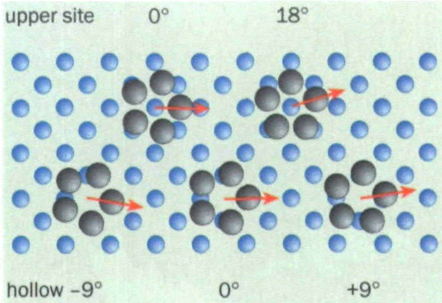
to each another compared with the strength of the forces between the lead and silicon atoms. These lead–silicon interactions must be strong enough to hold the pentagonal lead clusters against the surface without breaking them apart. Moreover, the crystals must be held in a preferred orientation that allows their fivefold symmetry to be observed and not averaged away. Clearly, this is much more challenging than trapping snowflakes.

The latest experiments carried out at the European Synchrotron Radiation Facility in Grenoble, France, and the Hamburg Synchrotron Radiation Laboratory, Germany, take advantage of the total external reflection of X-rays from a dense medium. In this case, the dense medium is liquid lead at the silicon surface (figure 1).

When the high-energy X-ray beam grazes the surface of the material at 0.03 degrees and less, the X-rays can penetrate through the silicon crystal and reflect from the silicon–lead interface. Within the liquid lead, the X-ray intensity decreases exponentially. As a result, the scattered intensity comes primarily from lead clusters trapped at the interface and not from the bulk liquid.

Reichert and co-workers found two main results. First, the interference pattern that they obtained from the liquid lead at the interface shows that the distances between the neighbouring lead atoms are the same as those found in the bulk liquid. This means that the lead clusters are not disturbed by the silicon surface and are characteristic of the bulk liquid. It also confirms the size of the proposed pentagonal units.



2 A view of lead pentagons with fivefold symmetry positioned on the silicon lattice. In the "upper" site (top), equivalent orientations of minimum atomic overlap are obtained by rotating the pentagon by 18 degrees. The "hollow" site (bottom) results in more overlap, with the most favourable orientations spaced 9 degrees apart.

Next, the team rotated the entire sample through 90 degrees in the plane of the square silicon lattice. If the lead clusters that are trapped on the silicon surface were arranged randomly, then the scattered intensity from the lead would not depend on this rotation. Instead, Reichert and co-workers found that the measured intensity is modulated as a function of angle and has five maxima in the 90 degree interval. This is very strong evidence that a significant fraction of the lead clusters are lined up in a fivefold symmetric set of orientations.

To understand why this should be the case, we need to consider the overlap between the atoms for a pentagonal lead cluster sitting on a silicon crystal lattice (see figure 2). In energy terms it is costly for the atoms to be in each others' way, so structures in which the overlap is minimized are favoured. This principle can determine the placement of the clusters as well as their orientation.

Compare the pentagonal lead clusters centred above a site occupied by a silicon atom with those centred on a "hollow" site between the silicon atoms. In the first case, the overlap between the lead and the silicon atoms is minimized, and an equivalent position can be achieved by rotating the cluster by 18 degrees. However, the correspondence between the silicon and lead atoms is different when the lead cluster is centred on a hollow site. In this case, comparable minima in overlap are reached by rotating the cluster by only 9 degrees. Calculations show that such configurations are less favourable in the first scenario. Because the team's scan showed five minima in the 90 degree rotation rather than ten, the X-ray measurements confirm the lead clusters' preference for the low-energy positions centred above occupied silicon sites.

Experiments such as these are now possible only because of the most recent advances in X-ray synchrotron radiation and instrumentation. And the prospect of continued exploration into the structure of materials is an exciting one.

Until now, some of the most basic states of matter, such as liquids, have been among the most uncooperative. In the future, they will take their place among regular crystals, quasicrystals and glasses: systems that – like snowflakes – are all different, but which will ultimately be understood according to a small set of basic principles.

Solar magnetism attracts an answer

From Mike Lockwood in the Space Science Department, Rutherford Appleton Laboratory and Department of Physics, Southampton University, and Duncan H Mackay in the Mathematical Institute, University of St Andrews, UK

These are interesting times for our understanding of the origins, evolution and effects of the Sun's magnetic field. Satellite missions such as Yohkoh, SOHO, Ulysses and TRACE have returned outstanding new data, and helioseismology has allowed us to see into the solar interior for the first time. The discovery of a shear layer between the surface of the Sun – the "photosphere" – and its centre has great implications for our understanding of the dynamo that is responsible for generating the solar magnetic field. Meanwhile, much research has been aimed at understanding the 11-year cycle in the field and the wide variety of phenomena that it modulates.

The solar magnetic field pokes through the photosphere in loop-like structures, particularly in "active regions" associated with sunspots (see figure). These loops rise up through the Sun's atmosphere, the "corona", so that some of the field is dragged by the solar wind into a region of space called the heliosphere, which extends far beyond our solar system. The so-called open solar flux that enters the heliosphere is roughly one-tenth of the flux that emerges through the photosphere.

Recent studies of the effect of the heliospheric field on the Earth's magnetic field have revealed that the open solar flux has more than doubled since 1900 (see *Physics World* September 1999 p21). This surprisingly large increase has been confirmed by studies of the galactic cosmic rays from which the Earth is partially shielded by the open solar flux. The products of galactic-ray bombardment found in ice sheets, tree rings and meteorites have steadily declined due to the increase in the protective magnetic field.

Now a model developed by Sami Solanki and Manfred Schüssler at the Max Planck Institute for Aeronomie in Germany, together with Marcel Fligge at the ETH in Zurich, provides new insight into why the open solar flux has changed so much. Their model considers the evolution of the flux from a new perspective and over a far longer period of time than previous simulations (*Nature* 2000 **408** 445).

The changes in the open solar flux also reflect some known changes in the number of sunspots and how they are spread over the solar surface. Although sunspots vary over a fairly regular 11-year cycle, they also vary significantly over timescales of 100 years or more. The origin of both the sunspot cycle and these longer-term secular variations are due to unknown features of the dynamo process that operate within the Sun (see *Physics World* December 1999 p56).

In recent years, detailed numerical models have been developed that follow the origin and evolution of the magnetic flux for up to a few years using a model of magnetic-flux transport. These models only consider how the surface field is affected by the differential rotation, poleward flow and convection of the photosphere and the sub-surface layers.

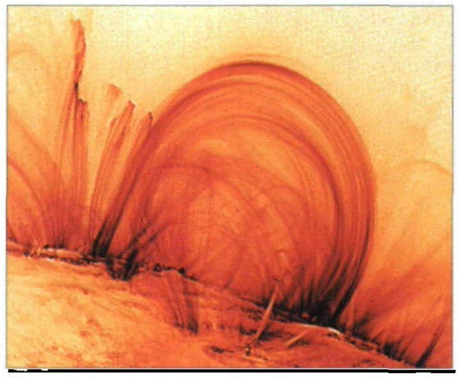
Such calculations have been carried out for individual field loops in the active regions of the photosphere. However, the real surface field is made up of many such field loops that are likely to interact with each other through the phenomenon of magnetic reconnection. This means that the real behaviour of the open flux will be far more complex than the simple sum of the effects due to individual loops.

However, Solanki and co-workers adopt a new approach. Rather than worry about how the open flux is distributed over the solar surface, they look at the balance between the overall generation and destruction of the total open flux.

To quantify the rate of emergence of new open flux, they cleverly exploited empirical equations that had previously been derived to help understand how the magnetic field modulates the total power output of the Sun. Because they were able to express this rate entirely as a function of sunspot number, they could apply their method to all the reliable sunspot data that have been collected since 1700. They also assumed that the rate at which the open flux is lost varies linearly with the amount of flux – an assumption that is consistent with results from other detailed models. The results are in excellent agreement with the observed variations.

A key insight that Solanki and co-workers obtained is the role of the length of the solar cycle. Long cycles allow the open flux to decay significantly before the new flux emerges, while a string of short cycles allow the net open flux to accumulate – as happened between 1900 and 1960.

This work is only the beginning. Future studies will generalize both types of model so that the detailed long-term evolution of the Sun as a whole can be studied. These models should consider the emergence of flux in both active and quiet regions of the Sun. In addition, various assumptions about the corona, for example, must be eliminated. In this respect, data obtained by SOHO and Ulysses over a full solar cycle will be very important, along with the new views of the Sun that we will obtain from future missions such as NASA's STEREO satellite and the European Space Agency's Solar Orbiter.



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Observations by the Transition Region and Coronal Explorer (TRACE) of magnetic-field loops emerging through the solar surface and into the solar atmosphere. The new model by Solanki and co-workers explains how the total magnetic flux that leaves the Sun has varied over the last few centuries, with interesting implications for Earth.

The implications of this work are considerable. Solanki and co-workers have explained the long-term variations of the open solar flux in terms of the change in the magnetic flux that emerges through the photosphere. Their model links the flux to surface magnetic phenomena such as sunspots, which lower the total irradiance of the Sun, and smaller magnetic flux tubes called faculae that increase the solar irradiance. Thus the work indicates why the open flux seems to be a good substitute for describing variations in the solar irradiance over the 120 years before we began making accurate measurements from space. It may also explain why the other variations – such as the length of the solar cycle and average sunspot number – give such similar results. These quantities are important for quantifying the relative importance of natural and man-made sources of global climate change, and how the balance between the two is shifting (see *Physics World* November 2000 p8).

Furthermore, the new model explains why the cosmic-ray flux on the Earth has fallen by about 15% since 1900. Cosmic rays are a hazard for humans, and for electronics in space and on board high-altitude aircraft (see *Physics World* May 2000 p21). Furthermore, we know that cosmic-ray-induced ions increase the production of aerosols that are large enough to allow clouds to condense in the Earth's atmosphere. What we do not yet know is whether or not this is a significant effect compared with the other mechanisms that lead to cloud formation (see *Physics World* February 2001 pp33–38). If we are to understand how any of these effects may change in the future, we must first understand the variations in the solar magnetic field.

Ions mimic the impact of meteorites

From Kai Nordlund in the Accelerator Laboratory, University of Helsinki, Finland

One of the many fascinating aspects of physics is the surprising scaling behaviour between the very small and the very large. Early last century, it became clear that the structure of the solar system and a single atom are both governed by attractive interactions that decrease with the inverse square of the distance to a massive central body. More recently, chaos theory has explained why similar fractal shapes are all pervasive in nature, from snowflakes and ferns to the shapes of entire mountain ranges.

Now another observation of atomic and planetary systems behaving in surprisingly similar fashion has been reported at Argonne National Laboratory in the US. When a large enough meteorite impacts on a planet or moon, it tends to eject large chunks of matter and form a crater with a rim. The size of the crater structure can be far larger than the initial projectile. Recent work by Robert Birtcher and Sandrine Schlutig at Argonne, together with Stephen Donnelly of Salford University in the UK, has shown that a single xenon ion impacting on a thin gold film can produce rimmed craters containing thousands of atoms (*Phys. Rev. Lett.* 2000 **85** 4968). At the same time, nanoparticles – large chunks of atoms – are observed exploding out of the film. In this case too, the craters and nanoparticles are huge compared with the xenon ion that produces them.

As with planetary systems, the reason such a large amount of matter can be displaced by a relatively small object is due to the projectile's initially large kinetic energy. The beam of xenon ions that Birtcher and co-workers used had a kinetic energy of 400 keV, some 10 million times more than the average kinetic energy of atoms at room temperature. In the field of ion-irradiation physics, it is well known that ions with such high energies can displace a very large number of atoms. Furthermore, in dense metals, such as gold, these displacements can occur in a very small region.

A few hundred femtoseconds after the initial impact, the displaced atoms form a roughly spherical or cylindrical region, where the material behaves much like a liquid under high pressure. Inside a crystal this liquid will quickly cool to leave a defective or amorphous zone in the material. In 1980 Karl Merkle and Wolfgang Jäger, then both at Argonne, showed that if the liquid zone forms near a surface, then the high pressure can rupture the surface, allowing much of the hot material to flow out and form crater-like structures (see figure).

These general features have been known for some time. However, in 1994 Mai Ghaly and Robert Averback, then both at the University of Illinois at Urbana-Champaign, predicted using computer simulations that the impacts of single high-energy atoms on dense metals should share all the essential features of asteroid collisions. Now Birtcher and co-workers have confirmed experimentally that the ion impacts do indeed eject large chunks of matter and form craters with a well in the middle and a roughly circular rim. The team ensured that fewer than one xenon ion per square nanometre bombarded the surface, and collected the gold nanoparticles on a thin carbon foil. They also viewed both