ASTRONOMY

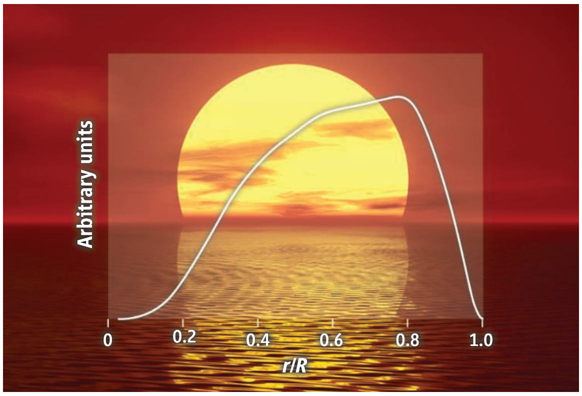
How Oblate Is the Sun?

Recent measurements show that the Sun appears to be rounder than current understanding predicts.

Douglas Gough

At the end of the 19th century there was much concern over Le Verrier's realization that the orbit of Mercury differed from that expected from Newtonian physics. After taking account of perturbations from other planets, there was an unexplained residual precession of the elliptical orbit that amounted to just 43 arc sec per century. It was pointed out by Newcomb that this residual precession might be explained by the Sun being oblate. Einstein then demonstrated that his new general theory of relativity accounted for almost all of the precession, assuming the Sun to be precisely spherical. Only a small 0.2% of the original discrepancy then remained to be explained otherwise, presumably by an oblateness caused by rotation of the Sun. The most natural way to determine the oblateness is simply to measure the apparent shape. However, despite many attempts over more than a century, that has not been possible with the required precision. The reason is that ground-based observers must contend with variations in the refractive index of Earth's atmosphere, which distort the image of the Sun. Only with instruments in space has it been possible to approach a useful measurement (*1*). On page 1638 of this issue, Kuhn *et al*. (*2*) present results from the Heliospheric and Magnetic Imager (HMI) on NASA's Solar Dynamics Observatory (*3*), indicating that the Sun appears not to be as flattened as it should be.

The visual oblateness of the Sun, defined as $\Delta_v = (R_e - R_p)/R$, where R_e and R_p are the equatorial and polar radii and R the mean radius, can be separated into two parts. One is the direct distortion $\Delta\Omega$ due to the pull on the surface layers by the centrifugal force, which



Solar distortion. Superposed on the setting Sun is a graph depicting by how much Ω^2 contributes to the distortion of the Sun's gravitational field as a function of distance from the center (*14*).

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is proportional to the square of the angular velocity Ω and which acts outward from the axis of rotation to make the equator bulge; the other is the aspherical deviation ΔΦ of the gravitational potential produced by the centrifugal force distorting the inside of the Sun, principally at mid-radii (see the figure). From the angular velocity of the visible surface (*4*), the former is determined to be $\Delta_\Omega \sim 8.4\ (\pm 0.2) \times 10^{-6}$. It was then expected that ΔΦ could be obtained by simply subtracting Δ_Ω from Δ_v. Had the entire anomalous precession been due to a solar oblateness, ΔΦ would have dominated the full oblateness, and the procedure would have been viable. But general relativity indicated that ΔΦ is much smaller, and helioseismic observations (*5*) indicate that it is only 3.3×10^{-7}, just 4% of Δ_Ω, thereby implying that Δ_v should be 8.7×10^{-6}.

The first of the modern observations were made serendipitously (*1*) using the guiding sensor for the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) (*6*). A rapidly rotating optical image of the solar limb was Fourier-analyzed with respect to the angle about the line of sight to estimate the quadrupolar component of the limb displacement. A major problem with the measurement, as with any other limb-shape measurement, is brightness contamination by sunspots and magnetically generated excess emission. In an attempt to eliminate the detritus, a magnetic-activity proxy was adopted to reject suspect data (*7*). The outcome was $\Delta_v = 8.34\ (\pm 0.15) \times 10^{-6}$.

Kuhn *et al*. present an analysis of limb-brightness data in a photospheric Fe spectral line obtained from HMI. The limb-darkening function was measured as a function of the angular orientation of the Sun's image at times when the spacecraft was rotated for calibration purposes about its pointing axis. Magnetic contamination was removed by rejecting limb-position data associated with brightness above some threshold that had been judged to yield a robust outcome. Detailed analysis (*8*) then yielded $\Delta_v = 7.56\ (\pm 0.40) \times 10^{-6}$.

Note that the uncertainties in the values of Δ_v are not significantly smaller than ΔΦ. Therefore, subtracting Δ_Ω from Δ_v is evidently not a viable procedure for determining ΔΦ (*9*, *10*). More startling, however, is that Kuhn *et al*. found Δ_v to be some 10% lower than the value of Δ_Ω expected from the surface rotation. Therefore, if their observations are correct, something else other than rotation must be affecting the limb. Until that is explained and quantified precisely, solar limb shape cannot provide a means to test gravity; helioseismology is, and will remain, the only accurate tool to do so.

The new oblateness measurements beg explanation. An expected polar temperature excess comes to mind (*11*); however, Kuhn's (*12*) estimate of the excess is just 1 to 2 K, which is grossly insufficient to explain the discrepancy. Alternatively, one could wonder whether polar support is boosted by an intense large-scale surface magnetic field; might not the intensity of the field demanded for that be plausible if the spatial variation in the differential rotation requires forces, perhaps magnetic, of sufficient strength to produce a shape distortion of similar magnitude to that produced directly by the differential rotation itself? That is not necessarily so, as any child in a playground who has spun up a merry-go-round with ease but then had difficulty holding on against the resulting centrifugal force well knows. Even if a magnetic hill were present, the surface material would surely drain away. What other possibility is left? Turbulent stresses from convection, perhaps? These newest data have left us with an intriguing new conundrum in solar physics: Why does the Sun appear to be so round?

References and Notes

1. M. D. Fivian, H. S. Hudson, R. P. Lin, H. J. Zahid, *Science* **322**, 560 (2008).
2. J. R. Kuhn, R. Bush, M. Emilio, I. F. Scholl, *Science* **337**, 1638 (2012); 10.1126/science.1223231.
3. P. H. Scherrer *et al*., *Sol. Phys.* **275**, 207 (2012).
4. J. G. Beck, *Sol. Phys.* **191**, 47 (2000).
5. F. P. Pijpers, *Mon. Not. R. Astron. Soc.* **297**, L76 (1998).
6. M. D. Fivian, R. Henneck, A. Zehnder, in *Innovative Telescopes and Instrumentation for Solar Astrophysics*, S. L. Keil, S. V. Avakyan, Eds., (SPIE, Waikoloa, HI, 2003), p. 60.
7. J.-P. Delaboudinière *et al*., *Sol. Phys.* **162**, 291 (1995).
8. Kuhn ***et al***. find no evidence for a variation of Δ_v associated with the solar cycle; the gravitational oblateness ΔΦ varies by less than 0.04% (*13*). Yet solar-cycle variations in more convoluted distortions in the gravitational equipotentials and perhaps the surface shape appear to occur. It is not clear whether these phenomena are causally related.
9. Fivian *et al*. (*1*) adopted a value for Δ_Ω quoted by Dicke (*10*), who had evaluated it using an inaccurate representation of the Sun's surface angular velocity Ω_s; that estimate of Δ_Ω is actually lower than Δ_v by approximately ΔΦ.
10. R. H. Dicke, *Astrophys. J.* **159**, 1 (1970).
11. J. L. Tassoul, *Stellar Rotation* (Cambridge Univ. Press, Cambridge, 2000).
12. J. R. Kuhn, in *Encyclopedia of Astronomy and Astrophysics*, P. Murdin, Ed. (Institute of Physics, Bristol, UK, 2001), article 2245.
13. H. M. Antia, S. M. Chitre, D. O. Gough, *Astron. Astrophys.* **477**, 657 (2008).
14. D. O. Gough, *Nature* **298**, 334 (1982).

10.1126/science.1226988