PERSPECTIVES: SOLAR PHYSICS

Order Amidst Turbulence

Juri Toomre

The Sun's magnetic field has profound impacts on our high-tech society. The energetic particles of the solar wind, coronal mass ejections, and explosive flares are all linked to changes in the magnetic fields that pervade the solar atmosphere. Such events can short-circuit satellites in space and darken power grids on the ground. Yet the origin of the solar magnetic fields remains a puzzle.

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The fields can be ordered on some scales and chaotic on others. During 22-year cycles of global magnetic activity, temporary magnetic disturbances (sunspots) erupt according to well-defined rules for field parity and latitudes of emergence. Compact, intense magnetic structures coexist with these large-scale ordered fields, but emerge randomly over much of the Sun's surface with little regard for the solar cycle. At both scales, the fields are probably generated in the deep shell of turbulent convection below the Sun's surface.

Helioseismology uses the acoustic waves that travel through the Sun to measure its interior properties, much like terrestrial seismology. Such studies have played a pivotal role in providing clues about how a large-scale dynamo may operate deep within the Sun to produce the ordered magnetic fields. On page 101 of this issue, Vorontsov *et al.* (*1*) take helioseismology an important step further. Applying new inversion techniques to frequency splittings of solar global acoustic modes, they reveal that localized variations in the Sun's differential rotation, called torsional oscillations, propagate in latitude along two branches—poleward and equatorward—as the solar magnetic cycle advances. Some of the rotational features appear to behave coherently over the full depth of the Sun's convection zone.

Early helioseismic studies provided evidence for a transition layer of strong radial and latitudinal shear at the base of the convection zone. This "tachocline" (*2*, *3*) separates the pronounced differential rotation with latitude throughout the convection zone (*4*, *5*) (which occupies the outer 29% by radius) from the apparently uniform rotation of the deeper radiative interior. The tachocline may be where the global dynamo operates, using the rotational shear to build up large-scale fields.

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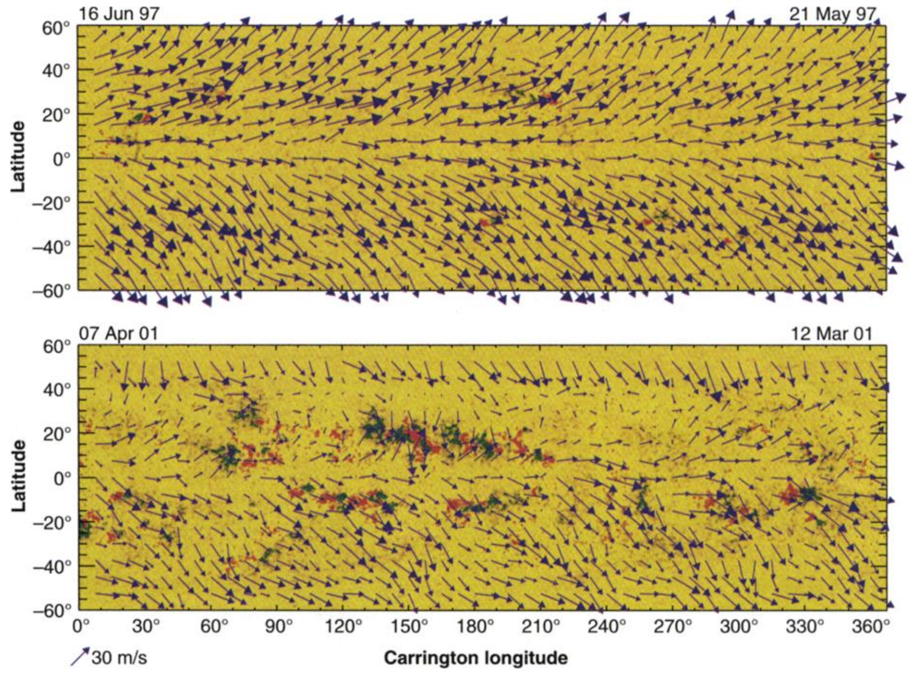
A possible signature of such dynamo action may be the recent helioseismic detection of changes in rotation rate near the equator that are in antiphase above and below the tachocline (*6*). The migrating bands of faster and slower rotation, and the more pronounced variations in rotation near the tachocline, are examples of coherent global responses that exist amidst the intense turbulence. The causal relations between the global dynamo and these evolving flows are still uncertain, but their presence places substantial constraints on how angular momentum can be redistributed as the magnetic cycle progresses.

Helioseismic studies have shown that the large-scale flow fields in which the coherent responses are embedded are highly complex. By mapping much of the solar disk as rotation brings new sites into view, synoptic maps of horizontal flows in the upper reaches of the convection zone have been constructed for individual rotations (see the figure) (*7*). The maps reveal remarkable weatherlike patterns, called Solar Subsurface Weather (SSW), including intricate meandering flows that may be associated with the largest scales of deep convection, evolving meridional cells with reversing circulations, and propagating banded flows.

As magnetic activity intensifies with advancing solar cycle, the flows clearly sense the presence of the active regions. The flow maps provide evidence for considerable symmetry breaking in the northern and southern hemispheres over the past 4 years of the solar cycle. The flows measured by Vorontsov *et al.* are spatial and temporal averages of the complex motions within the convection zone. The global modes that they use provide only the latitudinally symmetric component of the zonal flows. The actual behavior of the bands of slower and faster rotation may differ in the two hemispheres.

Because of the high electrical conductivity of the plasma that makes up much of the solar interior, fluid motions, electrical currents, and magnetic fields should be interminably linked. Strong fields can grow as a result of vigorous stirring even from a feeble seed magnetic field. Such small-scale dynamo action within the intense turbulence of the convection zone may yield the observed chaotic fields. Generation of the powerful and ordered fields, such as the toroidal flux tubes that break through the solar surface to form sunspot pairs, may require a more complex process.

The global dynamo is now thought to involve several elements working in concert (*8*, *9*). The building of strong toroidal fields would occur in the tachocline, where the prominent rotational shear can stretch



Solar current events. Synoptic maps with latitude and longitude of the horizontal flows of SSW at a depth of 10,000 km, deduced from localized helioseismic probing. Two complete solar rotations are shown, the upper from 1997 when the Sun was relatively quiet and the lower from 2001 when the Sun was magnetically active. Underlying these flow maps are surface magnetic field patterns (red and green indicate opposite polarity). All velocities are relative to the surface differential rotation rate.

CREDIT: D. A. HABER, B. W. HINDMAN/UNIVERSITY OF COLORADO poloidal magnetic fields (which are oriented in meridional planes and brought downward by the convection) into gradually intensifying toroidal fields. As a result of the stable density stratification in the tachocline, the toroidal fields can reside in the tachocline for some time before magnetic buoyancy and other instabilities disrupt these flux concentrations and drag them upward until they ultimately emerge as loops at the surface. The weaker poloidal field is thought to be regenerated either in the convection zone through cyclonic turbulence or near the surface through the breakup of twisted active regions. The turbulent convection will pump the poloidal field back into the tachocline to continue the overall process of large-scale field generation.

Recent mean-field dynamo models (*10*, *11*) have shown that an interface dynamo, in which the toroidal and poloidal fields are generated in separate regions, can produce field strengths similar to those inferred from observations. Advances in massively parallel supercomputing are gradually allowing more realistic three-dimensional simulations of the essential components of the global dynamo. Detailed models are emerging for how turbulent convection in spherical shells redistributes angular momentum to yield a pronounced differential rotation (*12*), and how magnetic fields can be pumped downward by the strong downflow networks inherent in compressible convection (*13*).

The continued interplay between helioseismic observations and theoretical modeling will be crucial for gaining a detailed understanding of the Sun's magnetic cycles. The helioseismic discovery of the tachocline has forced profound changes in solar dynamo models. The temporal variations revealed by the new generation of helioseismic instruments are now showing that large-scale ordered and evolving flows accompany the magnetic changes (*1*, *6*, *7*). There are likely to be other surprises as such probing continues throughout a solar cycle.

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PERSPECTIVES: COLLOIDAL SYSTEMS

Playing Tricks with Designer "Atoms"

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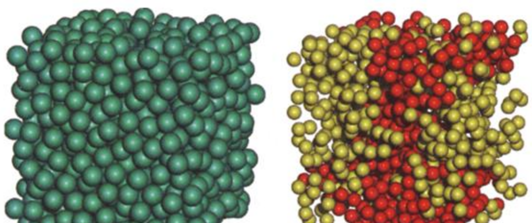
Tailor-made, submicrometer particles will be the building blocks of a new generation of nanostructured materials with unique physical properties. Two articles in this issue on pages 106 and 104 (*1*, *2*) show how the macroscopic physical properties of colloidal suspensions—solutions of particles with diameters ranging from tens of nanometers to micrometers—can be influenced dramatically by tuning the interactions between their building blocks. This work is not only important for materials science. It also allows us to address some longstanding fundamental questions about the nature of liquids, crystals, and glasses.

Just over a century ago, J. H. van't Hoff received the first Nobel prize in Chemistry for his groundbreaking work on osmotic pressure. He had found that the osmotic pressure of dilute solutions depends on the concentration of dissolved molecules, in the same way that the pressure of a gas depends on the concentration of gas molecules. Subsequent theoretical work by Onsager (*3*, *4*) and others showed that the analogy that van't Hoff had noted for dilute solutions is valid at arbitrary densities. This implies that, just as atomic gases may condense at high pressures to form a liquid and eventually a solid, macromolecules in solution may undergo a transition to a "liquid" or "crystalline" solution state at sufficiently high osmotic pressure.

This phenomenon is often observed in colloidal suspensions. Although colloidal particles are much larger than atoms (a micrometer-sized colloid may contain billions of atoms), they nevertheless exhibit the same phases as, say, argon: vapor, liquid, and crystal. Like simple molecules, the phase behavior of macromolecules in solution is completely determined by the nature of the forces acting between the constituent particles.



Snapshots of computer-generated repulsive and attractive glasses. The repulsive glass **(left)** was generated by compressing a system of hard spheres to a volume fraction of 59%. The particles can only move in "cages" formed by their neighbors. The attractive glass **(right)** was generated at a much lower volume fraction (22%) by introducing infinitely short-ranged ("sticky") interactions between the hard colloidal spheres. The particles shown in red all belong to a single percolating cluster and cannot move at all. This extreme example illustrates the fact that, in an attractive glass, the particles are more strongly confined than in a repulsive glass, even though the overall density of the attractive glass may be much lower.

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This is where matters become interesting. The forces acting between small, spherical molecules all depend in a qualitatively similar way on intermolecular separation. As a result, all such substances exhibit very similar phase behavior, an observation already quantified in 1880 by Van der Waals in his "Law of Corresponding States." If the forces between macromolecules in solution were similar in shape to those between gas atoms, then all colloidal suspensions would exhibit the same phase diagram as an assembly of argon atoms. However, the forces between macromolecules in solution come in all sorts and shapes. Furthermore, we can "tune" these forces by choosing an appropriate combination of solvent, solute, and additives. Hence, far from being simply a scale model for atomic fluids, colloidal suspensions can form new states of matter, the building blocks of which are large "designer atoms."

With such tailor-made colloids, we can investigate some longstanding questions. For instance, what happens to the freezing transition if all attractions between the colloidal particles are switched off? This question was first addressed systematically in the 1950s by computer simulations (*5*, *6*). The answer—no attraction is needed for freezing—is somewhat counterintuitive because a crystal phase formed by colloids that behave like hard elastic spheres ("hard-core colloids") has a higher entropy than the liquid phase at the same density. Yet it was confirmed in experiments on hard-core colloids (*7*).

Subsequent experiments (*8*) showed that mixtures of large (L) and small (S) hard-sphere colloids could form surprisingly complex

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