

The Sun's oblateness appears to be constant

A precision measurement finds its equatorial bulge somewhat smaller than expected and seemingly unaffected by the solar cycle.

Like all spinning celestial bodies that are or once were fluid, the Sun is oblate. Its waist bulges, but ever so slightly. That makes the Sun's oblateness—the fractional difference between its equatorial and polar radii—difficult to measure, especially with ground-based instruments constrained by atmospheric turbulence. Robert Dicke and coworkers at Princeton University tried hard half a century ago. They hoped to discover a departure from spherical symmetry large enough to affect Mercury's orbit and reconcile its known precession rate with Dicke's alternative theory of gravity.

Successive measurements by various groups over the next decades made it clear that the Sun's oblateness was only about a part in 10^5 , much smaller than what's required by Dicke's modification of general relativity. But half a century of solar-oblateness measurements from the ground, from balloons, and recently from space have yielded results suggesting that the Sun's shape might in fact be variable. Contributing to that suggestion was the considerable inconsistency among those sporadic measurements.¹

The Sun's brightness and surface magnetic activity vary in rough accord with the 11-year cycle of sunspot abundance. "So why not its shape?" asks Jeffrey Kuhn (University of Hawaii), Dicke's graduate student in the 1970s. "After all, our understanding of the solar cycle is fundamentally incomplete."

A team led by Kuhn has been using NASA's orbiting *Solar Dynamics Observatory* (SDO), launched early in 2010, to measure the shape of the limb (the solar disk's edge) with record precision and look for variation over the solar cycle. Now they have published the oblateness results from the SDO's first two years.² In terms of angles subtended at Earth, they report that the Sun's equatorial radius exceeds its polar radius by 7.2 ± 0.5 milliarcseconds, with no evident departure from constancy. The Sun's diameter, 1.4×10^6 km, subtends about half a degree on the sky. So the difference between radii is barely 5 km. For comparison, the polar radius of the

much smaller but faster-spinning Earth is flattened by 21 km.

Profiling the Sun

The Sun is a ball of spinning and flowing gaseous plasma. Its surface is seen to rotate with a latitude-dependent period that's shortest (24.5 days) at the equator. Its precise shape depends on the unseen internal distribution of rotation rates and on magnetic and flow stresses at the surface.

The SDO has unique capabilities for measuring that shape with high precision. The principal imager on board has 16 million pixels. That's 16 times as many as its predecessor had aboard the pioneering *Solar and Heliospheric Observatory* (SOHO), launched in 1995. For both instruments, measuring the limb's shape has been a part-time sideline. Both were designed primarily for helioseismology—the Doppler measurement of acoustic oscillations on the Sun's surface as a way of studying its interior. It's through helioseismology that the Sun's internal rotation rates are thought to be reasonably well known except near the presumably rigid core and within a few percent of the radial distance from the surface. One of the Kuhn team's objectives was to test oblateness predictions from internal-rotation models based on the helioseismic data.

Helioseismic observation can live with the small imperfections that inevitably distort an optical system's axial

symmetry. But they prevent straightforward measurement of the solar limb's tiny departure from perfect circularity. So to measure the Sun's shape, the SDO must image the solar disk thousands of times while rotating about its line of sight. That roll maneuver is carried out for about eight hours twice a year, to calibrate the observatory's instrument. And that's when the team takes its shape data.

Unlike its successor, SOHO was not originally designed for such shape measurements. In fact, SOHO lost its lock on the Sun during an attempted roll maneuver in 1998 and remained out of commission for several months.

Figure 1 shows the limb-shape data from one SDO roll sequence, together with the best Legendre-polynomial multipole fit to all the data from the six roll maneuvers undertaken through this past April. The fit extends up to the fourth-order (hexadecapole) moment. Odd-order moments, being north-south antisymmetric, are not considered.

The best fit's 5-km difference between equatorial and polar radii is small even when compared to the altitudes of typical turbulent perturbations on the Sun's surface. "So our task is like satellite altimetry of sea level to better than a centimeter on a wavy ocean," explains Kuhn. "You have to average over thousands of individual measurements."

Looking for cyclic change

In figure 2, the best-fit quadrupole and hexadecapole coefficients, C_2 and C_4 , for each roll maneuver are plotted against the maneuver's date. (To fourth-order

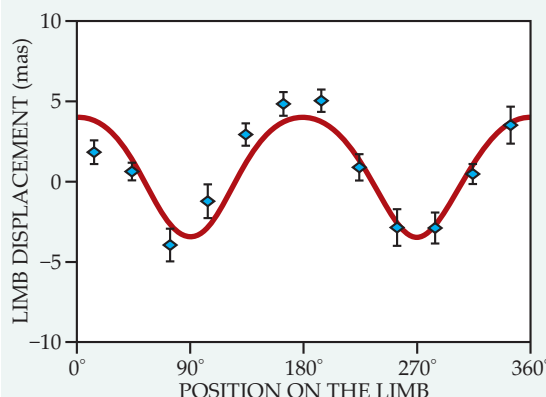


Figure 1. Angular displacement (in milliarcseconds) of the Sun's limb from its mean radius, as subtended at Earth, plotted against angular position on the limb, with 90° being the solar north pole. The illustrative data points are from a single roll maneuver by the *Solar Dynamics Observatory*. The curve shows the best Legendre-polynomial fit (up to fourth moment) to all the data from six such

maneuvers by the SDO over two years. It yields an equatorial radius only about 5 km longer than the polar radius. (Adapted from ref. 2.)

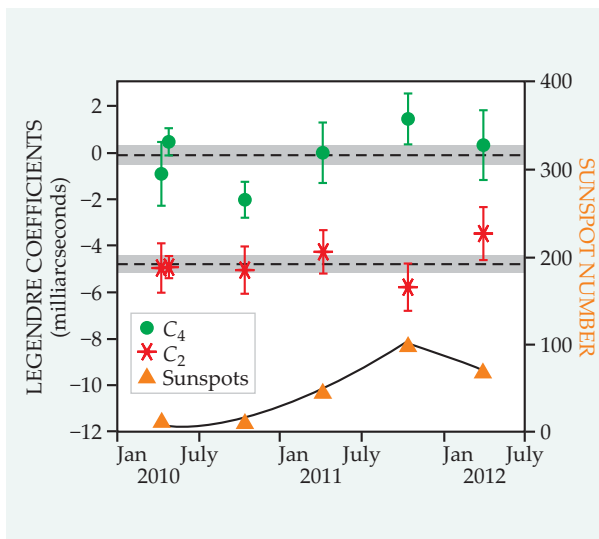


Figure 2. Best-fit Legendre-polynomial coefficients C_2 (quadrupole) and C_4 (hexadecapole) for each of the *Solar Dynamics Observatory's* data-acquisition maneuvers are consistent with constancy over two years. Bands indicate the two-year averages and their uncertainties. But C_4 , though consistent with zero, exhibits a suggestive marginal correlation with the three-day average of sunspot numbers for each acquisition date. (Adapted from ref. 2.)

approximation, the difference between equatorial and polar radii is given by $-3C_2/2 - 5C_4/8$.) Within errors, both coefficients are consistent with constancy over the two years. Furthermore, C_4 is consistent with zero; it contributes very little to the solar oblateness.

But the figure also shows the number of sunspots at the time of each data acquisition. And one sees a marginal hint of positive correlation between C_4 and the sunspot cycle, which had its last minimum in mid-2009. Such variation of the hexadecapole moment, with little or no variation in the quadrupole moment, might be due to cyclic changes in magnetic stresses localized at mid-latitudes or in near-surface flows.

Quite apart from the question of temporal variation, the new oblateness measurement is three standard deviations below the value predicted from prevalent rotation models based on the helioseismic data. "You can't resolve that substantial discrepancy by slowing

the spin of the model sun's core, about which helioseismology is agnostic," says Kuhn. But the discrepancy might be accounted for by a little slowing of rotation within a few percent of the surface.

"It's something of a surprise that the oblateness doesn't seem to vary with the sunspot cycle, as so much else near the solar surface does," says Kuhn. "Of course, we're only about three years past the last minimum and we hope to keep taking data for a full cycle. But the cyclic activity rises faster than it decays. The solar maximum is expected early next year."

Bertram Schwarzschild

References

1. For historical reviews, see J.-P. Rozelot, C. Damiani, *Eur. Phys. J. H* 36, 407 (2011); *Eur. Phys. J. H* (in press), doi:10.1140/epjh/e2012-20030-4.
2. J. R. Kuhn et al., *Science* (in press), doi:10.1126/science.1223231.

Flow geometry controls viscous fingering

A gradient in channel depth can suppress the instability that occurs when a less viscous fluid invades a more viscous one.

In the early 20th century, petroleum engineers noticed that water pumped into porous, oily rock does not displace the oil uniformly but instead penetrates it through a process now known as viscous fingering—the tentaclelike flow of one fluid into another. When Philip Saffman and G. I. Taylor analyzed the problem in 1958, they realized that instabilities at the fluids' interface naturally emerge as long,

propagating fingers. Small perturbations at an otherwise flat interface create local pressure gradients that force the less viscous fluid into regions just ahead of each perturbation. As the fluid speed locally increases, so do the pressure gradients, and the positive feedback drives the fingers' growth.

Saffman and Taylor also realized that they could capture the essential

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