Sunspots are dark because they are the sites of strong magnetic fields, which locally suppress the transport of energy by convection (Thomas and Weiss 1992, Stix 2002, see also Proctor in this issue pages 4.14–4.20). They are the most prominent magnetic features on the Sun, although they are as nothing compared to their analogues, the starspots that appear on magnetically active stars. Ever since sunspots were first observed through telescopes, in the time of Galileo, it has been realized that there is a distinction between the dark featureless umbra at the core of a spot and the less dark penumbra that surrounds it (see the box “Historical sunspot observations”). The penumbra has a filamentary structure, with largely radial rays that are alternately bright and dark, but the actual fine structure of its magnetic field has only been resolved within the last 10 years, raising a major challenge to theoreticians as a result (Martínez Pillet 1997, Solanki 2003, Thomas and Weiss 2004).

Figure 2 shows a remarkable new image of the solar photosphere, obtained with unprecedented resolution by using adaptive optics on the new Swedish 1 m Solar Telescope on La Palma (Scharmer et al. 2002). This enlargement shows penumbral filaments in detail, as well as some fine structure in the umbra of the sunspot. The tick marks are at intervals of 1000 km. (Royal Swedish Academy of Sciences.)

The magnetic geometry of a sunspot

The observed magnetic field is strongest at the centre of a sunspot, where it rises to a value of about 3000 G, and falls off to a strength of around 1000 G at the outer edge of the penumbra, as depicted in figure 3a. The field is vertical
The earliest depiction of sunspots (in 1128) is a rather fanciful representation (Stephenson and Willis 1999), but the first drawings by Scheiner and by Galileo, based on telescopic observations, already show some sunspots with dark cores. In his "Rosa Ursina," published in 1630, Scheiner emphasizes the distinction between the dark nucleus of a sunspot and the shadowy ring (which, confusingly, he terms an "umbra") that surrounds it (see figure 3 of Weiss 2001). Telescope technology gradually advanced so that, by the end of the 18th century, the solar photosphere could be observed in greater detail. With his 10-foot telescope, William Herschel (1801) noticed that the surface of the Sun had an uneven, mottled appearance owing to the granulation (which he called "corrugations"). Sunspots he regarded as "openings" through which one could see "a most magnificent habitable globe" below. The openings were surrounded by "shallows" and he observed that "Shallows have no Corrugations, but are tufted." This is the first observation of fine structure in sunspot penumbrae.

What that cause might be remained uncertain until 1908, when Hale measured the Zeeman splitting of magnetically sensitive iron lines in sunspots, and demonstrated the presence of strong magnetic fields. Hale and his colleagues also determined the orientation of the field and found that its inclination to the vertical increased from zero at the centre of a spot to about 80° at its edge.

It has taken a further 90 years to establish the fine structure of this field.
at the centre but its inclination to the vertical, shown in figure 3b, increases to an average value of about 70° at the periphery of the spot. The azimuthally averaged field configuration in an idealized sunspot therefore takes the form that is sketched in figure 4a. This axisymmetric configuration is, however, misleading, and azimuthal structure must be included in order to explain both the magnetic configuration of a sunspot and the flows associated with it. It has long been known that there is a nearly horizontal, radial outflow in the outer penumbra (the Evershed flow) and that, owing to the strength of the penumbral magnetic field, this velocity must be along the field. This observation is therefore in contradiction with the sketch in figure 4a. If the field were nowhere horizontal in the penumbra then no horizontal flows should be found.

What recent observations have revealed is a much more complicated inhomogeneous structure, as shown in figure 5 (Title et al. 1993, Solanki 2003). The field inclinations in penumbral bright and dark filaments differ by about 35°, so that at the edge of the spot the fields in the bright filaments are inclined at about 50°–60° to the vertical while those in the dark filaments are nearly horizontal (so that on average the field is tilted at 70°). The difference persists to the umbral–penumbral boundary, where the average inclination is about 45°. Thus the magnetic field in the penumbra has an interlocking-comb structure that is shown schematically in figure 4b. Observations also demonstrate that the Evershed flow is indeed confined to the dark filaments and this issue is therefore resolved – only to be superseded by another. Ultraviolet and X-ray observations from space reveal loops that follow field lines emerging from the penumbra, like those in the TRACE image of figure 6, and then extend across vast distances before returning to the solar surface, very different to the configuration of the dark filaments. This implies that the two sets of field lines in the bright and dark filaments must remain distinct – a result that poses some major theoretical problems. What causes this extraordinary interlocking-comb structure? How is it formed and how is it maintained?

Some new physical process is apparently required, and the clue comes, once again, from further observations of the dynamics of the dark filaments. Although some of the Evershed flow continues out along a shallow magnetic canopy that hugs the solar surface (Solanki et al. 1994), most of it plunges down below the solar surface just outside the penumbra, or even within it (Rimmele 1995, Stanchfield et al. 1997, Schlichenmaier and Schmidt 2000). Corresponding reversals of the vertical component of the magnetic field have also been confirmed (Westendorp Plaza et al. 1997, Solanki 2003) so that the field dives below the solar surface. An extra mechanism is needed to make the field return in this manner and to keep magnetic flux submerged below the solar surface outside the penumbra. An isolated tube of magnetic flux must be in pressure equilibrium with its surroundings, and the contribution from magnetic pressure requires that the internal pressure, and hence the density, must be less than in the surrounding region. Thus the tube tends to be buoyant and to rise (a process known as magnetic buoyancy). So there has to be some competing effect that drags these magnetic fields downwards.

The spot is surrounded by small-scale granular convection cells, visible in figure 5a, which are themselves embedded in a large annullar cell with a radial outflow (the moat), as shown in figure 5b. The moat cell is a particularly large and stable example of the supergranules (with diameters of 20000–30000 km) that cover the solar surface and sweep weak fields to their boundaries (Weiss 2001). The supergranular motion is relatively slow and tranquil compared with that in the turbulent granulation. This granular convection is, we believe, responsible for holding the returning flux tubes submerged below the solar surface – a process known as magnetic pumping (described in detail below).

We therefore claim that flux pumping is responsible for the existence of the two-component penumbra with its filamentary structure and interlocking-comb magnetic fields (Thomas et al. 2002, Weiss et al. 2004). This leads to the overall physical picture of a sunspot that is sketched in figure 7. Within the dark filaments, some magnetic flux tubes hug the surface along the elevated magnetic canopy but others dive downwards and are held there owing to magnetic pumping by the small-scale turbulent convection that forms the photospheric granulation. Thus the interlocking-comb structure of the magnetic field in the penumbra owes its origin to the interaction between the spot and its surroundings.

Further support for this picture comes from observations of magnetic features outside the penumbra. The moat cell, which is superimposed on the granulation, is enclosed by a ring of magnetic field with the same sign as that in the spot itself. It is to be expected that the radial outflow in the moat should sweep magnetic flux...
to its periphery. Evidence for the presence of submerged magnetic flux is provided by the behaviour of moving magnetic features (MMFs) within the moat itself (Shine and Title 2001), which can be seen in figures 3 and 5. There are several different types of MMFs, all of which travel outwards across the moat as indicated in figure 8. Of these, the most significant are those of Type I, which correspond to flux loops emerging through the surface with the field in the inner leg pointing in the same direction as that in the spot. This is the appropriate orientation for a sample of the magnetic field that is held down below the granulation.

In the next section we describe a highly idealized model of the pumping process that keeps such fields submerged, and argue that this process is robust.

**Flux pumping**

In a highly conducting fluid, such as the ionized plasma below the solar photosphere, magnetic fields are expelled from vigorously convecting eddies. More generally, inhomogeneous turbulence tends to transport magnetic flux down the gradient of turbulent intensity (Tobias et al. 2001, Weiss 2003). This process of turbulent diamagnetism has been demonstrated in numerical calculations, with spatially modulated turbulence driven by external forcing in a field that is initially uniform (Tao et al. 1998). In the final state, magnetic flux is clearly segregated from the motion. In the case of a three-dimensional convecting layer, what happens depends on whether the fluid is compressible or not. With an incompressible fluid, the layer has up–down symmetry and there is no distinction between upwards and downwards flux expulsion. This symmetry is broken in a stratified compressible layer: convection then takes the form of broad isolated rising plumes surrounded by a network of cooler sinking fluid (just as in the solar granulation). The sinking fluid is focused into rapidly descending plumes located below the corners in the network (Spruit et al. 1990).

Because magnetic fields tend to move with the fluid, they are swept aside by the gently rising and expanding plumes, to be captured and dragged downwards by the vigorously falling and contracting plumes. Hence magnetic flux is pumped preferentially downwards. This process is robust and has been demonstrated in a variety of numerical investigations (Tobias et al. 1998, 2001, Dorch and Nordlund 2001).

It is not yet feasible to model the interaction between turbulent convection and a magnetic field with the presumed geometry of a sunspot. Nevertheless, an idealized configuration, which represents the behaviour of magnetic fields in...
the moat outside the spot, can yield important information about the dynamics there. The turbulent granulation is driven by the strongly superadiabatic gradient, caused by ionization of hydrogen, immediately below the photosphere; superimposed on it is the gentler, large-scale supergranular circulation, which extends downwards to a region that is only marginally superadiabatic. To model this numerically, we take a fully compressible layer that is strongly superadiabatic, and place it above a second layer that is adiabatically stratified. The upper layer convects vigorously, with broad rising plumes that impinge upon the upper surface and are enclosed by narrow sinking sheets. The latter develop into rapidly descending plumes, some of which penetrate into the lower layer, where convection is much weaker, as shown in figure 9. Once the system has settled into a statistically steady state, a thin sheet of unidirectional horizontal field is introduced into the middle of the upper layer and its subsequent evolution is followed (Thomas et al. 2002, Weiss et al. 2004). Magnetic fields are initially carried upwards and spread throughout the upper layer, so that a proportion of the flux escapes through the top boundary, but then flux pumping takes over and the remaining flux is pumped downwards and expelled into the lower layer (figure 9). The volume-rendered image in figure 10 shows the strong downwards plumes, represented by surfaces of constant enstrophy (the square of the vorticity) and a selection of suitably chosen field lines, for such a calculation. Within the turbulent upper layer there is a tangled incoherent field, but below it the field is more nearly in its original direction. Further details of this model calculation are contained in the box “Flux pumping calculation”.

**Outstanding problems**

Such calculations confirm that flux pumping really works and is a robust effect. Thus the turbulent convection that produces the solar granulation should be able to hold magnetic flux below the surface, allowing occasional stitches to emerge as MMFs (figure 8). The same process should also be able to capture magnetic fields emerging horizontally at the edge of the sunspot and to drag them down below the photosphere. Further, more elaborate calculations are still needed in order to confirm this picture.

Adding the new ingredient of flux pumping provides a mechanism for maintaining the filamentary penumbra once it is established, but does not explain how it arises in the first place. The latest observations show that even the tiniest pores are surrounded by a finely fluted rim (Scharmer et al. 2002). The magnetic field within them is concave towards the external plasma, but the configuration is stabilized because the flux within the flux tube at a given level is less dense than that outside. The stable modes can nevertheless be excited to some finite level by turbulent motion inside and outside the pore. As a pore grows it eventually reaches a critical size and develops into a protospot with a rudimentary penumbra (Leka and Skumanich 1998). Simple models indicate that the field at the edge of a pore becomes increasingly inclined to the vertical as the total magnetic flux increases, and so it is natural to suppose that a convectively driven fluting instability sets in at some critical inclination.

Evidence for such an instability has recently emerged from a highly idealized model calculation, with an incompressible (Boussinesq) fluid in a rectangular configuration (Tildesley 2003, Tildesley and Weiss 2004). The nonlinear development of this instability leads to a filamentary pattern – though the filaments are rather fat. Further support for an instability is given by some nonlinear calculations involving compressible magnetoconvection in a cylindrical geometry, which suggest that increasing the imposed field strength leads to increasingly non-axisymmetric patterns (Hurlburt and Alexander 2003). As a protospot accumulates more magnetic flux, it rapidly acquires a fully developed penumbra. This sudden change can be explained as an interaction with the surrounding turbulent convection. Once the fluted pattern is sufficiently developed, the lower field lines will be grabbed and pumped downwards by the surrounding granules. We should expect the resulting jump to be subcritical, and this is indeed the case, for the smallest spots have significantly less flux than the largest pores (Rucklidge et al. 1995).

Any realistic global model of a sunspot must also include a description of convective transport within the spot itself, for it is clear that the reduced energy radiated from the umbra and penumbra can only be supplied by convection. Since the fields in the bright and dark filaments apparently remain distinct, it becomes necessary to describe two different forms of convection in the penumbra. Convection is apparently much less efficient in the dark filaments, with their more horizontal fields, than it is in the bright filaments, where it seems to take the form of a time-dependent pattern that migrates either outwards or inwards, depending on the inclination (Weiss et al. 2004).

Within the umbra itself there are faint bright features (umbral dots) which can be discerned in figure 2, and these apparently correspond to spatially modulated oscillations (Weiss 2001). To include all these effects, together with convection in the ambient plasma, in a detailed
Flux pumping calculation

The model calculation is carried out for a perfect gas in a cuboidal box with dimensions $6 \times 6 \times 2$ dimensionless units, with gravity acting in the vertical $z$-direction and periodic lateral boundary conditions. The stratification can be described by a polytropic index $m$. The upper half of the box is initially strongly superadiabatic, with $m=1$, while the lower layer is adiabatically stratified, with $m=3/2$ ($S=0.0$). After a statistically steady state is reached, a thin sheet of field in the $y$-direction is inserted. The left-hand pair of images in figure 9 show the vertical velocity and the distribution of magnetic energy a short while later, while the right-hand pair show the pattern much later, when magnetic flux has been pumped downwards. Detailed results are summarized in figure 11. The vertical distribution of the horizontally averaged field $\langle B_y \rangle$ at various successive times is shown in figure 11a. The initial sheet first spreads upwards; then, as some flux escapes through the upper boundary, the rest is gradually pumped downwards until it leaks through the base of the box. Figure 11b shows that more than half of the remaining flux is pumped downwards into the lower half of the box. Essentially similar results have also been obtained when the polytropic index in the lower layer is chosen so that it is weakly superadiabatic, with $m=1.495$ ($S=0.01$; Weiss et al. 2004), or mildly subadiabatic, with $m=1.75$ ($S=0.5$; Thomas et al. 2002). These results, taken with those previously published for a strongly stable lower layer (Tobias et al. 2001), confirm that flux pumping acts robustly.

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Sunspots

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**Conclusion**

Happily, progress with observational techniques is matched by theoretical advances, and as fine structures are revealed they can be modelled with the aid of powerful computers. Nevertheless, as we have indicated, there is much that remains to be explained. The sunspot penumbra is an old problem but progress is still driven by observations, which reveal features that no theoretician would have dared to predict. Moreover, it is the small scales that determine the large-scale structure. Luckily, we can see fine structure on the Sun — but other astronomers observing other stars are less fortunate.

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