The subsurface structure of a sunspot, with the magnetic field extending upwards and outwards from the visible surface. The short, straight arrows indicate the fluid motion deduced from tomography, flowing inwards and then downwards between the separate magnetic flux bundles.

Duvall *et al.* report the first observational look at the fluid motions beneath the visible surface. Their analysis concentrates on an active region of the Sun, and shows a downward flow travelling at 2 km s^{-1} to a depth of 2,000 km beneath a sunspot, implying the radial inflow predicted by theory. The extension of the inflow to the central region under the spot implies that the magnetic field at depths of $\sim 1,000 \text{ km}$ is separated into many intense flux bundles⁵, to allow the inflow to stream through the relatively field-free interstices (see figure).

The downflow was detected by looking at solar vibrations. The continual turbulent convection within the Sun is a source of sound waves, exciting thousands of modes of oscillation. Conventional helioseismology studies the density, temperature, mean molecular weight, and rate of rotation of the Sun as a function of depth by precise measurement of the frequencies of these modes, but it cannot give information about the local fluid motion. In contrast, helioseismic tomography can discern the fluid motion by measuring the correlation of acoustic motions at many pairs of points on the surface of the Sun. The ray path and transit time by which a sound wave propagates from one point to another can be calculated from the known temperature and molecular weight. A delay indicates a head wind somewhere along the ray path, and an early arrival indicates a tail wind.

The effect of a magnetic field is somewhat more complicated, as it increases the sound speed perpendicular to the field but not parallel. Using a computer to compare the thousands of pairings between many points allows construction of a map

of fluid velocity as a function of depth below the surface, as well as providing basic information on the form and strength of the mean magnetic field.

Sunspot dynamics are beginning to come under the direct eye of observation. The authors emphasize that this initial breakthrough is only the first exploratory application of tomographic analysis to the activity within the Sun. Observations are possible at substantially higher resolution and to greater depth. Such observations are needed, for the convection beneath the surface of the Sun is a magnetohydrodynamic jungle. It is conjectured that the complicated magnetic field observed at the surface of the Sun is an indication that the flux tubes (or 'fibrils') are in a

complex tangled state throughout much of the convective zone, extending to a depth of about $2 \times 10^5 \text{ km}$. The field intensity, characteristic diameter and degree of entangling of the fibrils is not known, so there is no way to calculate the details of their dynamic interaction with each other and with the fluid. Yet the generation of the magnetic fields responsible for the sunspot cycle and for the associated 11-year variation in brightness depends critically on the mean motion and interaction of individual magnetic fibrils. It is their buoyancy and convective transport that are responsible for flares, extreme ultraviolet emission, X-rays, the corona and the solar wind.

Then when we reflect that the Sun is just an average main sequence star, it becomes clear that until we understand it, we understand little of other stars. There is also the practical need to understand the effects of solar variation on our climate. Helioseismic tomography is a promising step in probing the magnetic jungle that has so much to do with the various forms of energy output of the Sun. □

Eugene Parker is at the Enrico Fermi Institute, the Department of Physics and the Department of Astronomy, University of Chicago, Laboratory for Astrophysics and Space Research, 933 East 56th Street, Chicago, Illinois 60637, USA.

1. Hale, G. E. *Astrophys. J.* **28**, 100, 315 (1908).
2. Duvall, T. L. Jr, D'Silva, S., Jefferies, S. M., Harvey, J. W. & Schou, J. *Nature* **379**, 235–237 (1996).
3. Biermann, L. *Vierteljahrsschr. astr. Ges.* **76**, 194 (1941).
4. Meyer, F., Schmidt, H. U., Weiss, N. O. & Wilson, P. R. *Mon. Not. R. astr. Soc.* **169**, 35 (1974).
5. Parker, E. N. *Astrophys. J.* **230**, 905–913 (1979).

DAEDALUS

War studies

J. B. S. HALDANE once claimed that a democratic election predicts the result of a civil war without having to fight one. He was oversimplifying. A war, civil or otherwise, is a competition for territory between rival tribes. A true substitute for war would have to predict, not just the 'winner', but also the final boundary between the tribes. Even the recent Bosnian settlement had to reflect roughly the military gains of the competing tribes. Daedalus wants to determine such gains not by war, but by war gaming.

All professional armies these days conduct simulated computer exercises: not silly shoot 'em up arcade games, but complex, serious simulations. The best of them can model a battle on difficult terrain between forces with men and weapons of disparate strengths and weaknesses, and predict the likely outcome. Daedalus wants a really big modelling program of this sort to be developed, and put at the disposal of the United Nations.

International mediation would be transformed. Instead of its blundering insertion of token forces, the UN would use satellite intelligence and ground observers to assess the whole situation. It would run the simulation, and predict the outcome. It could then say to the two sides: "This is what will happen. Instead of expending vast amounts of blood and treasure proving it, why not accept the result, and save yourselves the trouble? Redraw the tribal boundaries from our computer output, exchange whatever populations would have been uprooted, and resume peaceful coexistence".

The biology of the proposal is sound; our cousins the apes do something like it already. Their rival tribes howl and threaten each other along their mutual territorial boundary, and the display predicts for both parties the result of a fight without the nuisance of having one. Computer war-simulation will do the same for us. Much development, however, will be needed to make it credible. For a start, it will have to replicate the early skirmishes before the UN was called in. Fortunately it need not be perfect. Much of the optimized final boundary will be insensitive to small errors: it will lie along stable, easily defended rivers, mountain ridges and so on. In any case, a small needless loss of territory is preferable to a crippling fight for a bit more. The big power blocs of the Cold War world are now breaking up into ever more squabbling tribes, each demanding its own territory and certain to be a permanent nuisance till it gets it. Daedalus's computer war-simulator should minimize the misery of the transition.

David Jones