Magnetic fields below, on and above the solar surface

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The Sun is the only star that can be studied in detail. The last decade saw a revolution in the scope, amount, and the quality of solar data. Coordinated quantitative observations link the processes in the deep interior to those in the outer atmosphere. Numerical simulations and theoretical modelling have produced detailed agreement with observations. The most important lesson the Sun is now teaching us is that the parallel development of quantitative measurements with numerical simulation and theory can produce a physical understanding of the complex nonlinear phenomena that occur over a wide range in densities, pressures, temperatures and plasma betas. Understanding the physics of the Sun is a major key to unravelling puzzles throughout astrophysics.

Keywords: Sun; magnetic fields; convection; numerical simulation; corona; dynamo

1. Introduction

The scope, amount and quality of solar data that are available to the scientific community increased dramatically during the last decade. The revolution began with the flight of the Japanese Yohkoh satellite launched in 1991, which still provides data on temperature and high-energy processes in the outer solar atmosphere as evidenced by X-ray emissions. The Yohkoh data clearly demonstrate that magnetic reconnection is a fundamental process controlling rapid high-temperature energy-release processes. The data flow accelerated with the launch in 1996 of the ESA-NASA Solar and Heliospheric Observatory (SOHO) that carries a set of 12 solar instruments. These produce a coordinated dataset that encompasses the entire Sun and its extended atmosphere, a volume that starts in the deep solar interior and extends to just before the Earth's magnetosphere. In 1998 the Transition Region and Coronal Explorer (TRACE) was launched into a Sun-synchronous orbit allowing high-cadence continuous high-resolution imaging of the solar surface, chromosphere, transition region and corona. The joint operation of the three imaging solar satellites create datasets that allow the study of the development of processes over a wide range of pressure, temperature, density and plasma beta and on scales that range from about 5×10^{-4} to 60 solar radii.

The new space data are complemented and enhanced by the collection of excellent digital image data collected by ground-based telescopes using fast large-format CCD detectors. Real-time image selection, adaptive optics and post-processing techniques have greatly improved the quality of data from the photosphere and chromosphere. The new higher-resolution images allow quantitative studies of the joint evolution of

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flow and magnetic fields in the lower solar atmosphere down to a scale of *ca.* 150 km or 0.2 arcsec.

The sharing of the databases collected by satellites and ground-based observatories is straightforward and common because of the availability of fast relatively inexpensive workstations with large-capacity disks. Careful specification of data management structures for both the space and ground experiments has made this efficient transfer possible. As a result, scientists use the Internet to transfer the relevant data required to study physical processes from their origin in the solar interior to their interaction with the Earth's outer atmosphere and the interplanetary medium. An IDL-based software system, SOLARSOFT (Freeland & Handy 1998), provides tools for alignment and analysis of data from both ground and satellite instruments.

The realistic numerical simulations of many solar processes is now possible because of the exponential growth of computing capability. The modern effort started with models of near-surface convection and the simulations of the concentration of magnetic fields in the convective downflows (Weiss 1964). There are now simulations of the rise of flux through the convection zone to the photosphere and into the corona. The high quality and range of the current solar observations provide strict tests for the predictions of the numerical simulations. Agreement of the simulations with the observations gives confidence that simulations are also valid in domains unobservable at present because of temporal and spatial scales. Simulations also provide estimates of quantities that are intrinsically unobservable. It is expected that simulations for phenomena that occur in the Sun can be extended to other stars and other magnetic structures in the Universe. In an increasing number of cases, theoretical analyses can provide understanding of the features produced in the simulations. These analyses yield insight into fundamental physical phenomena that are important in a broad variety of situations. In a real sense the Sun is a laboratory for astrophysics.

The discussions below outline the interplay of observation, numerical simulations and theory, from the deep interior to the interaction with the Earth and the interplanetary medium.

2. Below the surface

Helioseismological measurements have precisely determined the run of sound speed from about 0.1 to 0.98 of the solar radius. This has allowed the determination of the equation of state, temperature and pressure throughout the solar interior. Comparison of the helioseismological inversion data with the most modern models of the solar interior (Schou *et al.* 1998) agrees to better than 0.2% almost everywhere in the solar interior. This has made the low level of the observed neutrino flux a problem in particle physics rather than in our understanding of stellar interiors. Shown in figure 1 is a plot of the difference between measurement and theory in the region from the deep interior to near the surface in the square of the sound speed. The region just below the convection zone has an anomalous jump in the difference between observation and theory that is taken as evidence of the site of the active-region dynamo.

The splitting of the oscillation frequencies allows the determination of the interior rotation profile. Although the rotational velocity cannot be determined very accurately below 0.1 solar radii, it is now clear that there is no significant angular momentum hidden in the solar interior. Figure 2 shows a plot of rotational period versus fraction of a solar radius for several latitudes. Note that the differential rotation penetrates to just below the bottom of the convection zone. This allows dynamo action to occur in the stable radiation zone. Arrows on the figure indicate the periods of surface rotation. These differ significantly from the rates at corresponding latitudes throughout the body of the convection zone. The different surface rate suggests that the active-region dynamo may only be connected to the surface for short periods of time (Schrijver & Title 1999). The rapid disconnection of the surface and subsurface fields helps to explain why the observed surface spreading of magnetic fields can be modelled by diffusion and surface flows alone.

Acoustic tomography, which is based on the correlation between velocities at sets of surface locations, is now being used to construct images of the temperature, pressure and sound speed in the top 10 000 km (between 0.98 and 0.995 of a radius) of the Sun. Half of the pressure drop in the convection zone occurs in this relatively thin shell. Of particular interest is how magnetic flux emerges and then disconnects from the flux tubes generated near the bottom of the convection zone. The shear across this region may be a source of energy for both large-scale flow systems and small-scale magnetic-field generation. Because of the sharp decrease in density, accurate numerical simulations are not yet possible. The production of good data across the shell from tomographic measurements may enable modellers to develop boundary conditions and appropriate approximations to make calculations tractable.

3. On the solar surface

Observations of the solar surface using real-time image selection, phase diversity, speckle interferometry and, most recently, adaptive optics have allowed measurements in exquisite detail (Berger *et al.* 1998) of the Sun's surface convective pattern and its evolution. Very recently, solar adaptive optics systems have emerged as operational systems and significant new results can be expected in the near future. Current data show that except in the vicinity of sunspots and pores the magnetic field is contained in the intergranular lanes. A variety of measurements both of images and spectra shows that the typical magnetic field strength is 1200 G and is contained in the 100 km-wide core of these lanes, so that the smallest observed flux elements are *ca.* 10^{17} Mx. Because the near-surface convection cells (granules) evolve on a time-scale of *ca.* 5 min, the small-scale magnetic-field pattern must also evolve on a similar time-scale. The edges of granules have a typical velocity of 2 km s^{-1} and may occasionally exceed the sound speed (10 km s^{-1}). As a result the magnetic flux elements at the cell edges are buffeted on time-scales of 10–50 s.

Numerical simulations of surface convection have reached a very high degree of sophistication (Stein & Nordlund 1998). Shown in figure 3 is a comparison of predictions of a numerical simulation and high-quality observations. Simulations show both the fragmentary character and the confinement of magnetic fields to the intergranular lanes (Blanchflower *et al.* 1998) by the convective flow. In all simulations of compressible convection vorticity is observed in the downflowing intergranular lanes (see figure 4). Vorticity has not yet been observed in the small magnetic features. However, the combination of adaptive optics and precision polarimetric spectra should soon provide evidence of the presence of vorticity and hence aligned currents in the magnetic structures. Given the presence of structured downflow columns in all of the simulations it would be surprising if twisted small-scale magnetic flux elements did not occur in the solar atmosphere. The interaction of the vorticity of the

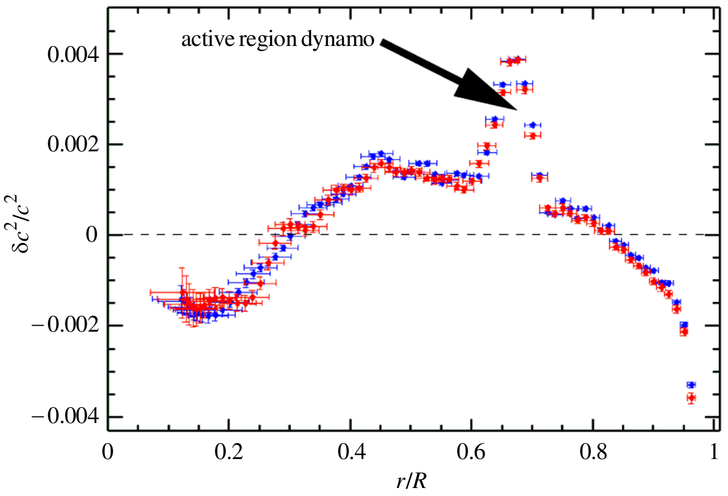

Figure 1. Plot of the difference between the measured and calculated square of the sound speed data from 0.1 to 0.95 of a solar radius. The two sets of inferred sound speed squared were obtained using different methods of obtaining the modal frequencies. The narrow peak in the difference occurs below the bottom of the convection zone.

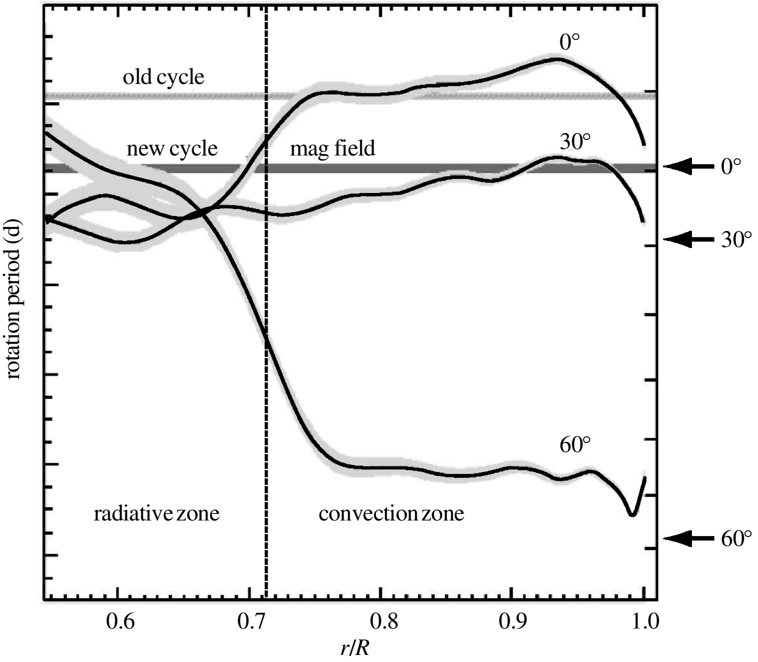

Figure 2. Plots of the solar rotation rate as a function of solar radius for latitudes of 0, 30 and 60°. Shown by arrows are the surface rates at 0, 30 and 60°. The horizontal lines show the mean rotation rates of old and new cycle magnetic fields during the period of MDI operations.

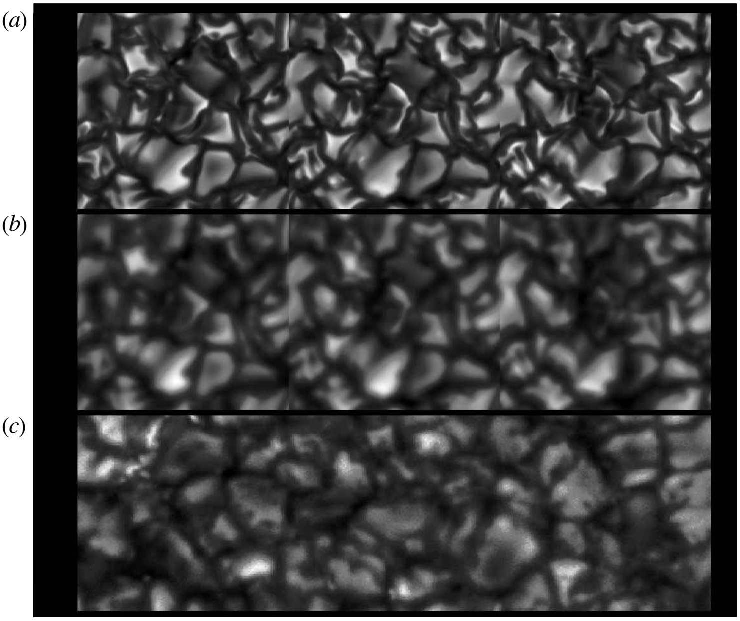

Figure 3. (*a*) A map of an instant in time of the surface continuum intensity from a time-dependent simulation of the top megametre of the convection; (*b*) the simulated continuum intensity map blurred by the modulation transfer function of a nearly perfect 50 cm telescope; (*c*) an image of the solar surface in an instant of excellent seeing using the 50 cm Solar Vacuum Telescope on La Palma.

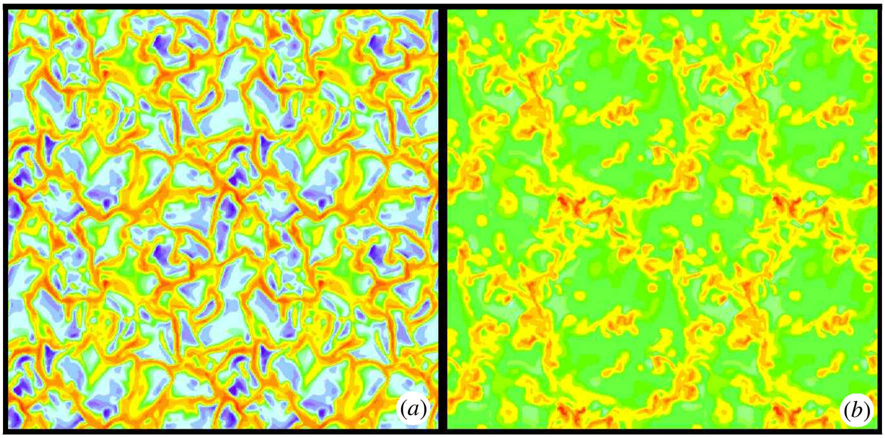

Figure 4. (*a*) The value of the local vorticity at the surface; and (*b*) at one megametre depth. Regions of high local vorticity are tinted in yellow–orange tones and low vorticity regions are tinted in blue–green tones. Regions of high vorticity are coincident with downflow.

downflow columns with the resulting twist of the magnetic flux tubes has not yet been observed, but it is a fascinating source of mechanisms for energy transport and release above the photosphere.

It has long been known that there is magnetic field nearly everywhere on the

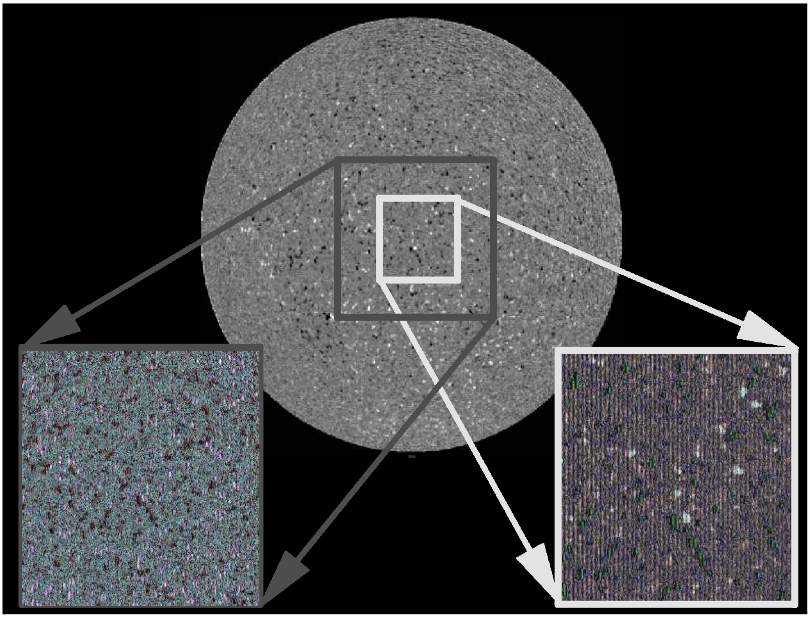

Figure 5. An MDI magnetogram. Regions of field strength of less that 5 G are shown grey, lighter (darker) regions have fields that point along (opposite) line of sight.

solar surface. In addition to sunspots and active regions, ephemeral regions occur on the scale of supergranulation (Harvey 1993); internetwork fields occur on the scale of mesogranulation (Martin 1988), and some fields even emerge on granular scales. Figure 5 shows the pervasive nature of the quiet Sun magnetic field. Figure 6 shows an example of ephemeral region flux emergence. Figure 7 is a time sequence of high-resolution magnetograms showing rapid flux appearance and disappearance on the spatial scale of a few arc seconds and a temporal scale of a few minutes.

Figures 6 and 7 demonstrate magnetic fields emerging and disappearing on the time-scales of convective patterns. This is a general property of the quiet Sun fields. The lifetimes of the magnetic structures are approximately the same as the convective structures with which they are associated. Until the flight of the magnetograph in the Michelson Doppler Imager (MDI) on the SOHO spacecraft it was difficult to accurately estimate either the amount or the rate of flux emergence in the ephemeral regions (Schrijver *et al*. 1997). This has now been shown to be 3×10^{21} Mx h^{-1}, which is sufficient to replace the quiet Sun magnetic field in *ca.* 40 h. In typical quiet Sun regions of more than a few tens of arc seconds the average absolute value of the magnetic flux density is in the range 2–6 G, while the mean magnetic flux density is in the range -0.4 to 0.4 G. The difference between the absolute and the mean flux density indicates the presence of a significant amount of mixed polarity field. In quiet Sun the net flux is one to two orders of magnitude less than the flux of either polarity.

Shown in figure 8 is a magnetogram overlayed by the boundaries of the convective flow pattern. First, the figure illustrates that the mixed polarity fields are in the supergranule boundaries. Second, the flow fields, the arrows on the diagram, imply that if the fields were not continuously replaced, then the flow along the boundaries

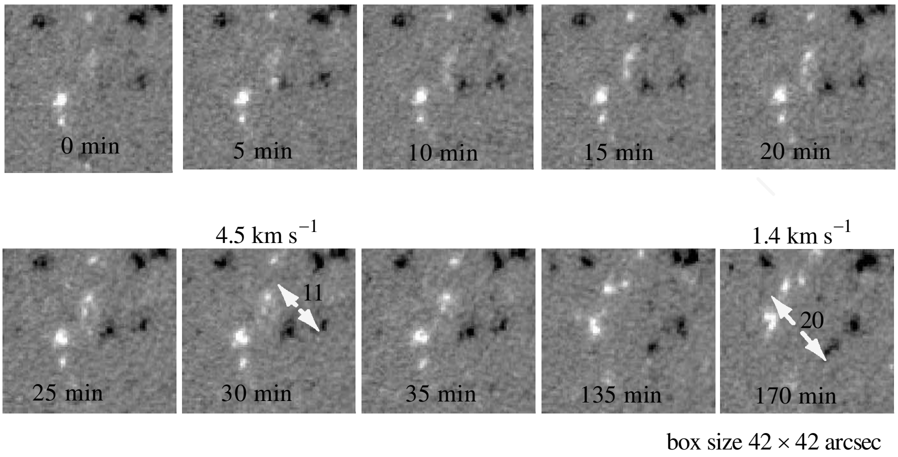

Figure 6. An MDI magnetogram time sequence showing the birth on an ephemeral region. The resolution of the images is 1.2 arcsec.

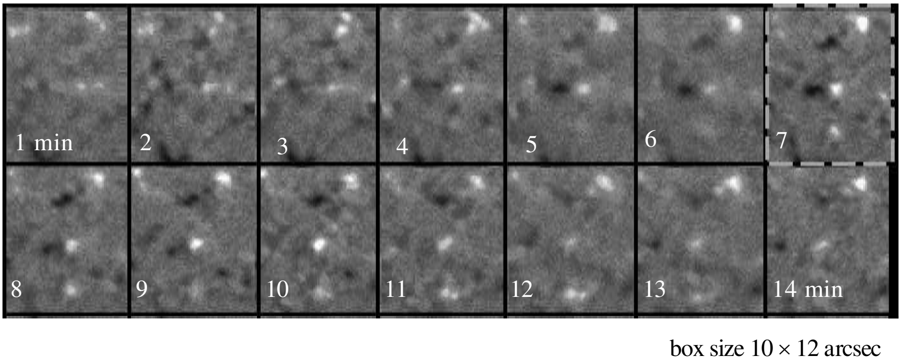

Figure 7. A La Palma magnetogram time sequence showing the appearance and disappearance of many magnetic elements. The resolution of the magnetogram is 0.3 arcsec. Note that the boxes are a factor of 15 smaller in area than those in figure 6 and span only 14 min of time instead of 170 min.

would sweep the mixed polarities together at a rate such that the total flux would drop by an order of magnitude in 20–40 h.

The mixed polarity field seen everywhere on the quiet Sun on the supergranular scale is called the 'magnetic carpet'. The carpet together with the supergranular flow field means that the average flux concentration in the quiet Sun only travels *ca.* 25 000 km, a little less than a supergranule diameter. As a consequence all field lines that connect into quiet Sun must reconnect on time-scales of at most a few days. In regions where there is a significant flux imbalance, such as active regions, the replacement time is longer—weeks to months. In addition the average flux concentration seen in MDI quiet Sun magnetograms has a size of a few arc seconds and a flux of 10^{18} Mx, which is 10 times that of the flux elements in the intergranular lanes, suggesting that all coronal fields may evolve on time-scales of a few minutes or less.

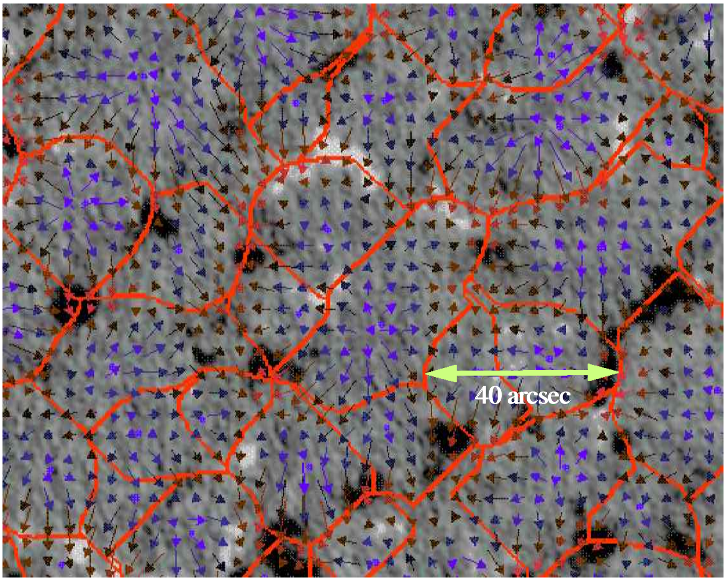

Figure 8. An MDI magnetogram overlayed by the boundaries of the supergranulation flow cells and an arrow field showing the directions and magnitude of the surface flow field.

4. Above the solar surface

The TRACE mission was constructed to observe, with high-resolution, rapid changes in the outer atmosphere and to associate these with events in the photosphere, chromosphere and transition region and in particular the photospheric magnetic fields. TRACE forms images over a temperature range from 4000 K to nearly 4 000 000 K. The normal time cadence for images in EUV lines, which span the temperature region from 600 000 to 4 000 000 K, is 20 s and visible and UV cadences, which span the temperature range from 4000 to 60 000 K, can be as fast as a few seconds (Handy *et al.* 1999). A primary result of the TRACE mission is that the transition region and corona are structured on a scale that is often limited by the telescopes' 0.5 arcsec (370 km on the Sun) pixel size. These fine structures are intermixed in temperature throughout the corona and they are almost never stationary. In some of the strong resonance lines there is sufficient density for significant scattering. That is, the assumption that the corona is always optically thin is not valid (Schrijver & McMullen 2000). Besides the emitting million-degree gases that define the corona, there is great deal of cool material (less than 30 000 K) intermixed throughout the outer atmosphere. The cooler gases are visible by the absorption of the EUV light from the million-degree gases. One of the most surprising results of TRACE has been the impossibility of tracing the connection between changes in the corona and the atmosphere below. At a few arc seconds resolution there is a clear association of the photospheric magnetic fields and the overlying coronal structures; however, the arc second resolution of TRACE shows that most loops are not connected to magnetic structures in the photosphere.

The fine structures seen in the TRACE images were anticipated both from the presence of the magnetic carpet and the images taken by the Normal Incidence X-ray Telescope (NIXT) (Golub *et al.* 1994). Because of the anchoring of the fields

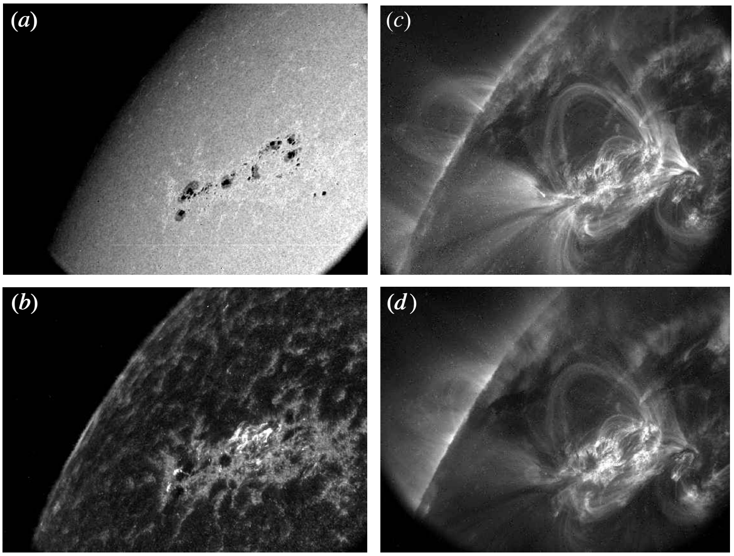

Figure 9. A sequence of TRACE images showing: (*a*) visible continuum; (*b*) UV continuum; (*c*) Fe IX, X at 1 000 000 K; (*d*) Fe XII at 1 600 000 K.

in the constantly churning convection zone, it should have been anticipated that all the coronal fine structure would evolve on time-scales of the granulation, *ca.* 5 min. (Little evolution had been noticed in the short duration of the NIXT rocket flights.) However, human imagination is no match for the wonders of nature and the movies produced by the TRACE instrument have forever destroyed the idea of a quiet uniform corona in an outer stellar atmosphere. A sampler of coronal dynamics movies is contained in a CD ROM published as a part of the TRACE first results paper (Schrijver *et al.* 1999). Shown in figure 9*a*–*d* are a sequence of images taken over a period of 2 min that exhibit the fine scale of the coronal temperature and density structure in the temperature range 4000–2 000 000 K.

5. Discussion

In the context of this discussion the most important lesson the Sun is teaching us is that the parallel development of quantitative measurements with numerical simulation and theory can produce a physical understanding of the complex phenomena that occur over a wide range in densities, pressures, temperatures and plasma betas and on a wide range of scales.

The magnetic carpet—ephemeral regions, on the scale of supergranulation; the weak internetwork fields, on the scale of mesogranulation; and the granulation scale fields strongly suggest that magnetic-field emergence and convective flow scales have a common origin. The question now is the physical reasons why the observed structural forms occur on the Sun. An easy answer is that we are just seeing multiple eruptions caused by convection of an underlying field generated by the deep dynamo. In the case of the ephemeral scale fields this can be shown to be false by the following simple argument. Interactions of two field concentrations of fluxes A and −B, A > B, will result in the disappearance of −B and leave a concentration of size (A−B), which is smaller in flux than A. If the pair B, −B reappears later, then the surface will have structures of size (A − B), B and −B. That is, the processes of merging flux will gradually grind the concentrations into smaller and smaller scales. The observed stable distribution function of flux concentration sizes requires that, at the very least, the small flux concentrations are replenished from beneath the solar surface.

Another possibility is that a significant fraction of the smaller-scale magnetic fields is generated by local dynamo action. Fast-dynamo action has recently been demonstrated in an incompressible simulation (Cattaneo 1999). As a result of the observations and the incompressible simulations, work on compressible simulations of fast dynamos is in progress in spite of considerable technical difficulties and the cost in computer time.

While the apparent complexity of the magnetoconvective process occurring below, in and above the solar surface is initially somewhat daunting, the magnetic interactions are mechanisms that have the capability of transforming significant amounts of both energy and momentum. The fast-dynamo simulations have yielded the result that the steady state magnetic field contains 25% of the energy in the convection. The energy stored in the ephemeral region flux is sufficient to heat the corona in the quiet Sun. The mechanisms, annihilation, reconnection, or waves, by which ephemeral fields are converted to heating of the corona are not yet known. By interacting with large-scale magnetic loops connecting widely spaced regions of different net polarity, the relatively small-scale ephemeral region reconnections can couple energy into larger-scale structures in a type of inverse cascade. Model calculations indicate that when the fast-surface and deep-active region dynamos interact the coupling can generate both the amplitude and the long- and short-period variations of the solar cycle. It is not unreasonable to assume that one or more fast-dynamo systems might couple with each other or larger-scale fields in other astrophysical domains (Schmidt *et al.* 1998).

I am indebted to the members of the MDI, TRACE and La Palma teams for the development and operation of their instruments, which produced many of the data discussed here. In particular, I acknowledge many interesting discussions with Karel Schrijver, Mandy Hagenaar, Theodore Tarbell, Richard Shine, Thomas Berger, Phillip Scherrer, Goran Scharmer, George Simon and Nigel Weiss. The MDI, TRACE, La Palma data analysis and operations are supported by NASA grant NAS5-30386 to Stanford University and NASA contract NAS5-38099 to Lockheed Martin Advanced Technology Center. Information about and data from MDI, TRACE and the ground-based observations at La Palma can be found at http://lmsal.com.

References

Berger, T., Lofdahl, M., Shine, R. & Title, A. 1998 *Astrophys. J.* **506**, 439.

Blanchflower, S., Rucklidge, A. & Weiss, N. 1998 *Mon. Not. R. Astron. Soc.* **301**, 593.

Cattaneo, F. 1999 *Astrophys. J.* **515**, 39.

Freeland, S. L. & Handy, B. N. 1998 *Solar Phys.* **182**, 29.

Golub, L., Zirin, H. & Wang, H. 1994 *Solar Phys.* **153**, 179.

Handy, B. (and 47 others) 1999 *Solar Phys.* **187**, 229.

Harvey, K. L. 1993 PhD thesis, Utrecht University.

Martin, S. F. 1988 *Solar Phys.* **117**, 243.

Schmidt, D., Schuessler, M. & Ferriz-Mas, A. 1998 *ASP Conf.* **54**, 1324 (CD ROM).

Schou, J. (and 23 others) 1998 *Astrophys. J.* **505**, 390.

Schrijver, C. J. & McMullen, R. 2000 *Astrophys. J.* (In the press.)

Schrijver, C. J. & Title, A. M. 1999 *Solar Phys.* **187**, 261.

Schrijver, C. J., Title, A. M., Hagenaar, H. J., van Ballegooijen, A. A. & Shine, R. A. 1997 *Astrophys. J.* **487**, 424.

Schrijver, C. J. (and 15 others) 1999 *Solar Phys.* **188**, 33.

Stein, R. F. & Nordlund, Å. 1998 *Astron. Astrophys.* **499**, 914.

Weiss, N. O. 1964 *Phil. Trans. R. Soc. Lond.* A **256**, 99.

Discussion

L. Harra (*Mullard Space Science Laboratory, University College London, UK*). The recent Yohkoh results of McKenzie and Hudson of an arcade flare on the limb show spines above the arcade. In your TRACE movie, it is very clear that the bright loops have a measurable separation. Is this equivalent to the separation of the spines, and have these spines been observed by TRACE?

A. Title. I really don't know. But direct comparison of Yohkoh and TRACE should answer this question. All these loops are essentially connected on the scale of the magnetic field on the surface, which is typically 3–4 arc seconds for local concentrations, so that's the typical scale. However, these are also three-dimensional structures, and it is not clear, especially when those nice dancing loops are shown, whether there are waves propagating through the structure that make the loops bright and then dark. Coordinated brightenings may result from a slowly travelling wave perpendicular to the structure.

E. R. Priest (*University of St Andrews, UK*). Can you explain the evidence against the suggestion that magnetic fields are simply bobbing up and down through the photosphere and continually being reprocessed?

A. Title. There is a detailed account in Schrijver *et al.* (1997). One can measure with MDI the surface distribution function and then essentially write down the statistical mechanics of collisions, fragmentations and the source function. You can't solve for the source function in all cases but you can put boundaries on it. You can show that, in order to maintain a distribution like this, the source function has constantly to input larger-scale structures. It is easy to understand why that is: whenever two magnetic field elements interact and disappear, what is left is smaller and so the process of constantly interacting magnetic fields in a convective flow generates smaller and smaller scales. Thus, you have to inject larger scales in order to maintain it. All of this has been looked at quite quantitatively by Mandy Haganar, who has just finished her PhD thesis.

B. Roberts (*University of St Andrews, UK*). You described the process of magnetic flux emergence and the idea of a magnetic carpet. Can he elaborate further on what he views the magnetic carpet to be, and how does it relate to Giovanelli's magnetic canopy?

A. Title. We don't know what the source of the magnetic carpet is, but certainly the calculations that Fausto Cattaneo has done suggest local dynamo action can occur in a convective flow. I don't think this has been proved, but if I were to bet, that's what I'd bet on. I wouldn't necessarily expect it to be caused only by granulation. Rather, I would think that every scale of convection that exists on the Sun would generate a magnetic field, the nature of which depends on the details of the convection.

B. Roberts. What about Giovanelli's canopy?

A. Title. In the quiet Sun the polarity is mostly mixed. That is, the total field with a resolution of about an arc second is one to two orders of magnitude greater than the net field. This means that most of the quiet Sun is covered with low, short loops. Giovanelli discussed a situation where the field in the surface is highly localized in largely unipolar vertical fields. Because of the rapid drop in pressure with height the fields rapidly spread laterally to form a canopy. At the height of a few thousand kilometres the magnetic geometry is very similar. The fields are nearly parallel to the surface and rapidly changing in direction, but the topology of the fields is fundamentally different.

I. W. Roxburgh (*Queen Mary and Westfield College, London, UK*). What might you find when you have a higher resolution?

A. Title. I really don't know. We designed TRACE specifically to examine the consequences of the carpet and we're constantly surprised by the things we see, so whatever I say ought to be taken with that thought in mind. But all of the numerical simulations will lead you to believe that there is twist, a vorticity, in all of these flux tubes which you don't see at all so far. Now the problem that I see is that we are not beginning yet to see the nature of the interaction between twisted flux tubes—the basic interaction on the smaller scale—and my concern is that these things happen sufficiently fast that there aren't enough photons in that process to see it in a reasonable exposure time. So, what I would say is that, if it were possible to observe this at the natural scale on which these phenomena occur, we'd see a whole new and exciting regime. I don't know how far we can pursue that with current technology but we'll certainly explore it.

E. R. Priest. My initial impression looking at some of these very fine-scale loops with TRACE is that there is very little evidence of braiding at all; has that actually been analysed quantitatively? And is my impression correct?

A. Title. Yes, braiding is rather rare, but we have not yet begun a systematic study. It's not a pervasive phenomenon. You have to remember, though, looking at these pictures, that magnetic field must exist everywhere and we're seeing things largely because of only small density fluctuations. We're just beginning to learn how to look at these pictures and to interpret them.