to know how critically their solution depends on the assumed values of some of the physical properties of the Earth's core and on the basic assumptions of their method.

Buffett *et al.* conclude that compositional and thermal buoyancy fluxes in the outer core are of comparable magnitude. In this regard, Stevenson *et al.*[7] suggested that the mode of powering the geodynamo may have changed during geological time. In the Earth's early history, the magnetic field was generated by thermal convection. After nucleation of the inner core (which they estimate to have happened 1,500–2,500 million years ago), the release of gravitational energy became the dominant source. It is interesting to speculate that the reason that Mars and Venus have essentially no magnetic field is that they do not have an inner core. □

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1. Buffett, B. A., Huppert, H. E., Lister, J. R. & Woods, A. W. *Nature* **356**, 329–331 (1992).
2. Lehmann, I. *Bur. Centr. Seismol. Int.* A**14**, 3–31 (1936).
3. Oldham, R. D. *Q. Jl geol. Soc. Lon.* **62**, 456 (1906).
4. Birch, F. *Am. J. Sci.* **238**, 192–211 (1940).
5. Kelvin, Lord *J. Victoria Inst. London* **31**, 11–35 (1899).
6. Gubbins, D., Masters, T. G. & Jacobs, J. A. *Geophys. J. R. astr. Soc.* **59**, 57–99 (1979).
7. Stevenson, D. J., Spohn, T. & Schubert, G. *Icarus* **54**, 466–489 (1983).

ASTRONOMY

Convective motion on the Sun

Nigel Weiss

HIGH-resolution observations are revealing the pattern of convection at the surface of the Sun. On page 322 of this issue[1], Muller *et al.* describe white-light observations made during an interval of exceptionally clear seeing at the Pic du Midi Observatory in the French Pyrenees. For a period of 3 hours they obtained images that were virtually unaffected by atmospheric distortion, so that resolution was limited only by the aperture of the telescope. This is the best sequence so far obtained and, after digital processing at the Lockheed Palo Alto Research Laboratory, it provides fascinating details about the structure of solar convection.

Seen in white light, the solar photosphere shows the well-known granulation first observed by William Herschel almost 200 years ago. Individual bright granules are surrounded by a network of cool, dark material and are separated by distances of 1,000–2,000 kilometres; the hot, bright material is rising and the cool material is sinking, so these cells are evidence of convection, which carries energy up to just below the visible surface[2]. By following the proper motions of individual granules, larger-scale cellular patterns (mesogranules and supergranules) can be detected. The new observations show how these structures evolve.

For the first time it is possible to explore the relationship between them, which provides clues to understanding the structure of convection deep below the surface. Explaining these velocity patterns is important not only in itself but also because of their interactions with solar oscillations and with magnetic fields. Although the Sun is the only star where such motions can be observed in detail, similar behaviour must occur in other cool stars. Moreover, the Sun is a unique laboratory for studying turbulent magnetoconvection in physical conditions that are unobtainable on Earth.

Techniques for processing such data were first developed at Lockheed in connection with the Spacelab-2 mission in 1985, but the data sets obtained then were limited to 28 minutes by the orbital period of the satellite. After aligning and 'destretching' the images it is necessary to eliminate distortion caused by solar oscillations with periods around 5 minutes. This is done by Fourier-analysing the data in two space dimensions and time, and then filtering out all supersonic variations. The resulting images are so clear that it is possible to track the proper motions of granules and hence to determine large-scale velocity patterns[3,4]. These methods have firmly established the existence of three different non-overlapping scales of motion: in addition to granules there are mesogranules, with a characteristic diameter of 3,000–10,000 kilometres, as well as the supergranules, with diameters around 30,000 kilometres, which are outlined by weak magnetic fields and have been known for 30 years.

Measurements of mesogranular velocities are complicated by the presence of exploding granules. These are particularly vigorous granules, which expand rapidly, displacing their neighbours, until they develop a cool core and break up. The Spacelab-2 observations showed that exploders occur preferentially near the centres of mesogranules and raised the possibility that mesogranular motion might be just the cumulative effect of these exploders[4]. Careful inspection of the new data from the Pic du Midi indicates, however, that individual exploders move in a systematic mesogranular velocity field and that mesogranules survive for several hours, much longer than the lifetimes of exploders[5]. Apparently both structures contribute to the measured motion and it seems likely that they are symbiotically linked[6].

Even more interesting is the relationship between mesogranules and the long-lived supergranules. The 3-hour run shows that mesogranules appear near the centre of a supergranule and are transported towards its boundaries, where they are destroyed. This is the most important result in the new paper. How should it be explained? One possibility is that these patterns represent two distinct scales of motion; another, perhaps more plausible, is that mesogranular motion is caused by parasitic instabilities of thermal boundary layers in supergranular convection cells[6].

What can be learnt from these observations about the structure of convection below the visible surface? Numerical experiments confirm that the stratification favours broad upwellings surrounded by rapidly sinking sheets which are focused into isolated plumes[7–9]. One possibility is that the plumes merge to give a continuously varying self-similar structure[7]. Another, suggested by the surface observations, is that there are coherent structures with separate scales. In that case, one might hope to detect structures with diameters comparable with the depth (200,000 kilometres) of the convection zone — but such giant cells have not been found. It now seems more likely that isolated supergranular plumes can sink almost to the base of the convection zone[6].

It is essential to provide a proper theory of stellar convection which is able to describe the velocity structures observed at the surface of the Sun. Only then will it be possible to explain the differential rotation profiles derived from helioseismology. If that is achieved, the next goal will be to produce a realistic model of the solar dynamo, which is responsible for magnetic activity in the solar atmosphere, including sunspots[10] and flares[11], which are being observed with ever-increasing precision. □

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1. Muller, R. *et al. Nature* **356**, 322–325 (1992).
2. Stix, M. *The Sun* (Springer, Berlin, 1989).
3. Simon, G. W. *et al. Astrophys. J.* **327**, 964–967 (1988).
4. Title, A. M. *et al. Astrophys. J.* **336**, 475–494 (1989).
5. Simon, G. W., Title, A. M. & Weiss, N. O. *Astrophys. J.* **375**, 775–788 (1991).
6. Simon, G. W. & Weiss, N. O. *Mon. Not. R. astr. Soc.* **252**, 1p–5p (1991).
7. Stein, R. F. & Nordlund, A. *Astrophys. J.* **342**, L95–L98 (1989).
8. Spruit, H. C., Nordlund, A. & Title, A. M. *A. Rev. Astr. Astrophys.* **28**, 263–301 (1990).
9. Cattaneo, F. *et al. Astrophys. J.* **370**, 282–294 (1991).
10. Livingston, W. *Nature* **350**, 45–46 (1991).
11. Golub, L. *et al. Nature* **344**, 842–844 (1990).