

Sunspots reveal their dark side

New theories have clarified the structure of sunspots but the latest observations have revealed intriguing dark cores in the bright filaments surrounding them

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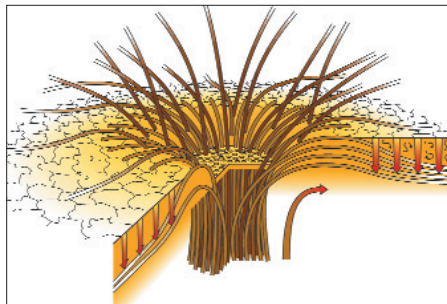
Solar physics is currently enjoying a golden age, but many fundamental questions about the nature of the Sun have not yet been fully answered. What generates the Sun's magnetic field? How is its atmosphere heated? And what governs the acceleration of the solar wind? However, over the past five years there have been significant advances in our understanding of solar magnetohydrodynamics – the subtle and intimate non-linear interaction between the Sun's magnetic field and the plasma of which the star is composed.

At the centre of the Sun's mystique are sunspots, dark regions in the solar surface that are often accompanied by bursts of activity such as solar flares. Sunspots have been observed for over two millennia, varying in number with a period of 11 years, and we have just experienced a maximum in the sunspot cycle. Moreover, there have recently been two important advances in our understanding of these giant solar features. The first is a theoretical model that for the first time can explain the filamentary structure of the penumbra of sunspots, and second is a stunning, high-resolution image of a sunspot that reveals that the penumbral filaments contain strange, dark cores.

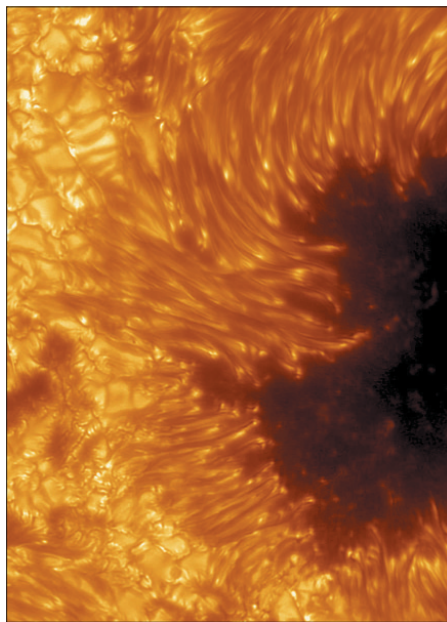
Sunspot dynamics

Some 100 years ago, George Ellery Hale realized that sunspots are the sites of strong magnetic fields. Indeed, sunspots are regions where huge tubes of strong magnetic field, which are generated in the Sun's interior, pass through the solar surface. In the vicinity of sunspots the solar surface is in a state of turbulent motion. Strong convection on small scales in the form of granules that are 1000 km across is superimposed on a weaker, larger-scale convection in the form of "supergranules". These superpositions are typically 15 000 km in diameter – about 2% of the Sun's radius. The granules form an irregular pattern of convection cells, which have centres that are bright and rise upwards and borders that are dark and fall downwards.

The central part of a sunspot, called the umbra, has a typical diameter of 15 000 km and is dark. It contains an almost vertical magnetic field, which inhibits the convection of the hot underlying plasma and therefore leaves the umbra cool. The umbra is surrounded by an annular region called the



1 A schematic of the interlocking comb structure of the magnetic field in the penumbra of a sunspot. Alternating bright and dark filaments emerge radially from the sunspot at different angles. Dark, low-lying filaments in which the magnetic field is almost horizontal are held down by convection pumping (orange/red arrows). Small-scale granular convection is indicated by the curved black arrows.



2 Part of the dark umbra and striated penumbra of a sunspot and surrounding granulation observed at unprecedented spatial resolution with the new Swedish 1 m Solar Telescope. The dark cores of the bright penumbral filaments, which are between 150 and 180 km wide, came as a great surprise to astrophysicists.

penumbra, which contains a magnetic field of intermediate strength that is inclined substantially with respect to the vertical.

The penumbra contains light and dark filaments that alternate radially, but the cause of these filaments remains a mystery.

Two classic review papers published 10 years ago by John Thomas and Nigel Weiss of Cambridge University and by Alan Title **[AUTHOR: Can you please provide Title's affiliation]** and colleagues,

respectively, summarized the properties of sunspots, noting that the light and dark filaments form an interlocking comb-like structure. The dark filaments are inclined at a small angle to the horizontal (which decreases outwards from the sunspot) and the light filaments are inclined at a larger angle. The bright filaments are composed of elongated "grains" that move mainly towards the umbra at about 0.5 km s^{-1} . The dark filaments contain a plasma outflow travelling at up to 6 km s^{-1} , which is known as the Evershed effect.

Thomas and Weiss, together with Steve Tobias of Leeds University and Nic Brummell of the University of Colorado, have now proposed a novel idea that clarifies the basic nature of the penumbra for the first time (J H Thomas *et al.* 2002 *Nature* **420** 390). They suggest that in the early stages of sunspot formation, when only the umbra is present (called a pore), a convectively driven filamentary instability initiates the formation of the penumbra with its interlocking comb-like field. A process known as convective pumping then drags the lower-lying field lines down through the solar surface at the edge of the spot. These form the cooler, dark filaments, while the other field lines remain more vertical and appear as bright filaments (figure 1). This interchange of bright and dark filaments probably discontinues after a certain time, leaving the dark filaments held down and the bright ones remaining vertical.

The key idea is that compressible granular convection consists of a series of cells that has broad, gently rising centres with strong down-flowing plumes at the junction of several cells. These plumes preferentially pump the magnetic field downwards, against both the weak, rising convective elements and the natural tendency for magnetic-flux tubes to rise by buoyancy.

This theory explains the structure of the penumbra, as well as how decaying sunspots with a penumbra exist with less magnetic flux than the largest pores. The Evershed outflow is explained as a siphon flow, driven in dark filaments along the low-lying magnetic fields from high-pressure penumbral footpoints. The abrupt disappearance of Evershed flow at the outer boundary of the sunspot is due to the magnetic field diving back down through the Sun's surface at the edge of the penumbra. Presumably no comparable flow is set up in the bright filaments because their greater inclination to the horizontal means that they are anchored much further away from the sunspot.

Sunspot viewed as never before

Göran Scharmer and colleagues at the Institute for Solar Physics in the Royal Swedish Academy of Sciences have presented a stunning image of a sunspot that will allow theoretical models such as the one described above to be tested (G B Scharmer *et al.* 2002 *Nature* **420** 151). This is the first scientific breakthrough achieved using the new Swedish 1 m Solar Telescope in La Palma. This instrument has an ingenious design that corrects for distortions in the Earth's atmosphere by changing the shape of its mirror 1000 times each second. The image shows half a sunspot with a spatial resolution that is twice as high as has ever been attained before (figure 2). Surprisingly, it reveals that many bright penumbral filaments – which are about 170 km wide – have dark cores of about half this width. Further, the footpoints of the filaments are either in or near bright penumbral grains or small bright features in the umbra called umbral dots.

This new discovery of dark cores in bright penumbral filaments represents an intriguing challenge to our understanding of sunspots. Are the bright filaments doubly convective rolls with a dark core that are cooling and sinking? Are they individual flux tubes the boundaries of which are heated by magnetic waves? And are the bright grains a mass motion or, as is more likely, a drifting wave pattern that tends to occur in compressible magnetic convection in an inclined field?

In order to answer these questions and gain a fuller understanding of the amazing complexity of sunspots, we eagerly await more observations from the Swedish Solar Telescope. In the longer term, complementary space missions such as Solar B, being built by Japan, the US and the UK, and NASA's Solar Dynamics Observatory also promise detailed observations of the magnetohydrodynamic processes in the Sun. Then there is the ground-based 4 m Advanced Technology Solar Telescope, due to be operational in 2010, which will be the largest and most capable solar telescope ever built.

It looks as if the golden age of solar physics is here to stay.