

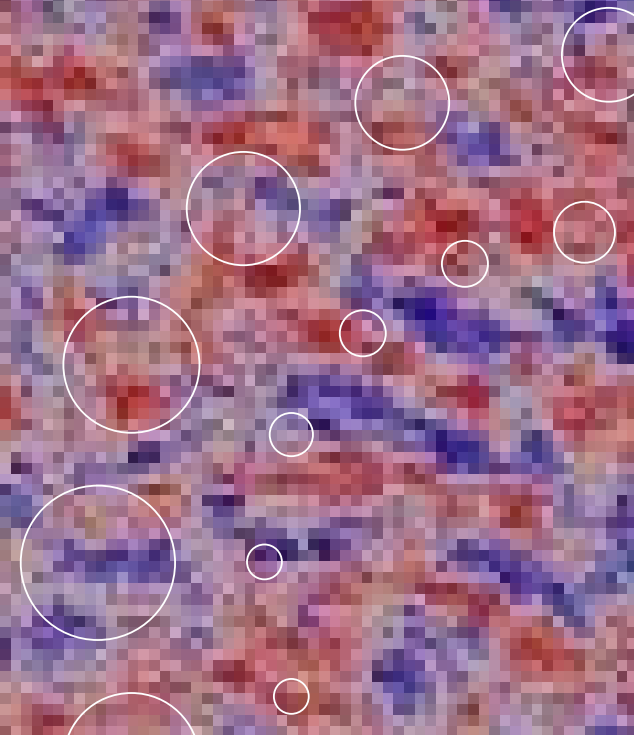
Sara F Martin

# The Sun's Magnetic Activity May Be More 'Superficial' Than We Thought

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PHYSICAL SCIENCES & MATHEMATICS



Scientists have long debated where solar cycle magnetic fields come from—deep within its interior or closer to its surface. Compelling new evidence suggests these fields may originate much closer to the Sun’s visible surface than previously thought, with important implications for understanding our star’s complex magnetic behaviour. The Sun’s activity also holds important implications for exoplanets currently being discovered around many solar-like stars.

## The Dance of Solar Magnetism

Every 11 years, the Sun performs a remarkable magnetic ‘dance’. Its north and south magnetic poles completely reverse, sunspots wax and wane across its surface, and it stores magnetic energy in localised regions until they explode into massive eruptive events that affect life on Earth. This intricate ballet of magnetic activity has fascinated scientists for over a century, but fundamental questions about how it works have remained difficult to answer.

For decades, prevailing theories have held that the Sun’s magnetic fields originated deep within its interior, either in a region called the convection zone or at the base of the convection zone. This vast convection zone extends from the surface, called the photosphere, to nearly 266,000 km deep. This zone is filled with superheated plasma, which constantly churns and flows, somewhat like boiling water. Most solar physicists have accepted the idea that these deep movements generate and amplify magnetic fields through a dynamo process; another example of an astrophysical dynamo process is the generation of the Earth’s magnetic field in its liquid outer core. Sara F. Martin from Helio Research in California has assembled compelling observational evidence that challenges this deep-origin model in a review paper of research.

Her conclusion, drawing on decades of solar observations and new analytical techniques, suggests that the strong, localised solar magnetic fields of the solar cycle may form much closer to the Sun’s surface—within 20,000 km below the visible photospheric surface, rather than down to 266,000 km, the deep base of the turbulent convection zone. This compelling evidence could revolutionise our understanding of solar activity and help improve predictions of space weather that affects Earth.

## Extending Time: The Previously Hidden Parts of the Solar Cycle

The story begins in the 1970s, when new observations from the McMath-Pierce Telescope at Kitt Peak National Observatory in Arizona revealed something unexpected. Using improved magnetic field measurements, researchers discovered that each solar cycle begins several years earlier and continues several years later than previously thought. Numerous, small, short-lived magnetic regions without sunspots

appear at high solar latitudes long before the larger, and longer-lived ones with sunspots form at low latitudes. These findings extended the known duration of solar cycles beyond their traditional 11-years.

Martin explains that the ‘extended solar cycle’ shows solar activity has a more complex pattern than once believed. Small active regions appear up to 4–5 years before the start of the sunspot phase and end 2–3 years after the sunspot phase. This means that solar cycles overlap more than 50% of the time. This raised the possibility: perhaps all magnetic activity—from the smallest ephemeral regions to the largest active regions with sunspots—share a common origin. To explore this, researchers needed to study more closely how these magnetic regions form and evolve.

## The Building Blocks of Solar Active Regions

One of Martin’s key contributions has been identifying and characterising ‘elementary bipoles’ (EBips)—tiny pairs of opposite-polarity, magnetic flux that appear to be the fundamental building blocks of magnetic active regions. These EBips emerge rapidly in single pairs, not in clusters, and their poles separate quickly until they interact with pre-existing magnetic fields. Typically, the separation distance is less than the average radius of a solar convection cell (about 15,000 km), much smaller than the Sun’s full radius of 696,000 km.

This pattern of emergence contradicts the widely accepted theory that active region fields rise as loops from deep, global-scale magnetic flux ropes. Such conceived flux ropes are twisted rings of magnetic flux, which encircle the Sun within or at the base of the convection zone, and are roughly parallel with lines of constant latitude. If such ropes were involved, we would expect EBips to appear simultaneously in tightly grouped clusters, one for each polarity, gradually expanding as the flux rope surfaced. Initially, EBips do appear as rising magnetic loops. However, observations show EBips surfacing one pair at a time in a continuous stream, not in clusters, only grouping after interacting with other magnetic fields. Sample measurements of EBip motions are shown in the lower panel of Figure 1 by two groups of lines, each within an orange circle.

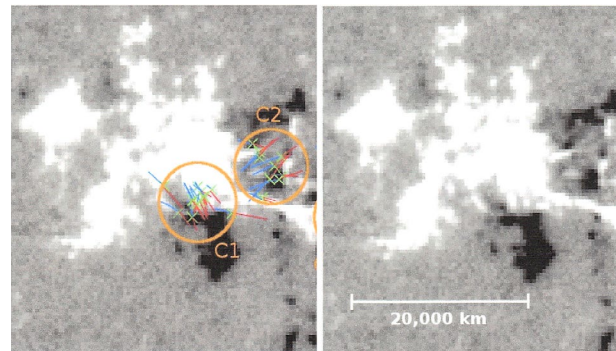
This behaviour suggests a different origin mechanism from the deep-seated, flux-rope model. A shallow origin was first proposed by Horace W. Babcock in 1947, who imagined loops appearing from large flux ropes close to the surface. Now, with high-resolution data showing EBips, it appears that the deep convection zone is too turbulent for such large flux ropes to survive intact.

## Sunspot Formation

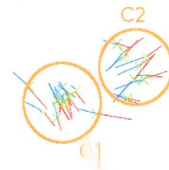
Similar polarity EBips lose their identity when they merge with existing magnetic fields of the same polarity. When about 8–12 EBips are packed closely together, they can form a small sunspot with the same polarity. Sometimes, only one magnetic pole of the coalesced EBips becomes a sunspot, while the other remains too diffuse. In such cases, although EBips still merge, their individual structure becomes indistinguishable due to current resolution limits, resulting in a dense magnetic field without visible sunspots.

These merged EBips, with or without sunspots, form what are known as 'simple bipolar active regions.' Often, one or more simple bipolar regions appear within an existing one. This results in 'active region complexes'. The more complex the region, the more likely it is to produce eruptions that eject large amounts of mass into space, creating what is now called 'space weather'.

Since EBips are similar in size and magnetic strength, the size of an active region depends on how many EBips emerge. Larger active regions likely form slightly deeper, but there's no solid evidence that even the biggest originate as deep as one-third the depth of the base of the convection zone, 266,000 km below the surface.



red lines = - pole  
blue lines = + pole



green x = site of origin

^ **Fig 1:** Trails of new elementary bipoles are represented by the lines with red and blue halves within the ovals. The initial site of each tiny bipole is at a green x between the positive pole (red half) and negative pole (blue half). The length of the red and blue halves respectively represent the motion of the positive and negative poles away from each other, until each pole either merged with magnetic flux of the same polarity or slowly cancelled (disappeared) with magnetic flux of opposite polarity. All active regions grow in the same way from elementary bipoles, the building blocks of active regions.

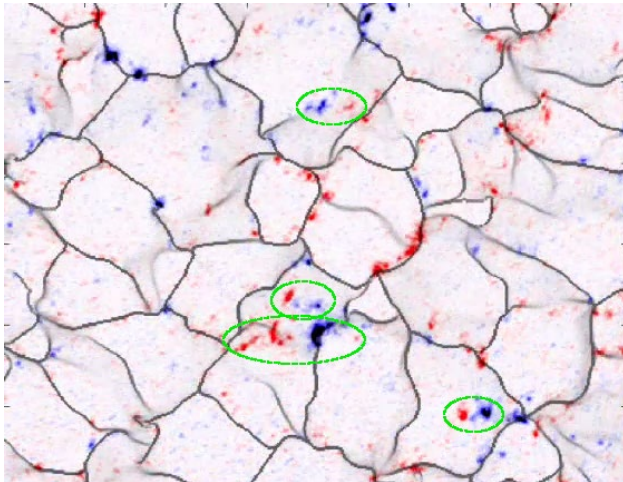
**Credit:** This illustration was created at Helio Research using magnetograms from the Helio Doppler and Magnetic Imager (HDMI) on board the Solar Dynamics Observatory in space.

## The Supergranule Connection

Martin's colleague, Karen L. Harvey, made a key observation: small, ephemeral active regions appear randomly regarding supergranule convection cells. These cells have strong flows that push decaying active regions to the boundaries of the cells. A random relation of small, new active region sites relative to convection cells is consistent with a shallow depth of origin.

Supergranules, about 30,000 km across and lasting 1–2 days, cover the Sun's surface and interact with magnetic fields of all active regions during both emergence and decay. The magnetic fields of active regions are detected using different filters and techniques than those which reveal supergranules beneath them. Shown in Figure 2 is a single frame from a movie made by Dr Hugh E. Potts in 2007 when he was affiliated with the University of Glasgow, where he superposed a movie of magnetic flux over a movie of the plasma motions. The black lines artificially show the boundaries of the supergranules. Within each cell, the magnetic plasma faintly appears at a point in the centres of every cell and pushes the magnetic fields towards the cell boundaries. This motion includes the four small new active regions shown inside green ovals. If the small active regions came from large depths, they would be expected to originate at locations of upflows in the centre of convection cells or possibly at the boundaries. But Karen L. Harvey found that small active regions appear with no consistent relation to the supergranular convection pattern.

Martin concluded, consistent with other researchers, that these small active regions must originate less than 5,000 km below the surface—as shallow as the chromosphere, which is proportionally like a medium-thick orange peel compared with the entire Sun.



^ **Fig 2:** The boundaries of supergranules are shown by black lines, here illustrated for one moment in time from a time-lapse movie created in 2007 by Dr Hugh Potts, while at the University of Glasgow. Within each oval is a new, small, growing active region. The initial positions of the active regions are random with respect to the supergranules, as found by Dr Karen L Harvey.

**Credit:** The original plasma and magnetic flux data in the movie are from the Michelson Doppler Imager (MDI) on board the SOHO satellite formerly in space, which preceded the Helio Magnetic Imager (HMI) that now records images of magnetic flux on board the SDO satellite.

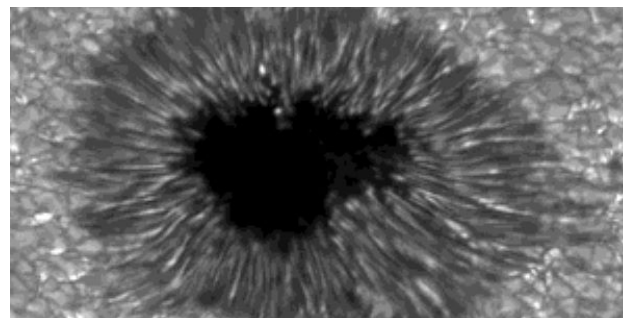
### Sunspots Growing Downward, Not Rising Up

Some of the strongest evidence for shallow magnetic field formation comes from how sunspots develop. The traditional theory suggests that sunspots formed deep within the Sun and rose to the surface like bubbles in a lava lamp. But Martin's analysis suggests the opposite: sunspots grow downward from the surface, forming through the coalescence of tiny EBips that first appear at the photosphere.

Visible downflows of plasma from the chromosphere and corona into the centres of forming sunspots are consistent with magnetic structures building downward from the photosphere rather than rising from below. The downflowing pattern of motions builds sunspots into

the shape of a toroid—like the inner tube of a tire floating on water—which then become trapped at sites of downflows at the vertices of convection cells. Dynamically, the sunspot fine-structure is more akin to the toroidal-like motions in a downward moving smoke ring. In nature, examples of toroids have two defining patterns: one is radially inward and downward from all directions into a central area, and the other is upward and radially outward from a central area. Notably, sunspots only develop the first pattern. These can remain stable for many hours to days before disintegrating.

Sunspots consistently reveal horizontal flows across the middle of the penumbra. These become downflows along the inner penumbral boundary, around the black central umbra. Examples of the opposite toroidal flow pattern with upward flows in the centre are solar convection cells illustrated in Figure 2, and in a smoke ring recently observed during a Mt. Etna volcanic eruption. Those with downward flows at their centres have a downward force as a whole. The consistent downward flows, seen in the penumbral fibrils, surround the black umbra at the centre of the sunspot. An example is seen in Figure 3.



^ **Fig 3:** An example of a high-resolution image of a Sunspot recorded on 20 September 1999. A radial pattern of penumbral fibrils encircles the central dark area known as the umbra. The image is a single frame from a time-lapse movie which shows the typical inward flows along the penumbral fibrils, which curve downward into the black umbra at the centre of the sunspot. Outward flows are seen but only near the outer one fifth of the periphery of the fibril pattern

**Credit:** The movie is available on the website of the Dutch Open Telescope.

### New Tools and Excellent Data Reveal Novel Insights

Modern helioseismology offers strong support for the shallow-origin theory. This technique lets scientists 'see' beneath the Sun's surface by analysing how sound waves travel through its interior, similar to how earthquakes reveal Earth's inner structure. While some studies suggest magnetic structures may exist at depths of 42,000 to 75,000 km, there is no observational evidence of magnetic flux concentrations forming deeper. This suggestion of the lack of deeper concentrations of magnetic structures is especially notable given the high sensitivity of current helioseismic techniques.

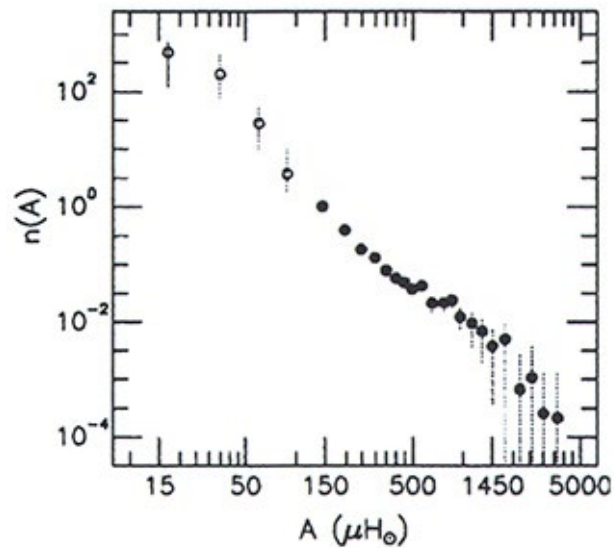
Rachel Howe and colleagues have detected small variations in the surface rotation rate of the Sun, known as torsional oscillations. The torsional oscillations follow the drift rate of the bands of active regions from high latitudes to the equator in both solar hemispheres. Surprisingly, the tiny torsional oscillations could be followed from the photospheric surface downward, to a depth of at least 60,000 km.

### A 'Principle of Active Region Formation for All Solar Cycles'

Another reason to suspect that active regions are shallow comes from their size and number distributions across solar cycles: the smaller the region, the more numerous they are. It applies to both low and high solar cycles. Karen L Harvey found that small regions without sunspots outnumber sunspot regions by a factor of ten or more, as illustrated in Figure 4 with data points copied from her original diagram. The points in bold type represent the active regions with sunspots.

Rather than thinking small active regions follow the trends of large active regions, Martin argues the reverse—large active regions mimic the patterns of small active regions. Since the solar astronomer Horace W Babcock, we have known that more small regions than large ones are present during all phases of solar cycles; but appreciation of their large numbers required new magnetograms with higher spatial resolution. Also, the dramatic space weather from the largest and most complex active regions tended to overshadow the subtle (but highly significant) trends of the more numerous, small, active regions.

Martin suggests that the number and distribution of small active regions may better predict the time of maximum in sunspot number and magnetic flux. A shift toward systematically recording and studying these small regions could prove more effective than relying on current methods focused only on the large active regions with sunspots.



^ Fig 4. The number of active regions is shown on the vertical axis versus the area of the same active regions on the horizontal axis. The nearly straight line of the data points shows that the number of active regions is highly correlated with their area. In other words, the smaller the active regions, the greater their population. This correlation is strong evidence that all active regions—large ones with sunspots and smaller ones without sunspots—belong to the same population. Therefore, only a single interpretation is needed for their origin. Because small active regions are known to originate from a shallow depth below the photospheric surface of the Sun, this graph is evidence that the larger active regions also form relatively close to the surface. The larger active regions could extend to larger depths consistent with their magnetic flux and lifetimes.

### A New Concept for Active Region Magnetism

Drawing on various lines of evidence from her research, and that of colleagues in her field, Martin has built a compelling case for a new concept of solar magnetic field generation. Instead of forming deep within the Sun and rising up, the magnetic fields appear to form in a relatively shallow layer just beneath the photosphere. The shallow-origin model helps explain features that the deep-origin theory struggles with, such as:

- sunspot flow patterns,
- the random appearance of small active regions relative to supergranule convection cells,
- the consistent size of elementary bipoles, and
- the systematic trend for smaller active regions to outnumber large ones.

A key part of this revised view is the role of downflows—regions where material moves from the solar atmosphere back into the Sun. Martin suggests these downflows, from gentle sinking at supergranule boundaries to dramatic plunges during solar flares, such as shown in Figure 5, may play a vital role in concentrating magnetic fields near the surface and enabling their formation in shallow layers.

### Future Insights into Solar Magnetic Fields

Although the evidence for shallow origins is compelling, many questions remain. Ms Martin and other researchers are particularly interested in understanding exactly how elementary bipoles are generated, and why small active regions are so numerous. Future high-resolution observations and improved helioseismic techniques may help resolve these questions. Martin hopes that a better understanding of these processes could enhance our ability to predict solar activity, which is crucial for protecting our increasingly technology-dependent society from the effects of space weather. This research challenges our understanding of how the Sun works, demonstrating how careful observation and analysis can overturn long-held scientific assumptions. As we continue to study our nearest star, we may find that many of its mysteries have solutions closer to the surface than we ever imagined.



^ Fig 5. The beginning of a solar flare is the brightest area at the base of the more extensive, associated erupting filament. As often happens, the erupting filament began before the flare. Combined with this solar image is a separate picture of the Earth, whose true diameter is approximately 1/100 of the diameter of the Sun.



## MEET THE RESEARCHER

**Sara F Martin**

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Sara F Martin has made significant contributions to solar astronomy throughout her extensive career spanning over five decades. After completing her BSc in Physics from Michigan Technological University in 1981, she established herself as a leading researcher in solar physics while employed successively at the Lockheed Solar Observatory Research Group, the San Fernando Solar Observatory of California State University at Northridge, and the Big Bear Solar Observatory of Caltech (before its transfer to New Jersey Institute of Technology). She co-founded Helio Research in 1995 and is known for her work on solar filaments, magnetic fields, and the solar cycle.

Martin has pioneered several breakthrough discoveries, including the ubiquity of cancelling magnetic fields on the quiet and active Sun, the chirality of filaments, elementary bipoles—fundamental to all solar active regions, the relationships between the magnetic field patterns of filaments, flares, and coronal mass ejections, as well as the role of photospheric magnetic reconnection in filament formation. Her innovative contributions include developing a multi-slit spectrograph and establishing fundamental concepts about eruptive solar events. From observations only, she developed a competitive theory of the magnetic structure of filaments. Her observational expertise inspired her husband, the former Douglas C Martin, to build the Martin Solar Telescope at Helio Research. She used this telescope extensively in continued studies of the dynamics and evolution of solar filaments, together with magnetic field data from other observatories and multi-wavelength data from satellites in space. Her recent work has focused on understanding solar cycles, which led to new hypotheses about solar cycle polarity reversals.

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### KEY COLLABORATORS ON SOLAR CYCLE RESEARCH

Dr Karen L. Harvey, Solar Physics Research Corporation, Co-author on three papers on ephemeral active regions

Dr John W. Harvey, Co-author of one paper on ephemeral active regions



### FUNDING RELATED TO SOLAR CYCLES

Mr Michael McDonald, Majority of funding for publication costs of a series of 3 articles on solar cycle topics in Scientia in 2025



### FURTHER READING

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