literature. The “Method” column indicates the technique used to analyze the data, while the “Variation” column summarizes whether the supergranule size increases (+), decreases (−), or shows no significant variation (0) with the magnetic field.

Reference	Data	Method	Variation
Sýkora (1970) [43]	Ca II K images	autocorrelation	+
Singh & Bappu (1981) [44]	Ca II K images	autocorrelation	−
Wang (1988) [45]	magnetograms	autocorrelation	+
Muenzer et al. (1989) [46]	Ca II K images	2DFT	+
Komm et al. (1995) [47]	magnetograms	autocorrelation	+
Hagenaar et al. (1997) [48]	Ca II K images	segmentation	0
Berrilli et al. (1999) [49]	Ca II K images	segmentation	−
Raju & Singh (2002) [50]	Ca II K images	autocorrelation	−
DeRosa & Toomre (2004) [20]	Doppler	segmentation	−
Huang et al. (2012) [51]	magnetograms	segmentation	−
Mandal et al. (2017) [52]	Ca II K images	autocorrelation	−
Chatterjee et al. (2017) [53]	Ca II K images	autocorrelation	−

2.3. Spatial Distribution and Regional Variations

Observations indicate that the properties of supergranulation exhibit significant variations across different latitudinal regions of the Sun. Sowmya et al. [54] analyzed Ca II K spectroheliogram data from the 23rd solar activity cycle. The study found that the fractal dimension of supergranulation decreases from approximately 1.37 at the equator to about 1 at 20° latitude, suggesting that the increase in solar rotation rate enhances the irregularity of supergranular boundaries. Given the direct relationship between supergranular cell size and fractal dimension, the study concluded that solar rotation influences the outflow intensity of supergranular cells, thereby affecting their size. The latitudinal dependence of the fractal dimension of supergranulation is a result of this influence. These findings are consistent with the results of Huang et al. [51]. Similarly, Raju [55] systematically analyzed the spatial scale asymmetry of the solar supergranular network using Ca II K spectroheliogram data from the Kodaikanal Observatory archives. The results showed that the spatial scales of the supergranular network exhibit nearly symmetric variations between the northern and southern hemispheres, but marked asymmetries are present in certain latitudinal regions. This asymmetry may be related to the interplay between solar rotation, magnetic field distribution, and convective motions. Additionally, the study found that the supergranular network exhibits consistent behavior in the chromosphere and extreme ultraviolet (EUV) bands, indicating that its dynamical characteristics maintain continuity across different layers of the solar atmosphere. The variation in supergranulation size with latitude is illustrated in Figure 5.

Kashyap and Hanasoge [56] investigated the multi-scale properties of solar surface convection using line-of-sight Doppler measurements from SDO/HMI, combined with spherical harmonic transforms and hybrid matrix inversion methods. The study revealed that convective flows at supergranular and smaller scales exhibit significant spatial distribution and temporal evolution characteristics, with the poleward flow showing particularly prominent power at supergranular scales.

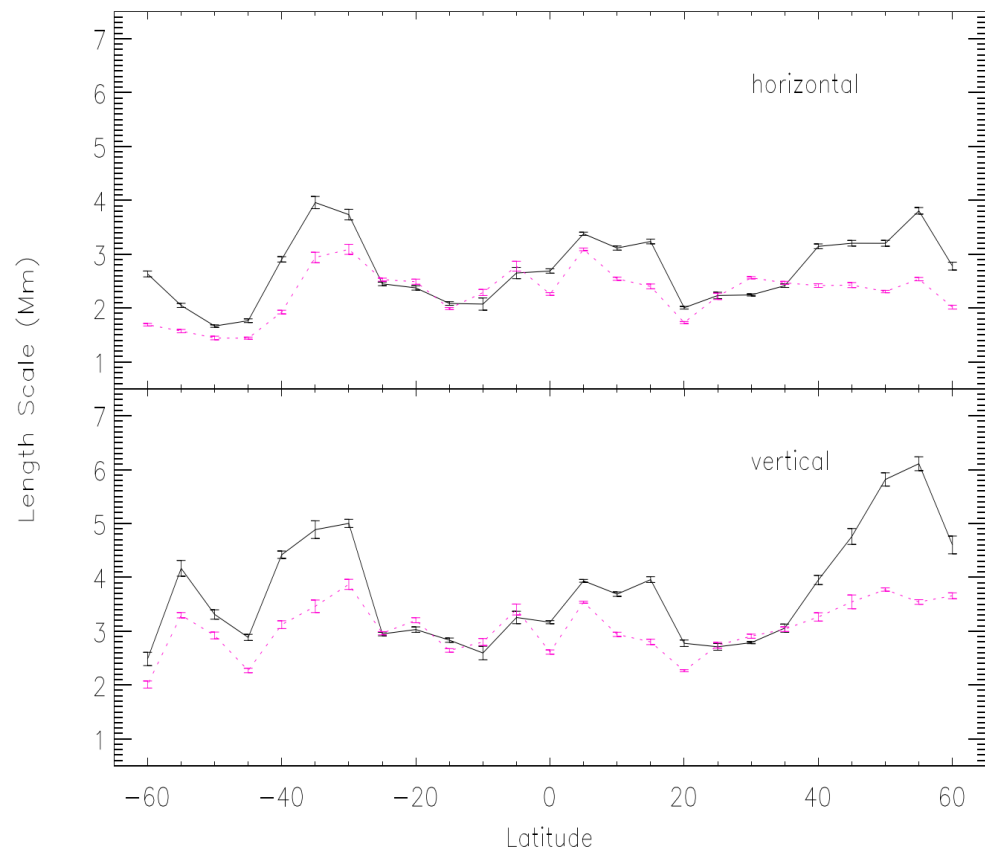


Figure 5. Variation in the horizontal and vertical field scales of supergranulation with latitude [55].

3. Theoretical Models

The formation mechanism and dynamical properties of supergranulation have long been one of the central questions in solar physics. Although observational data have provided crucial insights into understanding supergranulation, its physical nature still requires further elucidation through theoretical models and numerical simulations. In recent years, researchers have proposed various theoretical models to explain the formation and evolution of supergranulation, primarily focusing on convection-driven models and multi-scale coupling models. The following sections review recent advances in the theoretical study of supergranulation from these two perspectives.

3.1. Convection-Driven Models

Supergranulation is widely believed to result from convective instabilities in the upper convection zone. In recent years, researchers have proposed improved models to explain its formation mechanism, primarily including thermal-driven models and shear-driven models.

Thermal-Driven Models

Thermal-driven models suggest that supergranulation may be driven by thermal buoyancy in the convection zone, where thermal gradients in the upper convection zone give rise to large-scale convective cells. Cossette and Rast [57] investigated the dynamical characteristics of supergranulation as the largest buoyancy-driven convective scale using high-resolution numerical simulations and theoretical analysis. The study employed a three-dimensional spherical shell model to simulate convective motions in the convection zone, with a focus on the role of buoyancy-driven convection in supergranulation formation. By comparing simulation results with observational data, the study found that the horizontal scale of supergranulation is approximately 30,000 km, and its dynamical characteristics are consistent with buoyancy-driven convection theory. The results indicate

that supergranulation represents the largest buoyancy-driven convective structure in the convection zone, with its formation closely linked to energy transport by deep convective motions. Additionally, the study revealed significant variations in the flow properties of supergranulation over the solar activity cycle, which suggests that magnetic fields play an important role in its evolution.

Hanson et al. [58] systematically studied convective phenomena at the supergranular scale on the solar surface by combining high-resolution solar observations with three-dimensional MHD numerical simulations. The study revealed the complexity and diversity of these phenomena and explicitly highlighted the limitations of traditional mixing-length theory at this scale. The results demonstrate that the interaction between magnetic fields and convective motions plays a critical role in supergranular-scale convection, while existing theoretical frameworks are insufficient to fully describe the coupled dynamics of these multi-physical processes.

Nordlund and Stein [59], Stein and Nordlund [60] explored the excitation mechanisms of solar p-mode oscillations. They found that solar p-mode oscillations are excited by random, non-adiabatic pressure fluctuations acting on the compression modes. Using numerical simulations, they evaluated the expression for the excitation rate of radial modes and found that excitation primarily occurs near the solar surface, particularly in the intergranular lanes and granule boundaries, where turbulence and radiative cooling are pronounced. They also discussed the generation mechanisms of non-adiabatic pressure fluctuations and the frequency dependence of mode excitation.

Shear-Driven Models

Shear-driven models propose that shear flows generated by solar differential rotation may induce large-scale turbulence in the upper convection zone, which evolves into the cellular structure of supergranulation. Rast [61] proposed a simplified model to simulate convective phenomena at different scales. Using numerical simulations, he investigated how small-scale convective motions (e.g., granulation) on the solar surface interact to form larger-scale structures, such as mesogranulation and supergranulation. The shear flows resulting from differential rotation may induce large-scale turbulence in the upper convection zone, which evolves into the cellular structure of supergranulation. Figure 6 illustrates the results of simulations with varying parameters, specifically the creation rate of new granular plumes (N_n) and the width of the advective flow profile (σ_f). The simulations demonstrate that both the creation rate (N_n) and the advection profile width (σ_f) are critical in determining the spatial and temporal scales of the emergent patterns. Higher creation rates and wider advection profiles lead to larger and more persistent structures. The results suggest that the collective advective interaction of small-scale granular plumes can naturally produce the observed mesogranular and supergranular scales. This supports the hypothesis that these larger-scale patterns are a result of the dynamic interactions of granular flows rather than being driven by separate physical mechanisms.

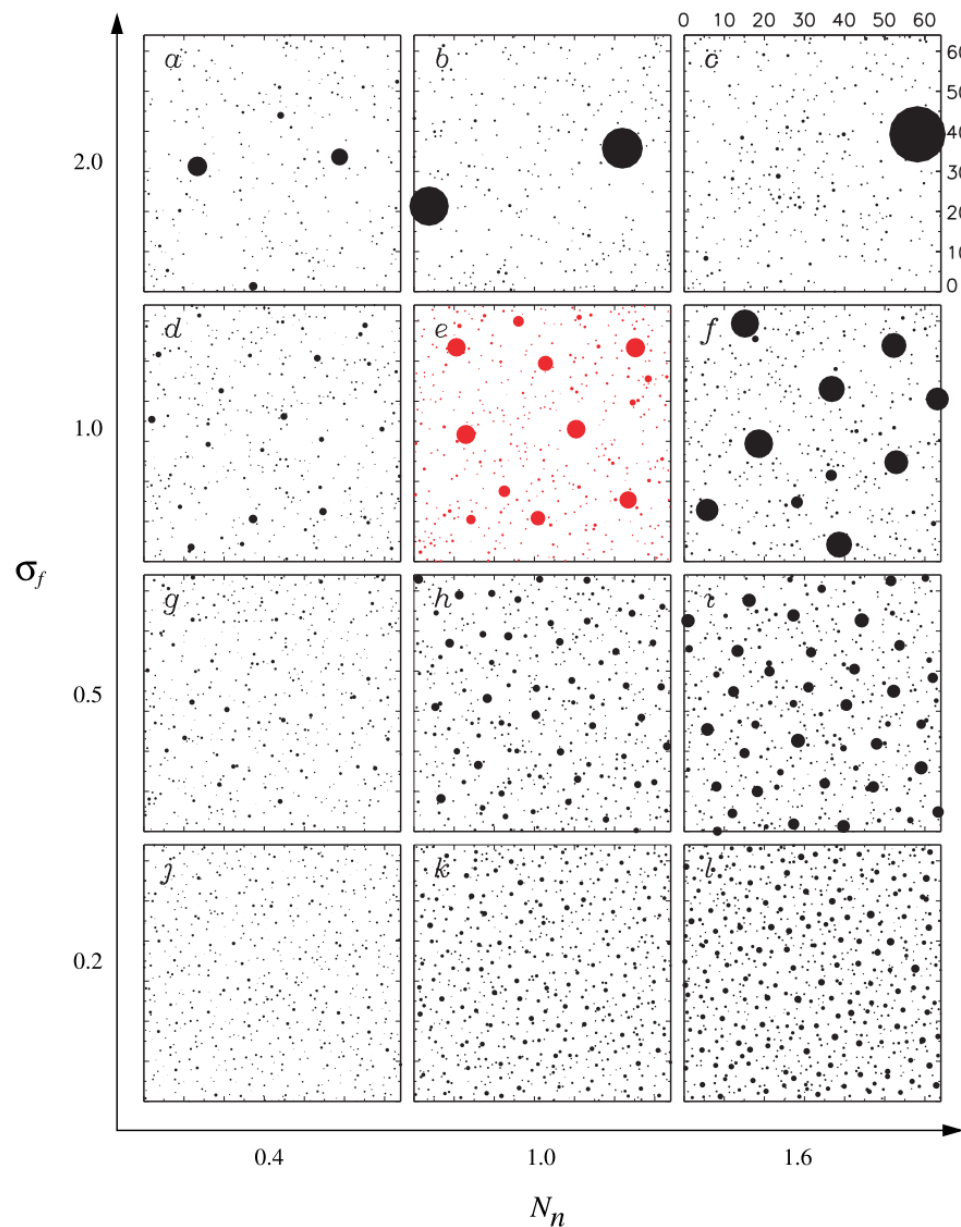


Figure 6. Snapshots of plume positions from n-body advective-interaction models with differing parameter values. The rate of new granular plume creation (N_n) increases from left to right, and the advection profile width (σ_f) increases from bottom to top. In each sub-figure, the x and y axes represent spatial dimensions in units of simulation grid points (pixels) [61].

3.2. Multi-Scale Coupling Models

Recent studies emphasize that supergranulation does not exist in isolation but is coupled with convective patterns at other scales, such as granulation and giant cells. This multi-scale coupling phenomenon provides new perspectives for understanding the formation and evolution of supergranulation.

Rieutord et al. [62] found that strong positive divergences (SPDs) play a key role in the spectrum of horizontal velocity fields, particularly being most active at scales around 4 Mm. Supergranulation may not represent a distinct convective scale but rather result from large-scale instabilities in the flow fields of granulation, with these instabilities manifested through the correlation of flows generated by SPDs. The superposition of granulation may provide the initial perturbations necessary for the formation of supergranulation.

Hathaway et al. [63] discovered evidence of giant convective cells persisting for several months by tracking the motions of supergranulation. These giant convective cells exhibit clockwise flow around high-pressure regions in the northern hemisphere and counterclockwise flow in the southern hemisphere, and transport angular momentum toward the equator and maintaining the rapid equatorial rotation of the Sun. These giant convective cells, referred to as “giant cells”, are expected to span the 200,000 km depth of the convection zone, with diameters of approximately 200,000 km and lifetimes of about one month. They are strongly influenced by the 27-day rotation of the Sun. Figure 7 presents the flow velocity maps of solar supergranules, the maps show the longitudinal and latitudinal flow velocities of supergranules, revealing large-scale and long-lived flow structures. These structures, particularly evident at higher latitudes, exhibit clear east-west and north-south alignments, indicating the presence of giant convection cells on the Sun. The observed flow patterns suggest that these giant cells transport angular momentum toward the equator, maintaining the Sun’s rapid equatorial rotation. The study also analyzed the interaction between supergranulation and giant cells, revealing that the background flow fields of supergranulation may be modulated by giant cells. Research indicates that giant cells not only influence the formation of supergranulation but may also affect its dynamical properties by modulating the background flow fields. For example, the flows of giant cells may enhance magnetic fields at supergranulation boundaries, thereby influence processes such as coronal heating and solar wind acceleration.

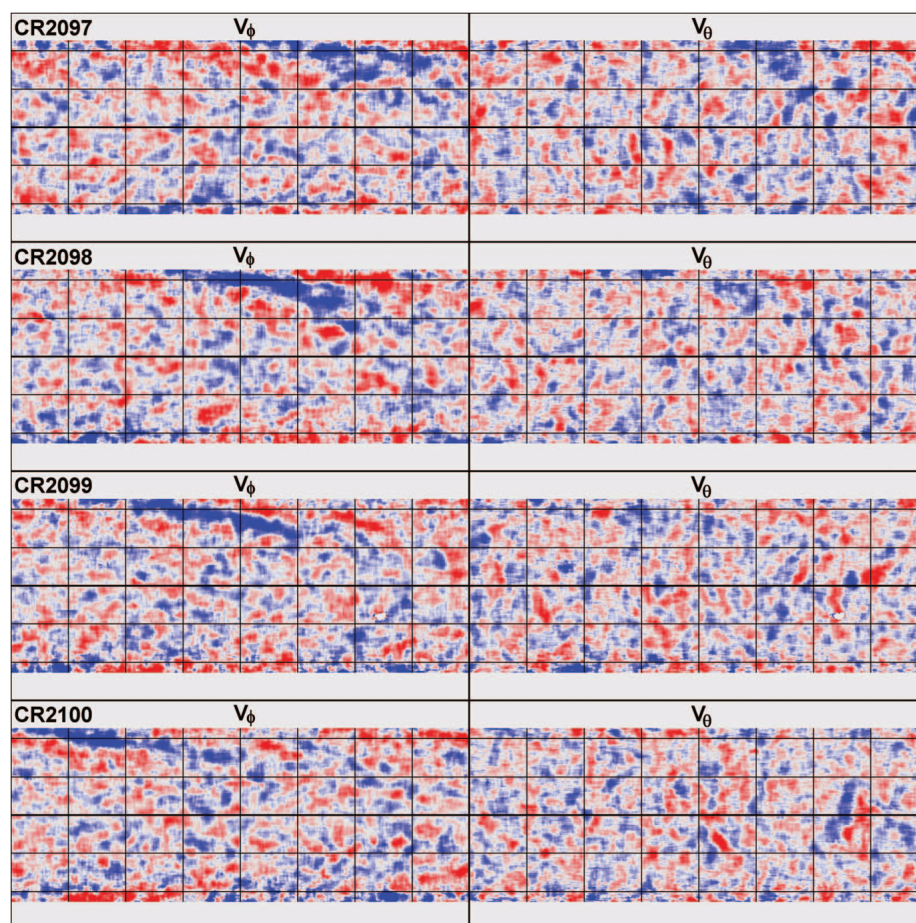


Figure 7. Flow velocity maps of solar supergranules. This sequence of Mercator projection maps illustrates the longitudinal and latitudinal flow velocities of solar supergranules observed from May to August 2010. The maps reveal large-scale flow structures, with prograde and southward velocities shown in red and retrograde and northward velocities in blue. The data indicate the existence of giant convection cells that play a crucial role in maintaining the Sun’s differential rotation [63].

4. Numerical Simulations

Numerical simulations are a crucial tool for studying the formation mechanisms and dynamical properties of solar supergranulation. In recent years, advancements in high-performance computing have enabled researchers to conduct high-resolution MHD simulations of supergranulation at both global and local scales. These simulations have not only revealed the flow and magnetic field structures of supergranulation but also provided important insights into its relationship with physical processes such as the solar activity cycle, coronal heating, and solar wind acceleration. The following sections review recent progress in numerical simulations of supergranulation, and focus on global simulations and local high-resolution simulations.

Global Simulations

Global simulations, which solve the MHD equations in a three-dimensional spherical coordinate system, can reveal the large-scale dynamical properties of supergranulation and its interaction with convective motions in the solar interior.

Miesch et al. [64] investigated the dynamics of giant convective cells in the solar convection zone and their role in sustaining differential rotation through high-resolution three-dimensional global simulations. Utilizing the Anelastic Spherical Harmonic (ASH) code, the study modeled a rotating spherical shell spanning from the base of the convection zone to 15 Mm below the photosphere. Figure 8 presents the flow structures at different depths within the solar convection zone, revealing the radial velocity distributions at the top of the convection zone ($r = 0.98$) and at a deeper layer ($r = 0.92 R$). The convection pattern at the top of the convection zone resembles granulation and supergranulation, featuring an interconnected network of downflow lanes. In contrast, the deeper layer exhibits prominent north-south convective channels that span the entire depth of the convection zone and persist for several months. These convective patterns and structures reflect the characteristics of rotating convection and are closely related to the Coriolis force and the spherical geometry. The simulations revealed that low-latitude giant cells manifest as coherent north-south downflow lanes propagating prograde relative to the mean zonal flow (~ 450 nHz), which transport angular momentum equatorward via Reynolds stresses to maintain differential rotation. At mid-to-high latitudes, isotropic downflows with intense cyclonic vorticity dominate. While near-surface convection is masked by small-scale turbulence (e.g., supergranulation), the deep-rooted giant-cell structures remain potentially detectable via helioseismic probing. This work offers critical insights into the interplay between large-scale flows and rotational shear in the solar interior.

Guerrero et al. [65] used global three-dimensional MHD numerical simulations, combined with analyses of convective kinetic energy spectra and differential rotation, to study the differential rotation properties of Sun-like stars and their relationship with convective zone dynamics. The study found that flows at supergranular and smaller scales substantially contribute to the formation and maintenance of differential rotation, and their dynamical behavior is closely linked to the distribution of magnetic fields and energy transport within the stellar interior. This work provides new theoretical support for understanding the differential rotation mechanisms of Sun-like stars and highlights the important role of supergranulation in multi-scale flows within stellar convection zones.

Brun and his collaborators have systematically revealed the formation mechanism of differential rotation in the solar convective zone and its sensitivity to turbulent parameters through global MHD simulations. A series of numerical experiments have shown that the Rossby number (Ro)—a key dimensionless parameter characterizing the relative strength of nonlinear advection to the Coriolis force—plays a decisive role in the latitudinal distribution of the rotation profile [66]. When $Ro > 1$, models generally exhibit an “anti-solar” rotation profile, where the polar regions rotate faster than the equator [67], which contradicts the

observed prograde equatorial rotation of the Sun. Further studies indicate that increasing the degree of turbulence in simulations (by raising the Reynolds number Re) enhances the amplitude of convective velocities, leading to an increase in Ro and thereby exacerbating the anti-solar rotation trend [68]. This finding highlights the challenge of balancing turbulent driving and rotational constraints in traditional global models when approaching realistic solar parameters, providing important theoretical insights for subsequent research on how to suppress excessive energy transport by large-scale convective structures.

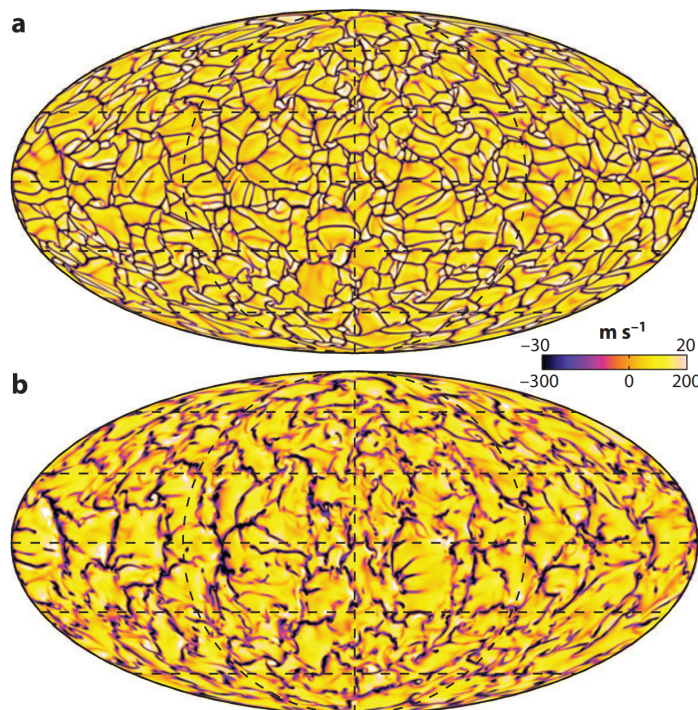


Figure 8. Flow structure in a high-resolution simulation of solar convection. The radial velocity is shown near (a) the top and (b) deeper within the convection zone ($r = 0.98 R$ and $r = 0.92 R$, respectively). Yellow/white tones denote upflow, and blue/black tones denote downflow. Each spherical horizontal surface is shown in a Mollweide projection, with dashed lines indicating latitudes of 0° , $\pm 30^\circ$, and $\pm 60^\circ$, and longitudes of 0° and $\pm 90^\circ$. The color table is linear, and peak velocity amplitudes are indicated by the color bar [64].

Local High-Resolution Simulations

Local high-resolution simulations, which solve high-precision MHD equations within smaller computational domains, can reveal the fine structures and dynamical properties of supergranulation, particularly the magnetic field enhancement and energy release processes at its boundaries.

Ustyugov [69] conducted three-dimensional MHD simulations of local supergranulation on the solar surface using a realistic solar physics model. The study included the equation of state for stellar matter and the diffusion approximation for radiative transfer, employing fully compressible radiative MHD equations combined with dynamic viscosity and gravity. The thermal structure of the solar photosphere, the scale of convective motions, and the penetration depth of convection were analyzed in detail. The results showed that the convective motions of supergranulation exhibit characteristic scale-dependent features in the photosphere, with the size and penetration depth of convective cells consistent with observational data. Additionally, magnetic fields were found to have a significant impact on the thermal structure of convective motions, particularly in terms of heat transport and convective stability in the radiative layer.

Rempel [19] performed MHD simulations covering the uppermost 2–6 Mm of the convection zone, exploring scales ranging from 2 km to 25 Mm, as shown in Figure 9. The study also investigated how the strength and distribution of photospheric and subsurface magnetic fields depend on resolution, domain size, and boundary conditions. The simulation results revealed that downflows at supergranulation boundaries may drive localized energy release through magnetic reconnection, representing a potential mechanism for coronal heating. Furthermore, the local simulations uncovered interactions between supergranulation and smaller-scale vortices, providing new insights into its dynamical behavior.

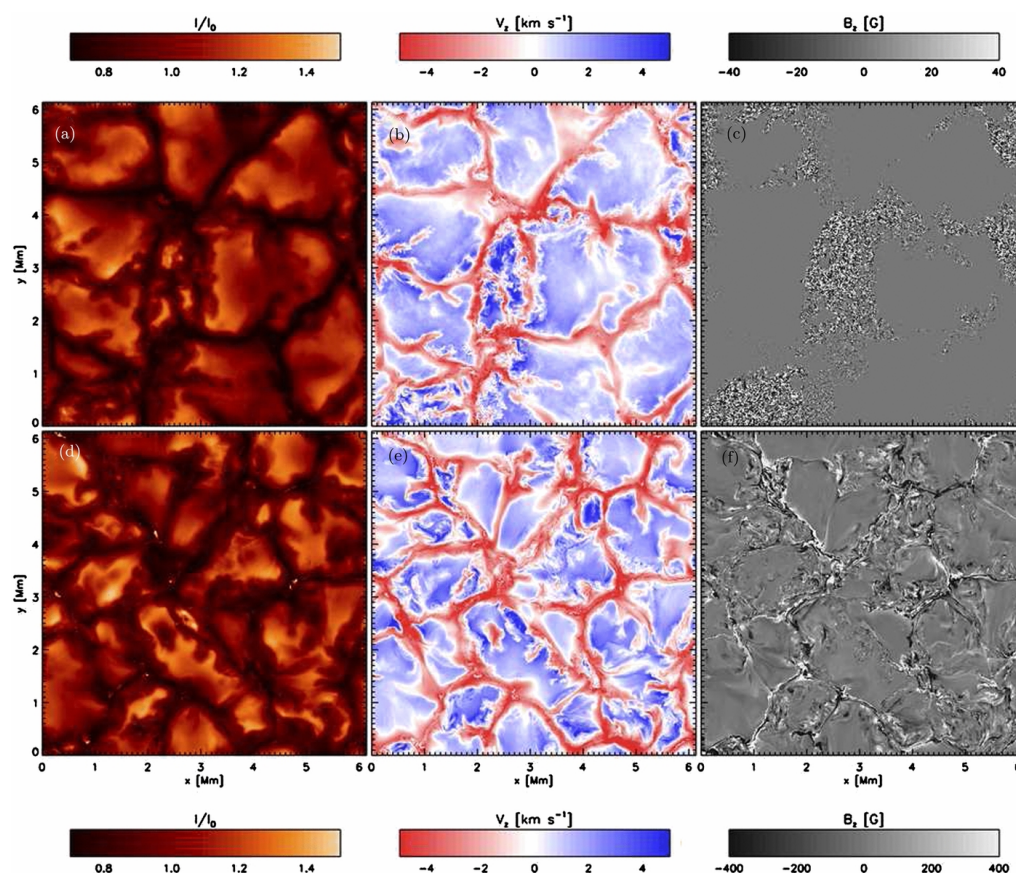


Figure 9. Maps of Intensity and flow fields at the surface of the solar convection zone, derived from local MHD simulations. The figure presents a comparison between the kinematic growth phase (panels (a–c)) and the saturated phase (panels (d–f)) of the simulation run [19].

5. Significance in Solar and Space Physics

Solar supergranulation is not only a crucial component of the solar convection zone but also plays a key role in the evolution of the solar magnetic field, coronal heating, solar wind acceleration, and the modulation of larger-scale convective patterns. The following sections review the significance of supergranulation in solar and space physics from three perspectives: magnetic field evolution, coronal heating and solar wind acceleration, and its influence on larger-scale convective patterns.

5.1. Impact on Magnetic Field Evolution

Supergranulation is a major driver of magnetic flux transport and evolution on the solar surface. Its horizontal flows transport magnetic flux from the interiors of convective cells to their boundaries, and form the supergranular network. This process is key for the global evolution of the solar magnetic field, including polarity reversals and the solar activity cycle [70,71].

Magnetic Flux Transport and Network Formation

Giannattasio et al. [72] used continuous 24-h magnetogram time series data from the Hinode satellite to calculate the average rate of change in magnetic energy density at supergranular scales in the quiet Sun. The results showed that regions with positive magnetic energy density changes coincide with regions where magnetic fields exhibit the longest decorrelation times, and the decorrelation timescales match the timescales of magnetic energy density changes. This indicates that the energy provided by electric fields, magnetic fields, and current densities in the photosphere plays a critical role in maintaining the magnetic fields within the supergranular network.

Magnetic Field Evolution and the Solar Activity Cycle

The horizontal flows of supergranulation not only influence the local distribution of magnetic fields but may also modulate the transport of magnetic flux, thereby affect the evolution of the solar activity cycle. For example, studies have shown that the scale, lifetime, and flow velocity of supergranulation exhibit significant temporal variations during solar minimum, and their dynamical behavior is closely related to the differential rotation and internal magnetic field distribution [39,40].

5.2. Coronal Heating and Solar Wind Acceleration

Downflows and regions of concentrated magnetic fields at supergranulation boundaries are active sites of local magnetic reconnection, which may drive coronal heating and solar wind acceleration. Additionally, turbulence and waves in supergranulation may transfer energy to the corona and heliosphere through the propagation of Alfvén waves [73].

(1) Wang et al. [74] used data from the Atmospheric Imaging Assembly (AIA) [75] and HMI on the SDO to investigate the relationship between supergranular converging flows and the formation of coronal plumes. The results demonstrated that supergranular converging flows play a key role in the formation of coronal plumes, with their horizontal flow fields closely linked to the evolution of coronal magnetic structures. Furthermore, the study found that supergranular converging flows can drive magnetic reconnection, leading to the formation of coronal plumes, highlighting the importance of supergranulation in energy transport and magnetic field evolution in the solar atmosphere.

(2) Cantoresi and Berrilli [76] used high-resolution magnetic field and EUV imaging data from SDO, combined with statistical analyses of magnetic fields at supergranular scales, to study the relationship between magnetic imbalance in supergranulation and the formation of coronal holes. The study found that magnetic imbalance (i.e., asymmetric distribution of positive and negative magnetic flux) at supergranular scales is a key mechanism driving coronal hole formation. This imbalance leads to the opening of local magnetic fields, facilitating the emergence of coronal holes. This work provides new theoretical support for understanding the formation of coronal holes and emphasizes the important role of supergranulation in the evolution of the solar atmospheric magnetic field.

(3) Lee et al. [77] used solar wind observations from the Parker Solar Probe and chromospheric network magnetic field data from SDO, combined with magnetic field extrapolation and plasma simulations, to study the relationship between the chromospheric network and solar wind switchbacks. The study found that small-scale magnetic structures in the chromospheric network and their dynamic evolution may be significant sources of solar wind switchbacks. These structures transfer energy to the corona and solar wind through magnetic reconnection and wave propagation. This work provides new observational and theoretical insights into the origin of solar wind switchbacks and highlights the critical role of the chromospheric network in solar wind acceleration.

(4) Yang et al. [78] used a three-dimensional MHD model to simulate the reconnection process between closed magnetic loops driven by supergranular convection and open magnetic fields in the solar photosphere. The study employed a stratified solar atmospheric model with temperature and density distributions, combined with the velocity fields of supergranular convection, to analyze the impact of magnetic reconnection on plasma injection into the solar wind. The results showed that magnetic reconnection driven by supergranular convection can release plasma from closed magnetic loops into open magnetic fields, forming the initial outflow of the solar wind. This process not only provides a source of material for the solar wind but also reveals the critical role of supergranulation in solar wind formation.

5.3. Influence on Larger-Scale Convective Patterns

Supergranulation may be part of larger-scale convective patterns, such as giant cells, and its flow properties can reflect deep convective processes in the convection zone. Studying supergranulation helps reveal the dynamics of the solar interior [63,79].

Between Giant Cells and Supergranulation

Hathaway et al. [63] discovered evidence of giant convective cells persisting for several months by tracking the motions of supergranulation. These giant convective cells exhibit clockwise flow around high-pressure regions in the northern hemisphere and counterclockwise flow in the southern hemisphere, and transport angular momentum toward the equator and maintain the rapid equatorial rotation of the Sun. These “giant cells” not only influence the formation of supergranulation but may also modulate its dynamical properties by altering the background flow fields.

Multi-Scale Coupling in the Convection Zone

The multi-scale coupling between supergranulation, granulation, and giant cells provides new perspectives for understanding energy transport and dynamical properties in the convection zone. For example, studies have shown that the flow properties of supergranulation exhibit significant variations over the solar activity cycle, which indicate that magnetic fields play an important role in its evolution [40,79].

6. Conclusions

Solar supergranulation, as a large-scale convective structure on the solar surface, is closely related to key physical processes such as solar magnetic field evolution, coronal heating, and solar wind acceleration. In recent years, advancements in high-resolution observational technologies (e.g., SDO, Solar Orbiter, GST, DKIST, NVST) and progress in numerical simulations and theoretical studies have deepened our understanding of the physical mechanisms underlying supergranulation. This review summarizes recent research progress on solar supergranulation from four perspectives: observational advances, theoretical models, numerical simulations, and its significance in solar and space physics. The main conclusions are as follows:

(1) **Observational Advances:** High-resolution imaging and Doppler observations have revealed the flow field structure and magnetic field distribution of supergranulation, particularly the enhanced magnetic fields and downflows at its boundaries. The horizontal flow fields of supergranulation exhibit typical cellular structures, and their dynamical properties are closely linked to the solar activity cycle. Additionally, the spatial distribution and regional variations of supergranulation reflect the influence of solar rotation and magnetic field distribution on its evolution. While high-resolution instruments like DKIST and Solar Orbiter have substantially advanced observational capabilities, discrepancies persist in datasets across different instruments. For instance, variations in supergranule size measurements between Ca II K spectroheliograms (e.g., Kodaikanal Observatory)

and magnetograms (e.g., SDO/HMI) remain unresolved, potentially due to differences in sensitivity to magnetic flux or spatial resolution. Additionally, long-term observational studies (e.g., Sowmya et al. [54], Huang et al. [51]) rely heavily on proxies like network magnetic fields, which may not fully capture the intrinsic dynamics of supergranulation. The reliance on autocorrelation and segmentation methods (Table 1) introduces uncertainties in scale determination, as these techniques are sensitive to noise and temporal/spatial averaging. Furthermore, the latitudinal dependence of supergranular fractal dimensions raises questions about whether solar rotation alone explains the observed asymmetry or if deeper convective processes (e.g., giant cells) play a synergistic role. These limitations highlight the need for standardized cross-instrument calibration and multi-wavelength campaigns to disentangle observational biases.

(2) **Theoretical Models:** Thermal-driven and shear-driven models provide different theoretical explanations for the formation mechanism of supergranulation, while multi-scale coupling models emphasize the interactions between supergranulation, granulation, and giant cells. Studies suggest that the formation and evolution of supergranulation may be driven by multiple physical processes, including thermal buoyancy, shear flows, and magnetic activity. Current theoretical frameworks remain fragmented. Thermal-driven models (e.g., Cossette and Rast [57]) successfully reproduce supergranular scales ($\sim 30,000$ km) but oversimplify magnetic field effects, assuming passive advection rather than active feedback. Shear-driven models (e.g., Rast [61]) link supergranulation to differential rotation but lack robust observational evidence for the predicted turbulence spectra. Multi-scale coupling models (e.g., Rieutord et al. [62], Hathaway et al. [63]) propose intriguing connections to giant cells, yet these lack direct observational verification due to the faint helioseismic signatures of deep convection. A significant gap lies in unifying these models: while thermal buoyancy and shear may coexist, their relative contributions under varying magnetic activity levels remain unquantified. Moreover, the exclusion of small-scale dynamo processes in many simulations (e.g., Rempel [19]) limits their applicability to the magnetically active Sun. Theoretical advancements must prioritize coupled magneto-convective frameworks and validate predictions against multi-scale observational datasets.

(3) **Numerical Simulations:** Global and local high-resolution simulations have uncovered the flow and magnetic field structures of supergranulation, particularly the magnetic field enhancement and energy release processes at its boundaries. Numerical simulations also indicate that interactions between supergranulation and smaller-scale vortices may be important mechanisms for coronal heating and solar wind acceleration. While global simulations (e.g., Miesch and Toomre [18]) capture large-scale dynamics, their coarse resolution ($\sim 10\text{--}50$ Mm) fails to resolve critical boundary-layer phenomena, such as magnetic reconnection at supergranule edges. Local simulations (e.g., Ustyugov [69], Rempel [19]) achieve finer resolution but often idealize boundary conditions, neglecting the interplay with global flows like differential rotation. A recurring issue is the mismatch between simulated and observed lifetimes: many models predict shorter-lived supergranules ($\sim 12\text{--}24$ h) compared to observed 1–2 day lifetimes, suggesting incomplete treatment of subsurface driving mechanisms. Additionally, the assumption of isotropic turbulence in simulations contrasts with observations of anisotropic network magnetic fields [15], implying oversimplified turbulent closure models. Future simulations must bridge scale separations, incorporate realistic radiative transfer, and validate against helioseismic inversions to improve predictive power.

(4) **Significance in Solar and Space Physics:** Supergranulation is not only a major driver of magnetic flux transport and evolution but also contributes to coronal heating and solar wind acceleration through mechanisms such as magnetic reconnection and Alfvén wave propagation. Furthermore, the interaction between supergranulation and larger-scale convective patterns (e.g., giant cells) provides new insights into the dynamics of the solar

interior. The role of supergranulation in coronal heating and solar wind acceleration, while widely hypothesized, lacks definitive observational confirmation. For example, studies linking network magnetic fields to solar wind switchbacks [77] rely on indirect correlations rather than causal evidence. Similarly, the proposed connection between supergranular flows and coronal plumes [74] remains speculative due to limited simultaneous multi-layer observations. The interplay with giant cells, though theoretically compelling, is hindered by the absence of direct helioseismic detection of giant cell flows. Furthermore, the assumed universality of supergranular processes—such as magnetic flux transport—may not hold in active regions, where strong fields dominate convective motions. These gaps underscore the need for coordinated multi-instrument campaigns (e.g., combining DKIST, Solar Orbiter, and Parker Solar Probe) to establish causal links across atmospheric layers.

Despite steady progress in recent years, many mysteries remain regarding the formation mechanism and dynamical nature of supergranulation. Future research should focus on the following areas:

(1) **High-Resolution Observations:** Utilize next-generation telescopes such as GST, NVST, DKIST, AIMS, and Solar Orbiter to obtain detailed structures and evolutionary properties of supergranulation, particularly high spatiotemporal resolution data on magnetic and flow fields at its boundaries.

(2) **Multi-Scale Coupling Studies:** Investigate the interactions between supergranulation and other convective scales (e.g., granulation and giant cells) to reveal its role in multi-scale energy transport within the convection zone.

(3) **Magnetic-Convective Coupling Simulations:** Develop higher-resolution and more sophisticated MHD models to study the role of magnetic fields in the formation and evolution of supergranulation, particularly their relationship with coronal heating and solar wind acceleration.

(4) **Solar Wind Connectivity Studies:** Further explore the connection between supergranulation and solar wind source regions through observations and simulations, particularly its role in solar wind switchbacks and the formation of high-speed solar wind.

In summary, the study of solar supergranulation not only helps reveal the dynamical properties of the solar convection zone but also provides critical insights into key physical processes such as solar magnetic field evolution, coronal heating, and solar wind acceleration. Future research should combine high-resolution observations, theoretical modeling, and numerical simulations to further elucidate the complex dynamical processes of supergranulation and its central role in solar physics.

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