PERSPECTIVES: SOLAR PHYSICS

News from the Solar Interior

Douglas Gough

The solar magnetic field changes dramatically over a 22-year cycle, as evinced by cyclical changes in the number and location of sunspots. This magnetic activity is commonly thought to be controlled in a thin shear layer in the solar interior, called the tachocline (*1*). On page 2456 of this issue, Howe *et al.* (*2*) report the first direct observations of dynamic activity near the tachocline, but the form of that activity comes as a surprise.

A view into the solar interior is made possible by the use of helioseismology (*3*), which measures the acoustic waves that propagate through the sun. From the data, information about temperature, composition, and motions can be extracted. For example, the angular velocity Ω in the solar interior can be inferred from the splitting by rotation of otherwise degenerate frequencies of global oscillations. It turns out that the latitudinal variation of Ω at the surface of the sun is largely maintained throughout the convection zone (see the figure). Immediately beneath that zone, however, there is an abrupt transition to essentially uniform rotation in the radiative interior. The transition region, known as the tachocline (*4*), is believed to extend through only a few percent of the solar radius, too thin to be resolved directly (*2*). Its existence is attributed to the abutting of the convection zone with the relatively quiescent radiative interior (*5*).

The mechanism of the solar cycle is not understood, but the many nascent theories all have a common theme (*6*). A relatively weak magnetic seed field whose field lines lie in a poloidal plane—a plane through the axis of rotation—is believed to migrate into the tachocline, having either been forced downward from the convection zone by the turbulent motion or, more likely in my opinion, by diffusing outward from the radiative interior. The varying speed of angular rotation in the tachocline causes the field to be stretched in the toroidal direction until it becomes buoyantly unstable, breaks away, and rises through the convection zone, rotating on its way to develop again a poloidal component that exceeds the initial poloidal seed. It finally emerges at the photosphere—the visible surface of the sun—to produce the host of magnetic phenomena that we observe, including sunspots. In the process of toroidal stretching in the tachocline, Lorentz forces are generated that oppose the shear, causing it to wane. These forces are released when the toroidal field breaks loose, and the shear returns to its initial state. One would therefore expect the tachocline shear to vary on the time scale of the solar cycle, probably with the 11-year period of the sunspot cycle (*7*).

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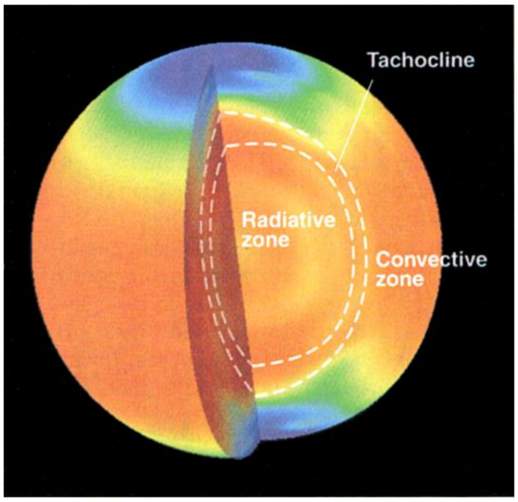
To test those ideas, evidence for temporal variation in the sun's angular velocity has been sought in helioseismic data. Indications were found during the rising phase of the last sunspot cycle (*8*), but the temporal resolution was too poor to follow the variation in detail. Data have now been obtained continuously for 4.5 years, and Howe *et al.* (*2*) have analyzed them to discover oscillations in the angular velocity immediately above and, at low latitudes, also below the tachocline. But the period of the oscillations they observe is not 11 years; indeed, the 4.5-year interval is insufficient to establish such a period. Instead, Howe *et al.* found a distinct periodic 1.3-year oscillation in the equatorial regions and a more complicated variation with a dominant period of 1.0 years at high latitudes. In the equatorial region, where the tachocline shear is positive (Ω increases outward), the oscillations above and below the tachocline are in antiphase, implying an oscillation in the tachocline shear. At latitudes near 60°, where the tachocline shear is negative, oscillations are perceptible only above the tachocline, in the convection zone. In both cases, the amplitude of the oscillation (maximum deviation from the mean) is about 10% of the jump in Ω across the tachocline at the latitude of the oscillation. The small 1.3-year signal observed at intermediate latitudes, near 30° where the sign of the tachocline shear reverses, is likely to be contamination from the equatorial oscillation, because the seismic measures of angular velocity are averages over finite regions in latitude (and radius).

These findings are surprising. Evidently they are not connected to the 11-year cyclic variation in an obvious way. Moreover, the different periods at low and high latitudes suggest separate—or weakly coupled—oscillators. What is the force that tends to restore the oscillator to its equilibrium position when it is disturbed? And what may be the driving mechanism?

Howe *et al.* (*2*) suggest that the restoring forces at both high and low latitudes are Lorentz forces. If that is so, the period of oscillation would be determined basically by twice the time it takes for an Alfvén wave (*9*) to propagate between the radii of the antinodes of oscillation (and is not explicitly dependent on latitude). This can be measured only for the low-latitude oscillator, for which antinodes can be seen both above and below the tachocline. The observed period and the distance separating the antinodes thus imply that the radial component of the magnetic field threading the tachocline is about 500 G. In half a sunspot-cycle period, the tachocline shear



The rotation of the solar interior. Representation of the angular velocity in the sun obtained from the Solar Oscillations Investigation on the Solar and Heliospheric Observatory (SOHO) (*12*). Red is fast and blue is slow. The tachocline is clearly seen near the base of the convection zone, at a distance of 70% of the solar radius from the center, beneath which the rotation appears to be almost rigid.

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would intensify that field perhaps sixfold, yielding 3000 G, which is comparable to the values estimated to induce buoyancy instability and, incidentally, is the strength of the field observed in sunspots. It is interesting to note that, to a first approximation, the oscillation period does not change as the field in the tachocline is intensified by the tachocline shear; the increased Alfvén velocity is compensated by the increased propagation path length.

It is a property of purely magnetic oscillations that are confined to the stably stratified radiative interior that they propagate around closed field lines and therefore suffer phase mixing and catastrophic dissipation (*10*). The connection of the field to the adiabatically stratified convection zone might provide a degree of global coherence, as in the case of a uniform liquid globe (*11*). Nonetheless, the tendency toward phase mixing may generate large gradients in the radiative zone, which could lead to instabilities causing slow vertical mixing. It could be this process that leads to the lithium destruction that, as Howe *et al.* point out, is required to explain the depleted photospheric abundance of lithium. It seems most likely that the oscillations are driven by direct interaction with the convection, particularly because of the need to provide energy to compensate for the dissipation from phase mixing. Angular-momentum transfer by rotationally modulated gravity-wave dissipation in the stably stratified radiative zone also comes to mind, but this can hardly explain the high-latitude oscillation in the convection zone, unless it is somehow coupled to the equatorial oscillation. An alternative interpretation of the nature of the oscillations is that the observed signal is the axisymmetric signature of nonaxisymmetric nonlinear inertial oscillations in the convection zone, whose restoring force comes from vortex stretching. It is unlikely, however, that such modes could penetrate into the radiative interior without a magnetic connection.

These comments may contain the germ of an explanation of the new observations, but much is left unexplained. For example, why are there apparently independent oscillators at high and low latitudes? And why are the high-latitude oscillations apparently confined to the convection zone? The helioseismic inversions reported by Howe *et al.* provide only an average of the motion in the northern and southern hemispheres. The complexity of the high-latitude oscillations might therefore be partly a result of a superposition of two or more disconnected and somewhat different oscillators in the two hemispheres. One might also expect the amplitudes and perhaps the locations of the oscillations to vary over the sunspot cycle and possibly also to see a superposed solar-cycle oscillation in Ω. To address these and other pertinent issues, the observations must be extended over at least a whole 22-year cycle.

The principal lesson from these new results is that the sun is dynamically more active than often assumed. In common with previous discoveries about the internal rotation—such as the latitudinally propagating subphotospheric zonal flows, the anomalously slow polar rotation, and the possibly slowly rotating core—it was not anticipated. We must therefore regard with considerable caution any inference about the internal structure of the sun, or of any other star, that is derived from the presumption that radiative zones are quiescent.

References and Notes

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7. Sunspots arise whatever the polarity of the solar magnetic field; alternate 11-year sunspot cycles have opposite polarity, yielding a 22-year magnetic cycle.
8. D. O. Gough *et al.*, in *Inside the Stars*, W. W. Weiss and A. Baglin, Eds., vol. 40 of Astronomical Society of the Pacific Conference Series (Astronomical Society of the Pacific, San Francisco, 1993), p. 304.
9. An Alfvén wave is a wave in the field lines that propagates at a speed proportional to the field strength and inversely proportional to the square root of the density of the material in which the field is embedded.
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PERSPECTIVES: STRUCTURAL BIOLOGY

Bit Players in the Trombone Orchestra

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Semiconservative DNA replication, the process by which prokaryotes and eukaryotes copy their DNA, depends on the activity of enzymes called DNA polymerases. Two identical DNA polymerases operate at each "replication fork"—the moving junction of double-stranded DNA where two new strands of complementary DNA are made. One of the enzyme pair synthesizes the leading DNA strand and the other the lagging strand (see the figure). But how are the activities of the two DNA polymerases coordinated, and what tells them when to start and when to stop? This responsibility falls to a cadre of bit players (auxiliary replication proteins) that are essential to the success of the overall replication enterprise (*1, 2*). One of these bit players is the replication primase, and the molecular structure of its polymerase domain is described by Keck *et al.* (*3*) on page 2482 of this issue. This report and other recent biochemical and mechanistic studies (*4, 5*) shed light on how the primase and other replication factors interact with DNA polymerases and with one another to direct and coordinate DNA synthesis at the replication fork.

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Coordinating the synthesis of the newly forming leading and lagging DNA strands is particularly difficult because the polarity of the DNA backbone dictates that polymerases can only synthesize DNA in one direction (that is, from the 5′ to the 3′ end). This means that the paired DNA polymerases at the replication fork must move in opposite directions along the two (antiparallel) DNA template strands. How they do this is best explained by the "trombone model" of replication (see the figure). In this model (*6*), looping-out of the lagging strand of template DNA permits the pair of DNA polymerases to synthesize the two new DNA strands in the same direction within the moving replication fork while actually moving in opposite directions along the template strands. To avoid the difficulties that would result from the generation of very long DNA loops, lagging-strand synthesis proceeds discontinuously, that is, through the production of short (one- to two-kilobase) pieces of single-stranded DNA (Okazaki fragments). This permits the periodic "resetting" of the loop of the trombone on the lagging strand, while leading-strand synthesis proceeds continuously. It is this functional asymmetry of the polymerases at the replication fork that provides both the opportunity and the need for the primase and other auxiliary proteins.

The primase is required because DNA polymerases cannot initiate DNA synthesis on their own; rather, they can only extend the 3′ end of a preexisting oligonucleotide that is hybridized to the DNA template strand. The primase takes care of this problem by synthesizing discrete RNA primers (11 nucleotides long in *Escherichia coli*) at defined positions on the DNA template. The DNA polymerase then extends the primers by synthesizing DNA. RNA priming need occur only once (at initiation) in leading-strand synthesis, but must occur repeatedly in the discontinuous synthesis of the lagging strand. [The RNA primers that are inserted into the newly forming lagging strand are subsequently removed by ribonuclease H and resynthesized against the template as DNA by another polymerase; breaks in the DNA backbone are sealed by DNA ligase (*1, 2*)].