Rotational Effects on Supergranulation- A Survey

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***Abstract*: - Supergranules are large-scale convection cells in the high solar photosphere that are seen at the surface of the Sun as a pattern of horizontal flows. They are approximately 30,000 kilometres in diameter and have a lifespan of about 24 hours. About 5000 of them are seen at any point of time in the upper photospheric region. A great deal of observational data and theoretical understanding is now available in the field of supergranulation. In this paper, we review the literature on the rotational effect of the supergranules and its relation to the solar dynamo model.**

***Key words*: supergranulation, sunspot, helosismology, magnetic field**

I. INTRODUCTION

The Sun, situated at the centre of the solar system, is the closest star to the earth. The light from the Sun heats our planet and makes life possible. The visible solar atmosphere consists of three regions, the photosphere, the chromosphere and the solar corona. Most of the visible light comes from the photosphere. The surface of the Sun, the photosphere, is beset with a cellular pattern caused by the convective flow of heat rising from the solar interior. Convection is the chief mode of transport in the outer layers of all cool stars such as the Sun (Noyes, 1982). The convection zone, which has a thickness 30% of the solar radius, lies in the sub-photospheric layers of the Sun. Convection is revealed on four scales, namely, granulation, with a typical size of 1000 km; mesogranulation, with typical size of 10000 km; supergranulation, with a typical size of 30,000 km; and giant granules, with typical size of 10^8 Mm.

Granulation – About 2 million granules are found at any point of time on the solar surface. They are columns of hot gases rising from below the photosphere with a velocity of about 1-2 km/sec. Each granule persists for about 8 minutes.

Mesogranulation – Mesogranulation originates at a greater depth than granulation. It is attributed to the release of the latent heat of partially ionized He I. Muller et al. (1992) have studied the evolution of solar mesogranules, which seem to survive for at least 3 hours. It is still not known clearly as to whether they represent waves or convection.

Supergranulation – This is believed to be caused by the turbulence that extends deep into the convection zone. These cells have a lifetime of about 24 hours. Broadly speaking, Supergranules are characterized by the three parameters, namely length L, lifetime T and horizontal flow velocity (Paniveni et al. 2004; Paniveni et al. 2011). Supergranules were discovered in the 1950’s by Hart (1954) but were studied in detail in the 1960’s by Leighton et al. (1962), who gave them their name. Leighton et al. (1962) showed that this cellular pattern of horizontal flows covers the solar surface and that the boundaries of the cells coincide with the chromospheric/magnetic network (Raju et al. 1998a; 1998b; Srikanth 1999a; 1999b). Typical supergranules have maximum flow speeds of ~500 m/s. The cell size spectrum has a distinct peak at wavelengths of ~35 Mm, where the supergranule spectrum blends into the granulation spectrum (Hathaway et al. 2000). A fractal structure of the cell sizes was reported by Paniveni et al. (2005).

Giant granulation – The existence of this scale was proposed shortly after supergranules were detected. These cells are expected to span the 200,000 km deep solar convection zone (roughly their horizontal dimension), have life times of ~1 month and observed to be heavily influenced by the solar rotation.

In the context of solar supergranulation, the pattern undergoes rotation that is roughly in tune with the solar plasma. The rotation rate of the supergranule Doppler velocity pattern was first examined by Duvall (1980). He used Doppler velocity observations, which allowed him to determine the rotation rate of the pattern near the solar equator by cross-correlating Doppler velocity maps obtained at different times. He found three interesting characteristics of the rotation rates:

1. The measured rotation rate was some 3% faster than the rotation rate of the surface plasma
2. Faster rotation rates were found for larger time differences between the cross-correlated map pairs
3. The full-widths at half-maximum of the cross-correlation coefficient curves were larger for larger time differences.

He concluded that these results were due to larger cells living longer and extending deeper into a shear layer in which the rotation rate increases inward below the surface. The Doppler features rotate more rapidly than the surface plasma and the larger features rotate more rapidly than the smaller features. It was noted that between $\pm 20^0$ latitude the supergranule rotation rate is 5 nHz (~1%) faster than the plasma. At the equator they found a rotation rate that increases from 460 nHz to 468 nHz. They suggest that there may be wavelike aspects of supergranulation that cause the Doppler pattern to rotate more rapidly than the plasma.

The physical origin of the solar supergranulation remains still debated, and it has recently been suggested that a significant component of the motion is not convective but due to the superposition of travelling waves of unknown origin. But line-of-sight Doppler velocity analysis done (Hathaway et al., 2005) yields similar super-rotation results, but the data do not include any wavelike properties. Also D H Hathaway et al. (2005) found that the Doppler velocity patterns appear to rotate at a rate significantly faster than about 14^0 per day. They also found that the apparent super-rotation is larger for larger cells. The super-rotation is largest at the equator. Beck and Schou (2000) measured the rotation of the Doppler velocity pattern using a Fourier technique and found that the larger cells rotate more rapidly than the smaller cells, but with apparent rotation rates that exceed the peak internal rotation rate. The observations are consistent with the original conclusion by Duvall (1980) that larger cells dominate the longer time lags and that these larger cells are more deeply anchored in a surface shear layer in which the rotation rate increases with depth. Recently, Hathaway (2012) found a one-to-one correspondence between the rotation rate of supergranules with increasing size and the rotation rate in this surface shear layer with increasing depth.

II. METHODS

We indicate here various techniques to study supergranulation. Typical software used for these purposes include IRAF (Image Reduction and Analysis Facility) software package and IDL (Interactive Data Language).

2.1. Dopplergrams

Doppler imaging, the oldest technique which is used to study supergranulation, only provides the line-of-sight component of the velocity field.

2.2. Tracking

This technique is used in three different algorithms. The local correlation tracking (LCT) – used to determine the motion of a feature across an image by maximising the correlation between small sub-images. The coherent structure tracking (CST) – identifies coherent structures in the image by a segmentation process and then measures their displacement. The ball tracking (BT) method follows the displacement of floating balls over the intensity surface of images in a time series. The motion of the floating balls traces the mean motion of granules; this is presumably a more effective computation.

2.3. Local Helioseismology

This method uses the propagation of acoustic or surface gravity waves to determine the velocity of the medium over which they propagate.

III. SOLAR DYNAMO

The solar magnetic field is believed to be generated by a magneto-hydrodynamic process known as the solar dynamo, which may be regarded as an electric generator producing magnetic fields and electric currents and that occurs naturally in the solar interior. It is safe to say that we don’t understand all the details of the solar dynamo, which thus remains a subject of active study.

To understand how the dynamo works, we recollect that the solar convection zone contains swirling plasma, which generates electrical currents, which in turn (by Ampere’s law) produce magnetic fields, which in turn, again, produce electric currents (by Faraday’s law) to close the loop! Further, the plasma flow must be three-dimensional, helical and turbulent in order to sustain the above loop. A key role is played by the differential rotation of the Sun, whereby the plasma at the equator moves faster than that at higher latitudes. This complicated motion of the plasma leads to the magnetic field lines being stretched, twisted and folded in the convection zone.

In particular, the *meridional* magnetic field (extending in the North-South direction) becomes transformed into an *azimuthal* magnetic field (extending in the East-West direction) and vice-versa. The Sun’s magnetic field is sustained as long as this cycle is not interrupted. Solar differential rotation is responsible for the first part of this cycle, which is sometimes called the *omega-effect*. Interaction of rotation and convection is responsible for the second part of this cycle, which is sometimes called the *alpha-effect*.

3.1 Sunspots

Sunspots are photospheric phenomena appearing for a few days or months as dark spots on the surface of the Sun, with size typically ranging from 1500 km to 50,000 km, which vary in a pulsating way during the sunspot’s lifetime. Their darkness is due to their lower temperature (3,000 -- 4,500K) relative to the surrounding plasma (about 6,000K), produced by convection-inhibiting magnetic-field flux concentrations. Owing to this brightness contrast and their large size, sunspots can be seen from the Earth. Zeeman observations show that every sunspot is mostly paired with another having the opposite magnetic polarity. The number of sunspots depends on the phase of 11-year solar cycle. At the time of emergence, sunspots may travel at the speed of the order of 100 m/s relative to the surrounding plasma. Sunspot-like structures have been inferred to exist on stars, and are called “starspots”.

The region surrounding sunspots is magnetically active, featuring secondary magnetic phenomena such as prominences, coronal loops, coronal mass ejections and magnetic reconnections. Sunspots comprise of an umbra, the darkest, central part, where the magnetic field is perpendicular to the solar surface and of the penumbra, the surrounding, less dark region with a more inclined magnetic field.

3.2 Life Cycle

When stress on the magnetic flux tubes in the Sun's convective zone, curled up by differential rotation, reaches a threshold value, they get ruptured and are pushed to the Sun's surface, appearing there as sunspots. Inhibition of convection at the rupture points lowers the convective flow, leading to the darkening.

By the Wilson effect, sunspots are depressions on the solar surface. From one solar cycle to next, in each pair of sunspots, the polarities of the sunspots switch between north/south to south/north. Sunspots mostly are found in groups.

Eventually sunspots decay because magnetic pressure causes the field concentrations to disperse. Helioseismological observations in 2001 based on the Solar and Heliospheric Observatory (SOHO) data, which were used to recreate a 3D image of the internal structure below sunspots; these observations show that a powerful downdraft underneath each sunspot forms a rotating vortex that sustains the concentrated magnetic field.

3.3 Period

During each solar magnetic activity cycle, which lasts approximately eleven years, the highest sunspot activity happens at the solar maximum (phase), and the lowest activity at the solar minimum. The Wolf number is the number of sunspots and groups of sunspots. The magnetic polarity gets switched over the cycle. In each cycle, sunspots appear early on at higher latitudes in both hemispheres, moving towards the equator as the solar maximum is approached. Sunspots from consecutive cycles sometimes co-exist, being distinguishable by the orientation of their respective magnetic field. The cycles have been numbered sequentially since solar observations were systematically begun in the 1750's.

The connection between magnetic fields and sunspots was first made by George Ellery Hale in 1908, who suggested that the full sunspot cycle including polarity reversal is 22 years. A first quantitative model for the dynamics at the surface layer of the Sun was provided by Horace W. Babcock.

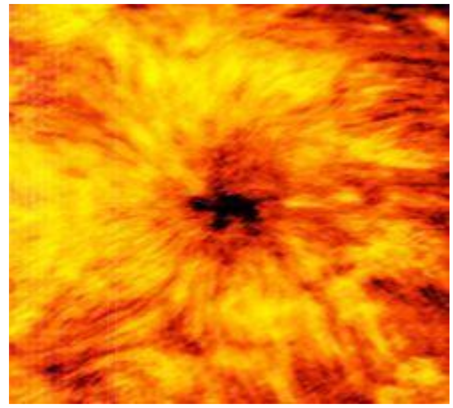
3.4 Solar Cycle

Although sunspot populations oscillate irregularly over the 11-year cycle, they also fluctuate over longer periods. E.g., in the interval 1900-1960, an upward trend in the solar maxima could be detected, diminishing in the subsequent decades.

Since the availability of satellite data in 1979, the correlation between solar radiation and sunspot number has been tracked, and found to be weak-- a variation of is correlated with the solar constant, about 1.3 $W \cdot m^{-2}$ variation of the average solar constant of 1366 $W \cdot m^{-2}$.

3.5 Modern Observation

Sunspots observations are now made with Earth-orbiting and terrestrial solar telescopes employing filtration and projection techniques, including spectrohelioscope, for viewing the Sun, and in particular sunspots, and for recording solar images. Sunspot rotation at the horizon can be captured in image via artificial eclipses that enable viewing of the circumference of the Sun.



Atacama Large Millimeter Array (ALMA), Chile, observes a giant sunspot in the 1.25 mm wavelength (http://www.almaobservatory.org)

As direct viewing of the Sun with naked eyes is harmful, projection or filtering must be employed for amateur observation of sunspots. Very dark filter glass, such as a #14 (very dark) welder's glass is suitable. The solar disk image can be projected by a telescope eyepiece onto a white screen without using any filter. Sunspots can be tracked on this indirectly viewed disk. Special H-alpha narrowband filters or Al-coated glass attenuation filters mounted on the front of the telescope allow for safely viewing the Sun directly.

3.6 Application

Owing to its connection to other forms of solar activity (faculae and the solar chromospheric network), the occurrence of sunspots can indicate space weather, and through that the suitability of the state of Earth's ionosphere for satellite communication and short-wave radio propagation. It has been suggested that even global warming is influenced by solar cycle and the solar activity. Famously, Europe's Little Ice Age (1300--1870) is correlated with the Maunder Minimum of sunspot activity. Sunspots themselves, in terms of the magnitude of their radiant-energy deficit, have only a weak effect on terrestrial climate in a direct sense.

IV. SUPERGRANULATION DEPTH

Supergranular properties mentioned so far are superficial in that they pertain to singular optical depth. However, the vertical extension of a supergranule is expected to yield information about its origin. Here, local helioseismology is crucial. Without it, we would be able only to measure derivatives of vertical variations at surface. Early studies derived information of vertical variation using lines forming at different depths. Using this method, Deubner (1971) inferred that the supergranular vertical flow component slightly increased, whereas the horizontal component slightly decreased, with photospheric depth. However, Worden and Simon (1976) concluded that the vertical component weakened with depth, based on Doppler data.

Combining the above considerations of the continuity equation with Dopplergrams and local correlation tracking November (1994) deduced that supergranular flow would vanish at depths greater than 24 Mm. Similarly, he also suggested the 7 Mm-scale mesogranulation also extended below the visible surface, as part of the supergranular vertical flow component. But Rieutord et al. (2010) conclude on a rather shallow vertical velocity scale height of just 1 Mm using a method based on divergences in velocity fields obtained from the Hinode data.

With the advent of local helioseismology, beginning with the late 1990s, supergranular flow could be studied at levels of greater optically thickness, though (Braun & Lindsey, 2004; Gizon & Birch 2005) not without reservations. With preliminary data from SOHO-MDI, Duvall Jr et al. (1997) were able to detect supergranular flows only to depths of a few Mm. Woodard (2007) reported a flow pattern at a depth of 5 Mm, as also Sekii et al. (2007) using new data from Hinode, while Duvall Jr (1998) estimated that supergranules extended to a depth of 8 Mm. But Zhao and Kosovichev (2003) found converging flows at the depth of 10 Mm and suggested that supergranulation extends to a depth of 15 Mm. Some evidence for return flow at depth greater than 5 Mm has been reported (Duvall Jr, 1998; Zhao and Kosovichev, 2003).

To summarize, the vertical extension of supergranulation still remains to be investigated in detail. Existing study points to a shallow structure, but is beset with uncertainty and poor statistical significance, owing in no small part to the inherent difficulty in implementing the required measurements.

V. ROTATIONAL PROPERTIES OF SUPERGRANULES

Rossby number is a dimensionless quantity that estimates the ratio of inertial to Coriolis forces in fluid dynamics. It is defined Ro = U/Lf , where U, L and f are characteristic velocity, length and frequency in question. The quantity Ro provides a good estimate of Solar global rotational influence on plasma dynamics. This has been verified by Gizon & Duvall Jr (2003), who reported a correlation between horizontal divergence in supergranulation and its vertical vorticity flips sign at the equator, being negative (respectively, positive) in the northern (resp., southern) hemisphere.

Supergranulation is known from dopplergram data to rotate 4% faster than the ambient plasma (Duvall Jr, 1980; Snodgrass & Ulrich, 1990), an effect now referred to as supergranular superrotation. Since then, local helioseismology has been extensively employed to study supergranular rotation. Superrotation was also reported by Duvall Jr & Gizon (2000), who applied the time-distance helioseismology to f-modes. Beck & Schou (2000) find that the superrotation of supergranulation persists at any helioseismologically probed depth. Applying time-distance helioseismology to MDI data, Gizon et al. (2003) derived divergence maps, whose time-series analysis revealed a 6--9 day period wavelike property of supergranulation pattern, which is much longer than the typical 1-day lifetime of an individual supergranule. The power spectrum for this supergranular signal in the vicinity of the equator had excess power in the prograde direction, thereby providing an explanation of the anomalous superrotation rate of the supergranulation. On the other hand, the wave's dispersion relation seems only feebly correlated with latitude (Gizon & Duvall Jr, 2004), which has been confirmed on basis of direct Doppler shift observations (Schou, 2003), which detected wave motions being largely aligned along the direction of pattern's propagation. These findings highlighted a new aspect of supergranulation, namely the influence of rotational and magnetic fields on convection.

Lisle et al. (2004) and Rast et al. (2004) disputed that the above power spectrum corresponds to oscillations. Instead, they argue, it betokens the superposition of mesogranular and supergranular flow components, advected by giant cells. Gizon and Birch (2005), who were able to identify supergranular rotation using helioseismology that the discovery by Lisle et al. (2004) of supergranular alignment along the Sun's rotational axis subject to the influence of giant cells, finds a natural wave-dynamic explanation.

By contrast, Hathaway et al. (2006) pointed out that the superrotation of the supergranular pattern inferred from the Doppler shift is an artefact due to projection effects along the line-of-sight. But here see Meunier et al., (2007c), have compared direct Doppler tracking with correlation tracking derived from divergence maps extracted from intensitygrams (Meunier & Roudier (2007), and admit the existence of such an artefact, while finding evidence for superrotation of the supergranulation pattern obtained from divergence maps, though at a lower rate than those reported by Duvall Jr (1980) and Snodgrass & Ulrich (1990).

VI. SOLAR MAGNETIC FIELDS AND CONVECTION AT MULTIPLE SCALES

The solar magnetic field's dissipation scale at the solar surface being somewhat low, the Sun's magnetic dynamics here is strongly coupled with convection at all observable scales, including the supergranular scale.

The Magnetic Network and Supergranulation

The chromospheric network was discovered in Ca II K line (393.4 nm) by the spectroheliograph method (Deslandres, 1899). By a comparative study of spectroheliograms, Dopplergrams and magnetograms, the strong correspondence between the chromospheric network, supergranulation and the magnetic network was established over half a century later (Simon and Leighton, 1964). Therefore, even though the underlying dynamics for this correlation is not fully understood, supergranulation can therefore be traced via spectroheliograms and magnetograms (Lisle et al., 2000; Del Moro et al., 2007).

The magnetic network consists of typically 1 kilo Gauss field concentrations (Solanki, 1993; de Wijn et al., 2009) along the edges of supergranules (Simon et al., 1988), in the down flow areas. We note that the correspondence between the magnetic network and supergranulation is not exact. For example, a 2% relative difference has been noted in their rotation rate (Snodgrass and Ulrich (1990)). The network distribution is not regular, but rather clumpy, along the supergranular boundaries of supergranulation cells, with individual concentrations about 16 Mm in size (Hagenaar et al., 1997). The chromospheric network appears to trace the supergranular pattern at the Solar surface. Indeed, this network can be explained by passive advection of magnetic elements arising at the supergranule center (Krijger and Roudier, 2003). By tracking magnetic elements, the horizontal flow velocity can be estimated around 350 m/s, in agreement with the value estimated via granule tracking (Lisle et al., 2000).

Good correlation between flows at even scales smaller than mesogranular and intense magnetic elements have been established by observations at the Swedish Solar Telescope (Dominguez Cerdena et al., 2003). Such a correspondence has been corroborated between mesoscale flows and the magnetic network through a combination of photometric Hinode and spectropolarimetric measurements (Roudier et al. 2009), and other studies (de Wijn et al., 2009 and Mueller, 2009).

VII. INTERNETWORK MAGNETIC FIELDS

Since about ten years ago, quiet Sun magnetic fields of mixed polarity have been detected on subgranular scales within supergranules (e.g. Cederna et al., 2003; Trujillo Bueno et al., 2004; Berger et al., 2004; Rouppe van der Voort et al., 2005; Lites et al., 2008). The term “internetwork magnetic fields” refers to these.

Although (believed to be) much weaker than the network magnetic fields, they do exhibit magnetic bright points (e.g. Muller, 1983; Nisenson et al., 2003; de Wijn et al., 2005; Lites et al., 2008) and constantly interact with network fields (Martin, 1988).

Internetwork magnetic fields were first reported by Livingston and Harvey (1971, 1975) and investigated later by others (e.g. Martin, 1988; Keller et al., 1994; Lin, 1995). Using the Swedish Solar Telescope (La Palma), Dominguez-Cerdena et al., (2003), Roudier and Muller (2004) and Rouppe van der Voort et al., (2005) have detected intranetwork fields at granular and subgranular scales. Orozco Suarez et al., (2007) and Lites et al., (2008) find reported magnetic variations in Hinode data even at scales of 100 km or smaller.

The strength, distribution and orientation of internetwork magnetic fields is still under active investigation. Various authors Martin et al. (1988), Keller et al., (1994), Lin (1995), Domínguez-Cerdena et al., (2003), Trujillo Bueno et al., (2004), and Lites et al., (2008) have cited values between 5-500 G for the strength of these fields.

This large spread can be attributed to a number of reasons, the most important being the cancellation effect in Zeeman spectropolarimetry, a widely used tool for investigating solar magnetism (Trujillo Bueno et al., 2004; de Wijn et al., 2009). This effect is due to field sign reversal at scales lower than the instrument resolution, which partially fails to detect small-scale fields. Lites et al., (2008) using Zeeman spectropolarimetry in Hinode observations report 11 G and 60 G fields for longitudinal and transverse fields on average, respectively. Perhaps, deviations from these average values can be attributed to stronger but spatially sparser fields. Hanle spectropolarimetric observations suggests an average magnetic field strength of 130 G (Trujillo Bueno et al. 2004), with magnetic fields being stronger at the intergranular lanes than at the granular center.

The above Zeeman estimates appear to show that internetwork magnetic fields tend to be horizontal, occasionally even connecting granules (Bommier et al., 2007; Orozco Suarez et al., 2007; Lites et al., 2008), but Martinez-Gonzalez et al., (2008), Asensio Ramos (2009) and Bommier et al., (2009) report an isotropic distribution of fields. This latter conclusion is also supported by complementary Hanle and Zeeman diagnostics (Lopez Ariste et al. , 2010). These authors find the internetwork fields to be highly disordered.

VIII. THE QUIET PHOTOSPHERE: MAGNETIC POWER SPECTRAL STUDIES

The magnetic field power spectrum for the quiet solar photosphere, across different length-scales, can be a useful window on the MHD physics. On the basis of wavelet analysis, structure statistics, etc. various researchers have reported a fractal or multifractal structure for solar surface magnetic fields right from the global to the smallest observationally accessible scales (Komm, 1995; Lawrence et al., 1995; Nesme-Ribes et al., 1996; Meunier, 1999; Stenflo and Holzreuter, 2002; Jan en et al., 2003; Stenflo and Holzreuter 2003a,b; Abramenko, 2005).

A caveat here is that current magnetic field studies, obtained either from ground-based or SOHO-MDI magnetograms, only cover the line-of-sight component and the size range of 1-100 Mm and to the line-of-sight component of the magnetic field. The Hinode mission can help reach magnetic fields below 1 Mm.

IX. ACTIVE REGION SUPERGRANULATION AND FLOWS

The interaction of supergranular flow within fields in active regions and sunspot neighborhood can shed light on how supergranulation evolves during the formation and decay of region of high magnetic activity. Moreover, flow pattern around sunspots can explain the interaction of supergranular flow and magnetic fields in the quiet photosphere.

A relevant observation here, derived from the solar convective kinetic energy power spectrum, is that supergranular flow becomes weak when two granule-size magnetic pores emerge, suggesting an inhibitory effect of fields on the flow (Rieutord et al. 2010). A familiar observation here, recently confirmed by Hindman et al. (2009), shows that supergranulation becomes relatively disorganised and even washed away in active regions.

Intrinsic flows and dynamics in sunspot regions have been studied (see reviews by Solanki (2003) and Thomas and Weiss (2008), in particular with help of local helioseismology (Lindsey et al., 1996; Gizon et al., 2000; Zhao et al., 2001; Haber et al., 2001; Braun and Lindsey, 2003; Haber et al., 2004; Zhao et al., 2004, 2009; Hindman et al., 2009). It appears that there is an annular outflow at the surface in the sunspot vicinity (Hindman et al., 2009), named the moat flow (Sheeley, 1969), with a corresponding return flow at a depth no greater than 2 Mm, suggesting that the moat circulation is relatively shallow. On the other hand, helioseismic inversions suggest that further off the sunspot umbra, larger-scale circulations with a surface inflow and a subsurface (over 10 Mm) outflow.

The moat flow structure has been studied in Dopplergrams (Sheeley and Bhatnagar, 1971; Sheeley, 1972), by tracking granules or other surface structures (Muller and Mena, 1987; Shine et al., 1987), by tracking sufficiently small magnetic elements (Sheeley, 1972; Harvey and Harvey, 1973; Hagenaar & Shine, 2005), or using helioseismology (Gizon et al., 2000). It emerges from these investigations that the moat outflow is akin to supergranulation (Brickhouse and Labonte, 1988), though having greater velocity-- about 1 km/s. The helioseismology of sunspot regions suggests that magnetoconvection in regions of strong flux can impact supergranulation by generating various inflow and outflow structures at different horizontal and vertical scales. The exact implications of this for supergranulation in the quiet Sun's magnetic network, merits further study.

X. SOLAR CYCLE VARIATION OF SUPERGRANULATION

Given the interaction between supergranulation and the solar magnetic network, the question of how supergranular size is influenced by solar activity is an interesting one. Singh and Bappu (1981) report a decrease of the chromospheric network cell size at the maxima with respect to the cycle minima of the cycle based on a study of spectroheliograms spanning consecutive seven solar maxima. This is in line with the conclusions of Kariyappa and Sivaraman (1994), Berrilli et al. (1999) and Raju and Singh (2002), but at variance with those of Wang (1988) and Muenzer et al. (1989), who find increased network cell size in regions of increased magnetic activity, as well as with those of Meunier (2003), who used MDI magnetograms pertaining the first half of solar cycle 23 to study magnetic elements of supergranulation-like size. These contradictions highlight the care, especially with respect to threshold, needed to be exercised in employing magnetic tracers.

Proxies not based on magnetic tracers have been used to measure of supergranulation size, positive divergence in velocity field, etc. De Rosa & Toomre (2004) and Meunier et al. (2008) have reported smaller supergranular sizes in periods of high magnetic activity than in those of lower activity. Meunier et al. (2007a) report a similar anti-correlation with regard to intra-supergranular fields, but in contrast, also find that larger supergranular cells correspond to stronger magnetic network fields. The above authors also report that large supergranular cells are absent in regions of strong internetwork fields, which suggests a dynamic influence of internetwork magnetic fields on supergranules. Thus, care must be taken to disambiguate the role of intra-cell, network and internetwork magnetic fields in their relation to supergranulation.

In respect to helioseismological studies, the solar cycle phase appears to be only weakly correlated (Gizon & Duvall Jr, 2004) with the dispersion in the supergranular oscillations (Gizon et al. (2003). But, Gizon & Duvall Jr. (2004) detected a correlation between supergranular power anisotropy and lifetime with solar cycle phase.

XI. CONCLUSIONS

The space-borne SOHO-MDI solar instrument has renewed interest in supergranulation. whose salient observational features such as lifetime, size, size distribution (Rajni et al. 2017) and flow strength are reasonably well known. On the other hand, further study is required to fully determine the strength of the vertical flow at the cell boundary, the height dependence of supergranular flow and the relation between solar magnetism and supergranulation (see Paniveni et al. (2010)). Local helioseismological analysis of observations at high-resolution can shed light on the second of these issues. .

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