The Solar Photosphere: Video Movies and Computer Simulations

What is new on the Sun? These days, quite a bit. Before, the solar surface seen through ordinary optical telescopes had become somewhat stale. The main interest in solar astrophysics had shifted to the outer solar atmosphere when radio techniques and space vehicles opened up the spectral regions in which the solar chromosphere and corona primarily display their fireworks, above all the spectacular flares. Then the identification of the 5-minute oscillations as global subsurface p-modes led to the advent of helioseismology, with strong emphasis on the solar interior. But now the recent IAU Symposium at Kiev on the solar photosphere* has shown a revival of solar surface studies—using new instruments, video techniques and computer simulations. These have produced a breakthrough in explaining the solar granulation and have already led to detailed predictions for similar convective phenomena in other stars; understanding magnetic fine structure appears in reach, and there is even hope for the magnetic field generators hidden in stellar interiors.

Solar surface studies started when Galileo pointed a telescope at the Sun and discovered spots on its face. Since then, centuries

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of study have shown the surface layers of this ordinary star to be highly complex, showing structural details, dynamical flows and magnetic elements in different sizes down to the resolution limit of the best telescopes, intricate patterns at various scales and temporal changes that range from seconds to centuries. Although it is clear that these phenomena must all follow from the well-known basic equations of hydrodynamics, radiative transfer and electromagnetism applied to turbulent gases, their interpretation has proven remarkably elusive.

The solar physics success stories lay elsewhere, in radiative transfer, plasma astrophysics, magnetic activity and helioseismology, and in each of these areas a direct link was established between solar and general astrophysics. Radiative transfer theory made solar physics "the mother of astrophysics" by providing basic tools for interpreting radiation received from any object. Plasma astrophysics obtained a strong impulse from the 1973 Skylab observations which displayed the solar corona as the nearest plasma physics laboratory where cosmic conditions apply. Cool-star magnetic activity became a hot topic when ultraviolet and X-ray observations with the IUE and EINSTEIN satellites showed that most cool stars possess hot outer atmospheres similar to the Sun's. Helioseismology now promises a direct link to stellar evolution theory by probing the Sun's interior. In contrast, solar surface morphology appears to be of no direct interest to non-solar astrophysics. The largest star in our night sky subtends a solid angle of only 10^{-9} of the solar disk; thus, solar-like surface detail remains unresolvable in other stars.

Why then spend much effort in studying solar surface details? Because the photosphere (the "surface" at optical wavelengths) represents a marked boundary layer between the interior and the outside of a star, an interface for the processes that connect these very different regimes, and the layer in which these processes are most accessible to observation. The radiative, dynamical and magnetic processes that transfer energy and matter from stellar interiors into space couple a vast reservoir in which equilibrium conditions apply to a higher degree than anywhere else in the cosmos to a surrounding near-vacuum far from equilibrium. The solar surface marks the step from dense to tenuous, from thermal to nonthermal control, from local coupling of the radiation field

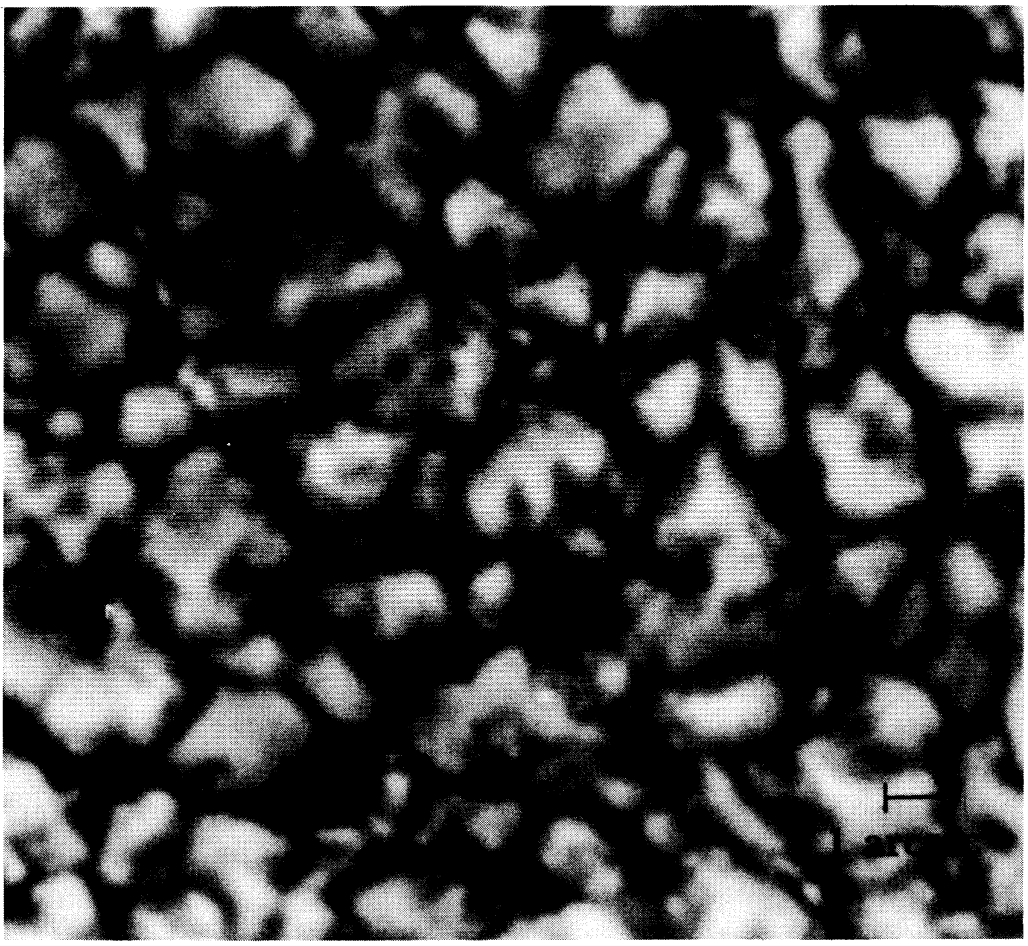

FIGURE 1 Solar granulation. The cellular appearance of the solar surface at 1″ scale is due to the convection which transports energy through the outer third of the Sun to the surface from which it is radiated away into space. The larger cells typically measure about 1,000 km. The cells evolve rapidly within their typical 10-min lifetime; many break up ("explode") into smaller fragments. This high-resolution picture shows many structures of sub-arcsecond size; the smallest mark locations of strong magnetic field. Areas without field show regular granulation with larger cells (lower left). Snapshot from a digital video movie obtained with the vacuum refractor of the Swedish Solar Observatory, Roque de los Muchachos, La Palma, wavelength 468.6 nm. Courtesy G. B. Scharmer, Royal Swedish Academy of Sciences.

to full transparency, from pressure domination to magnetic structuring, and from hydrodynamic stability to supersonic outflow, the step being so abrupt that it results in the multitude of intricate phenomena which we observe. These surface processes hold the key to how a star achieves this transition and, at the same time, they constitute a well-equipped physics laboratory, not only for solar physics but for astrophysics in general. The fact that explanations have remained elusive for so long implies that there is much to learn with sufficient observational and interpretative sophistication. The Kiev symposium showed that this era has started.

The solar granulation (Fig. 1) (the changing tesselated pattern of small cells seen in white light, first described by William Herschel in 1801) now becomes the second solar surface phenomenon to be understood, the other one being the explanation of the 5-minute surface waves as global *p*-mode oscillations. This new breakthrough comes from advances both observational and theoretical, independent but fortuitously simultaneous.[1] Granulation observation changed with the introduction of new analysis techniques of which the development was triggered by NASA's Solar Optical Universal Polarimeter (Lockheed Palo Alto Research Laboratory; principal investigator A. M. Title) flown on Spacelab 2 in 1985. SOUP provided granulation observations free from the blurring and distortions which the Earth's atmosphere inevitably introduces in ground-based data and free from the image motion which troubled earlier balloon observations. They showed how strongly the Sun itself smears its appearance with its 5-minute oscillations, leading to the development of three-dimensional Fourier filtering techniques in which the spatial and temporal signatures of the oscillations are used to isolate the granular signal. The SOUP team then used a correlation algorithm to measure the lateral displacement of granules in time, thus mapping horizontal flows on the solar surface in contrast to the vertical flows routinely measured from the Doppler shift of spectral lines. To visualize these horizontal flows they introduced the "cork" concept in which artifical corks are sprinkled on the observed solar surface in digital video movies to reveal its longer-lived currents and cellular streaming patterns even while individual granules come and go. Analyzing cork behaviors with such movies exploits the excellent pattern-recognition capabilities of human vision; it led to the discovery of horizontal flow fields patterned in "mesogranular" cells, glimpsed before but now surely detected at a scale of 5,000–7,000 km intermediate between granulation (1,000 km) and supergranulation (30,000 km). The SOUP movies also showed how frequent and important the "exploding granule" phenomenon is, in which large granules located in mesogranular divergence centers develop a dark center, expand abruptly and spread a horizontal disturbance impacting on other granules.

Spacelab 2 and SOUP were carried by Challenger; further flights were cancelled after that shuttle exploded. However, it was found that the cork algorithm also works reasonably well for computer-processed ground-based observations of the very best quality. Such quality is reached regularly by the superb new solar telescope of the Swedish Solar Observatory, part of the Roque de los Muchachos Observatory on La Palma in the Canary Islands. It is a 50-cm vacuum refractor of unusual design (G. B. Scharmer, Roy. Swedish Ac. of Sci.) and of excellent optical quality. The problems of ground-based observing are minimized by the exceptionally good view (atmospheric tranquillity) often present at the La Palma site and by employing a real-time "image-grabbing" system which every few seconds selects, digitizes and stores the best images from sequences taken at a rate of 25 frames per second with a CCD TV camera. The larger-scale distortions which the atmosphere inflicts on these images are subsequently removed by pattern recognition and correlation techniques; the end result is a digital movie good enough for cork analysis. A striking result[2] was the discovery of a large persistent whirlpool traced by granulation.

The digital granulation movies came just in time to confirm theoretical predictions obtained from numerical simulations (most notably those of Å Nordlund, Univ. Copenhagen and R. F. Stein, Michigan State Univ.). These take advantage of the current generation of supercomputers to study solar convection with a realism which cannot be obtained analytically because the nonlinear terms describing the advection of plasma properties dominate far too strongly in the solar regime. The solar convective flows span many density scale heights while combining very weak molecular dissipation with large radiation losses at the surface; such flows are difficult to tackle. Understanding comes from time-dependent three-dimensional fully compressible model calculations; indeed they reproduce the features now observed: granules with the proper sizes and velocities at the surface, exploding granules as a natural result from the breakup of the balance between radiative cooling and thermal supply when large granules spread too wide, and an interesting topological pattern with depth that may explain the differrent observed scales of granular organization. Whereas just below the surface the computed updrafts are broad, gentle and nearly without structure, the descending flows converge into thin filaments ("fingers") that connect repeatedly, at different depths, into larger, deep-reaching plumes on their way down. The surface granules appear as very flat pancakes, exhibiting the smallest scale of horizontal patterns in the down-drafts of which the topological connectivity in deeper layers produces stepwise larger scales; the different scales on the surface appear to map these different connecting depths. Also, the downward plunging plumes have much horizontal vorticity, in agreement with the vortex found last year.

What about other stars? D. Dravins (Univ. Lund) and Å. Nordlund (Univ. Copenhagen) have obtained similar numerical simulations for the granulation on four stars, sampling differences in surface gravity and effective temperature (Fig. 2). The subgiant β Hyd has the largest predicted granules (10^4 km) and the dwarf α Cen B the smallest (10^3 km), the scales referring to the diameter at which the largest granules explode by effectively collapsing under their own weight. Procyon is predicted to have the most vigorous convection while in the coolest stars the granulation layer is located just below the visible surface, out of sight. (We are lucky that the solar surface and its pancake layer coincide—we might have missed an interesting phenomenon).

In view of the fact that each of these stars is smaller than a solar granule on our sky, it is quite amazing that there is already a substantial amount of observational information which corroborates these computer results: stellar granulation research has quickly evolved to the desirable stage in which detailed predictions are compared with detailed observations. The reason is that although granules are very small (there are about a million present at any one moment on the solar disk), they are spread rather homogeneously over the surface and leave a signature even in the spectrum of an unresolved star, consisting of tiny wavelength shifts and small asymmetries of the spectral line profiles which are measurable with high-quality spectrometers. The measurements are fitted well by the simulations for cool stars, indicating that the computer granules indeed reflect reality. For hotter stars, however, the observed profile asymmetry reverses: a "granulation dividing line" seems to run through the Hertzsprung–Russell diagram (D. F. Gray, Univ. Western Ontario) which is not understood. Numerical simulation

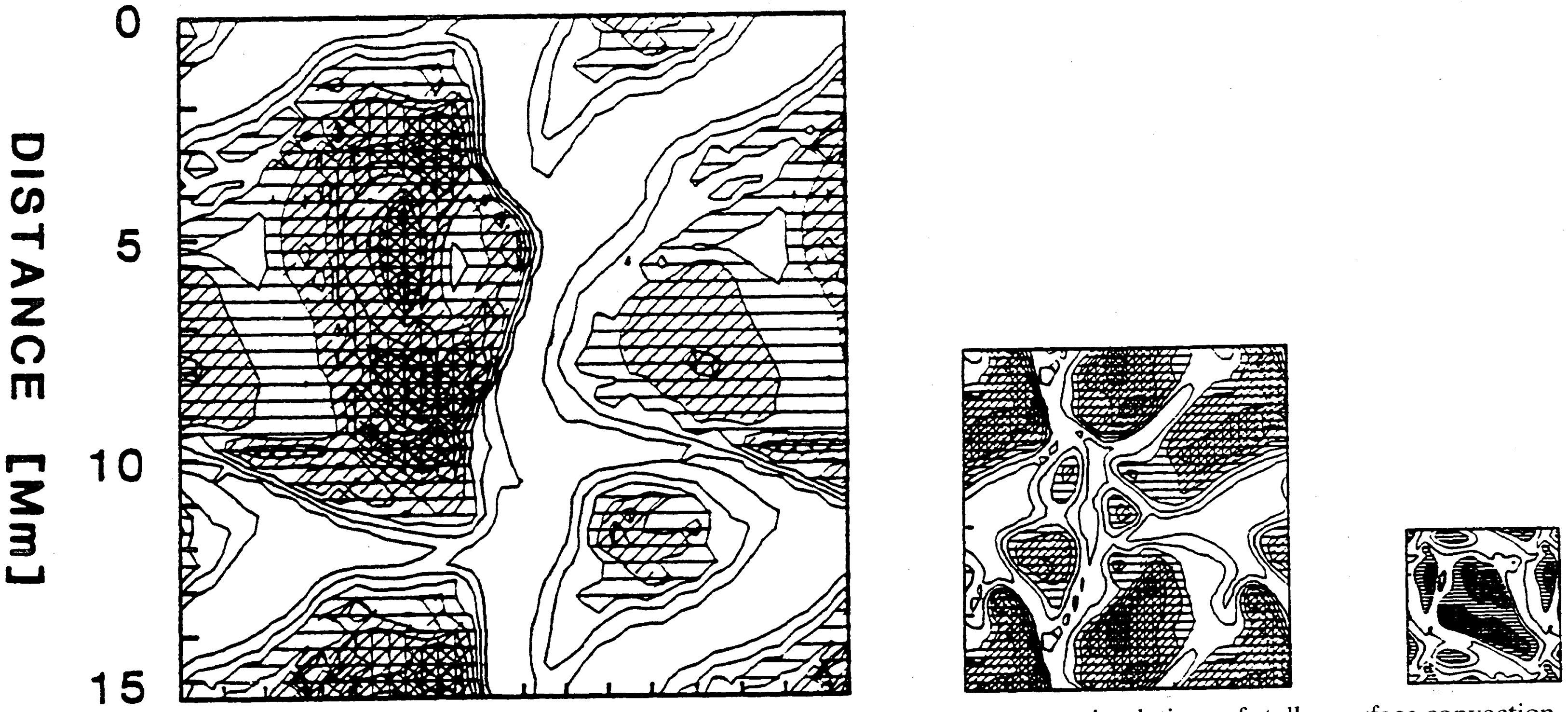

FIGURE 2 Stellar granulation. Synthetic white-light images from numerical supercomputer simulations of stellar surface convection. Representative surface patterns on three different stars, showing increase of granule size with decreasing stellar surface gravity. The two leftmost pictures are for G-type stars at solar temperature (5800 K) but with ¼ and ½ solar surface gravity, respectively. Solar granules are more similar to those on the cooler (5200 K) K-type dwarf (α Cen B) at right, but during the coming billions of years, the Sun will evolve to lower surface gravity, and its granulation will evolve along. Figure adapted from D. Dravins and Å. Nordlund, Astron. Astrophys., in press.

has been performed for one hot star, namely Sirius (D. Gigas, Univ. Kiel); it indicates that vigorous vertical flow patterns exist in a thin layer in the Sirius atmosphere, and therefore that hot stars may also have small-scale surface structuring even though they do not possess deep convection zones.

Another solar surface phenomenon of large current interest is the magnetic field (Fig. 3). It is structured very differently from the rather uniform dipole field of the Earth, existing largely or perhaps completely in the form of discrete elements in which very thin "flux tubes" are assembled into bigger "flux ropes." Sunspots are the most familiar example; they are the largest of such flux concentrations and display the strongest fields, up to 0.4 Tesla. Smaller are the pores which often combine into spots, and yet smaller are the "thin flux tubes" which are now believed to be the main ingredient of the solar magnetic field. These are slender filamentary concentrations of strong magnetic field (about 0.15 Tesla) and low gas pressure. They presumably cut vertically through the solar surface and are thought to play an important role in the heating of the solar corona and of the coronae of other cool stars; the level of cool-star activity seems to depend primarily on the number and the spatial configurations of such flux tubes, but the precise heating mechanisms are yet unknown. There are many studies of the hydromagnetic and magnetohydrodynamic wave modes of flux tubes and on their electrodynamical coupling to the upper atmosphere, and application to other astrophysical objects such as accretion disks around neutron stars has started: flux tubes have become very popular objects for theoretical astrophysicists.

While the thin flux tube concept has grown into an elaborate field of current research, the inferred tubes are so thin that their observational signatures cannot be resolved with present observation techniques: their predicted diameters are of the order of 100 km, or 0.1–0.3″ on the Sun. Valuable empirical modelling comes from spatially unresolved polarimetry with the Fourier Transform Spectrometer of the National Solar Observatory at Kitt Peak (S. Solanki, ETH Zürich and Univ. St. Andrews). It delivers the properties of typical individual flux tubes even though they are not resolved: most flux tubes apparently belong to such a sharply defined class, without much spread in field strength, that their spatially averaged polarization signature does indeed describe individual tube structure. It cannot deliver insights into the mor-

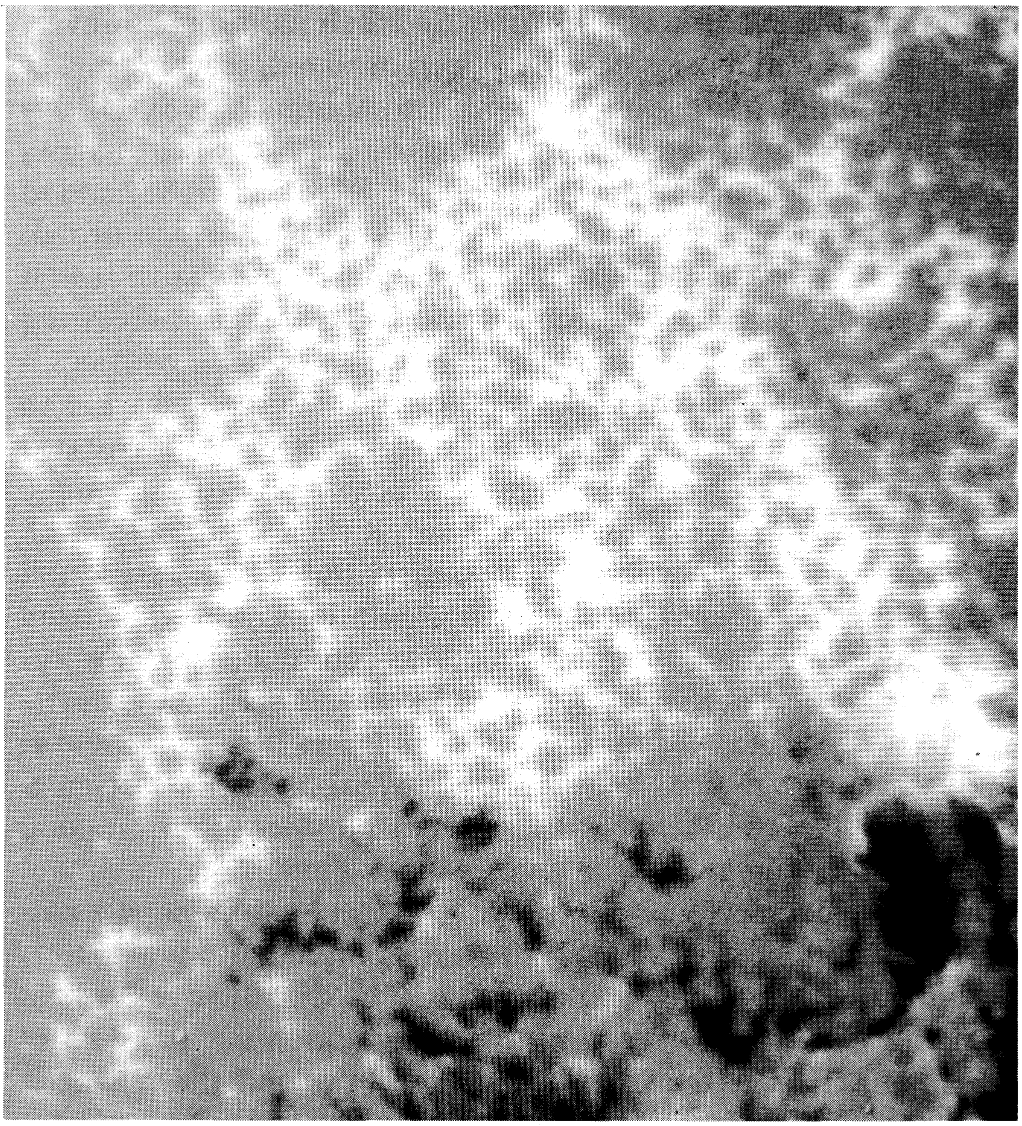

FIGURE 3 Solar magnetic field. In active regions on the solar surface, the magnetic field consists of small grains arranged in cellular patterns of large variety, with intricate fine structure down to the spatial resolution limit of about 0.3″. (Tick marks are 2″, frame size 85″ × 85″, 1″ measures 730 km on the Sun.) This is a young active region, "young" meaning that the magnetic field has emerged not long before. The cells display self-similar behavior with fractal dimension 1.6 over a range between 0″ and 10″. Simultaneous white-light images show that the granulation is abnormal in magnetic regions, showing many more small structures; the 5-min oscillations are also inhibited. White is positive polarity, black negative, of the longitudinal component (vertical to the surface) of the magnetic field vector, averaged over each spatial resolution element. Because most grains are not spatially resolved, their field strength is not directly measurable; the fluxes shown here are typically 15–100 mT per pixel and the noise level is about 6 mT per pixel. Image taken from a digital video movie constructed from observations in the Fe I 630.2 nm line with NASA's Solar Optical Universal Polarimeter at the Swedish Solar Observatory, Roque de los Muchachos, La Palma, on Sept. 29, 1988. Courtesy T. Tarbell, Lockheed Palo Alto Research Laboratory.

phology and the evolution of the tubes and their patterns; however, solar magnetogram movies have now been obtained, reaching higher spatial resolution than ever before by combining the SOUP instrument with the Swedish refractor at La Palma. Such magnetograms are made from images taken in left- and right-handed circularly polarized light using the two flanks of a Zeeman-broadened spectral line. A 2.5 hour image series of a young active region was obtained at La Palma last fall; advanced computer processing was used to align and derotate the frames (compensating for guiding errors and the apparent rotation of the field of view due to the Earth's rotation) and to remove large-scale atmospheric distortions. A digital video movie results, which displays the magnetic field structure and its evolution very well. It clearly shows that the magnetic field in the whole area consists indeed of very small grains. They are ordered in cellular configurations displaying many scales, and they move about with time, continuously being rearranged into new patterns. Of special interest is their initial emergence, marking the outbreak of new magnetic flux from below; the observations indicate that the grains mark footpoints of magnetic loops that rise through the surface and then drain, in good agreement with magnetohydrodynamic modelling.

Outside active regions, the field is organized into a coarse network of more regular sized cells measuring about 40″ in diameter. Its boundaries are thought also to consist of flux tube concentrations; they seem to correspond to the supergranular boundaries and it is likely that the hydrodynamical flows and the magnetic flux tubes cause this network pattern through mutual interaction. Studying such evolution requires extended observation, longer than a single observing day. A new cooperation between the Big Bear Solar Observatory in California and the Huairou Observing Station of the Beijing Observatory in China provides such longer-duration magnetogram movies. The two observatories have similar video magnetographs and operate in tandem, one taking over when the Sun sets at the other; since they are 11 hours apart in longitude, continuous observing can be achieved in summer and uninterrupted movies of over seventy hours duration have already been obtained. They show continuous slow rearrangement of the network patterns and indicate that there is persistent migration of patches of weak magnetic field from the cell interiors to the boundaries. The existence and nature of such weak "intranetwork fields" are still under discussion; they may represent a manifestation of the solar magnetic field wholly different from the strong-field flux tubes.

What causes the solar magnetic field, its structural patterns and its well-known activity cycle? The solar dynamo, hidden in the interior, remains an enigma, but there are promising developments. The linear mean field theories constructed over the years cannot cope well with the multiperiodicity and short phase stability which the cycle seems to display, and current theoretical efforts are directed to nonlinear and stochastical modelling. P. Hoyng (Lab. Space Res. Utrecht) has re-initiated research into turbulent dynamos while A. A. Ruzmaikin (Acad. Sci. USSR, Troitsk) has proposed that there is a strange attractor in the dynamo's phase space. Such concepts are now open for detailed study using supercomputers, making the important step from simplification for the sake of analytical tractability to nonlinear realism. There are also new observational constraints on the dynamo, in addition to the high-resolution and long-duration surface observations described above: from helioseismology which furnishes measurements of the differential rotation and its variation with depth and latitude within the solar interior, and from observations of activity cycles and surface field distributions of stars other than the Sun.

What will the future bring? The progress described here represents the beginnings of a new era in solar surface studies. There are new optical telescopes in the making: a large German solar observatory is coming into operation at Izaña on Tenerife; the French will install a major solar telescope there which will be particularly suited to polarimetry; the international LEST project (Large Earth-based Solar Telescope) aims to build a next-generation 2.5-m solar telescope at the Roque de los Muchachos on La Palma or at Mauna Kea on Hawaii; most ambitious is NASA's Orbiting Solar Laboratory, a 1-m solar telescope to be put into orbit which will be the solar physics counterpart of Space Telescope. But also the digital video techniques permit new ways of image processing and analysis, the advent of cheap but powerful graphics work stations brings these within the grasp of poor university departments, and an especially large advance is foreseeable in computer simulations for which massive parallelism and customdesigned hardware will bring orders of magnitude improvement. Thus, future studies of the solar surface will benefit from better observations, better data analysis and better theoretical interpretation all at the same time. This is a promising prospect; not only has the era of understanding the solar surface finally started, there should be much more to come.

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