On the constancy of the solar diameter

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Abstract

Why does the solar luminosity vary and could it change on human timescales by enough to affect terrestrial climate? As important as these questions are, we lack answers because we do not understand the physical mechanisms which are responsible for the solar irradiance cycle (1,2). Progress here depends on discovering how changes in the solar interior affect energy flow from the radiative and convection zones out through the photosphere. Measurements of small changes in the solar radius are a critical probe of the Sun's interior stratification and can tell us how and where the solar luminosity

is gated or stored. Here we report results from a sensitive 3 year satellite experiment designed to detect solar diameter fluctuations.

Variations in the Sun's irradiance (and by implication its luminosity) (1) with an amplitude of 0.1% have been observed from space for more than 2 decades (2). Although our immediate energy source is the solar photosphere, this radiated energy originates from the nuclear conversion of H to He in the deep solar interior. Energetic photons require nearly a million years to diffuse out of the core region, implying that the emergent luminosity at its outer boundary is effectively constant on solar cycle timescales. Thus, given the observed variability at the photosphere, there must be an intermediate energy reservoir.

Several mechanisms exist for storing energy during a solar cycle (e.g. gravitational or magnetic fields) and each leads to distinct perturbations in the equilibrium stellar structure and changes in the diameter. It follows that a sensitive determination of the solar radius fluctuations can reveal the cause of the solar cycle changes. The magnitude of the radius fluctuation, compared to the irradiance change, during a solar cycle contains important information on where and how energy is stored. We take $W = \frac{\delta r/r}{\delta I/I}$ to describe the ratio of radius and irradiance changes over a solar cycle. Various models predict a wide range of values for W. For example, depending on the details of the solar model and the form of the perturbation, theoretical estimates of W range between 2×10^{-4} (3), 8×10^{-4} (4), $5{\times}10^{-3}$ (5) and $7.5{\times}10^{-2}$ (6). Given the solar cycle irradiance amplitude of 0.1% a radius sensitivity of at least 70 milliarcsec is needed to observationally discriminate between some of these models.

Ground-based measurements of the solar radius exist over the last 300 years (7), however the results are controversial and inconsistent. Historical data show that the Sun's radius may have been larger during the Maunder Minimum, which coincided with extremely cold periods in Europe and the Atlantic regions (7). These results are also suggested by the French CERGA radius measurements which found a larger solar radius during solar minimum (8). In contrast, Ulrich and Bertello (9) and Basu (10) found a positive correlation between apparent radius changes and the solar activity cycle. There are also hints of periodic solar radius variations over time scales of 1,000 days to 80 years (4), but the measurements are generally neither consistent nor conclusive (7,11,12). Helioseismic data have also been used to derive solar radius fluctuations (13). These data imply a solar radius change of 10 milliarcsec between 1996 and 1998, an amplitude much smaller than the ground-based optical measurements. These contradictory results highlight the necessity of more sensitive efforts to measure the Sun's radius.

Given the small magnitude of the diameter change signal in the ground-based measurements, it is clear that solar radius observations are limited by "seeing" affects in the Earth's atmosphere. This has also been recognized by

Sofia and his collaborators in their development of the balloon borne Solar Disk Sextant (14). The Michelson Doppler Imager (MDI) instrument (15), which is one component of the Solar and Heliospheric Observatory (SOHO) satellite, offers the promise of very accurate solar radius measurements which can only be obtained from space.

The MDI instrument was designed primarily for Doppler observations, although it is producing unique astrometric data because of its accurate pointing and imaging capability from above the Earth's atmosphere. The data and analysis approach used here to measure the radius change is similar to the effort to obtain accurate solar limb shape measurements (16). The dataset consists of a 6 pixel wide annulus of intensity measurements obtained from solar images produced during the routine operation of the MDI experiment. The 1 minute cadence images are low-pass filtered (to remove solar 5-minute p mode intensity oscillations) and the limb pixels (2"/pixel) are downlinked every 12 minutes. These data were obtained between April 19, 1996 and June 24 1998. Data obtained after the SOHO recovery in Nov. 1998 have not been used because of frequent instrument mode interruptions and focal length calibration difficulties.

Each image is first calibrated with a "flat-field" which removes pixel-pixel intensity calibration variations to an accuracy of about 1% . Accurate (to 0.02 arcsec) image centers are derived using an iterative least-squares technique. Limb darkening functions (LDF) are computed from histograms of the pixels in each of 16 angular subregions around the limb. Each 22.5 degree sector yields a LDF for that angular bin within about 6 arcsec of the limb. Figure 1 shows a family of LDFs, $I(r, \theta_i)$, for a typical image. These limb profiles are significantly broader than either the true solar limb or the telescope diffraction limit because MDI images are defocused to minimize aliasing due to the relatively large (2 arcsec) pixels.

The limb position $\delta r(\theta_i)$, from each bin is obtained by finding the inflection point in the LDF. This is determined by fitting $dI(r, \theta_i)/dr$ to a Gaussian plus quadratic background. The zero of this function is taken to be the limb position. Low order optical aberrations are effectively eliminated by averaging the radial limb postion around the limb, over the 16 angular bins. The apparent solar radius derived in this fashion is shown in Figure 2. The apparent angular diameter variation due to the eccentricity of the satellites orbit dominates this measurement. The lower plot in this figure shows the residual obtained after subtracting the expected orbital solar radius changes. Obvious discontinuities in the residual radius are caused by known instrument mode interruptions, when path length changes were imposed in the optics to change the effective focal length of the MDI telescope. These data also show a small residual yearly variation which is more clearly visible in Figure 3.

The residual annual radius variation has an amplitude of approximately 0.1 arcsec and shows a secular increase of about the same amplitude over the period between 1996-1998. The origin of this systematic variation is now recognized to be caused by the changing thermal environment of the SOHO spacecraft. Changes in the temperature of the MDI front window can cause small but measurable changes in the telescope focal length. A temperature gradient of a few degrees from the center of the window to the aluminum cell at the filter edge can produce a weak lens effect with a focal length of a few kilometers. This is sufficient to change the telescope focal length by a few parts in 10^4. Evidence of this appears in Fig. 3 which also plots the temperature of the front window, T(t), over the same time period. Both the annual and the secular change (due to degradation of the front window and increased absorptivity) are apparent in the temperature record. To account for the temperature induced radius changes we use a statistical two-parameter model of the form, $\alpha + \beta T(t)$ obtained by least-squares fitting this function to $\delta r(t)$. The daily average residual, $\delta r'(t)$, is the temperature-corrected solar radius which is plotted in Figure 4.

The radius fluctuation measurements, $\delta r'(t)$, define an upper limit on possible secular variations. The residual linear variation in the Sun's radius using the data in Fig. 4 is 8.1 ± 0.9 milliarcsec/year. We have also searched for evidence of a solar cycle variation by fitting a smoothed sunspot function to $\delta r'(t)$. Figure 5 plots the fourier smoothed sunspot number record, S(t), during the last solar cycle. The MDI radius data and the ground-based measurements obtained by CERGA are also plotted. Here we also use a two-parameter linear model of the form $\alpha + \beta S(t)$ to fit for a solar cycle variation in the two radius change datasets. We find that the CERGA data yield $\beta_{CER} = -1.3 \pm 0.1$ while the MDI data imply $\beta_{MDI} = 0.3 \pm 0.03$. These coefficients have units of milliarcsec per sunspot number. The MDI observations imply that solar radius fluctuations are significantly smaller in magnitude and of the opposite correlation sign than expectations founded on ground-based data. From β_{MDI} and the peak-to-valley excursion of the sunspot function, δS, one would conclude that the solar cycle radius variation is $\delta r_{cycle} = \delta S \beta_{MDI} = \ + 21 \pm 3$ milliarcsec (for comparison CERGA yields $\delta r_{cycle} = \ - 100 \pm 5$). In fact, because we cannot rule out the existence of unmodeled slow temperature or MDI instrument changes, we believe that δr_{cycle} represents an upper limit to the magnitude of a real cyclic solar size variability. Thus we take 2×10^{-2} as the upper limit of $|W|$.

The MDI helioseismic radius measurements have higher accuracy but exhibit a large yearly variation which is strikingly reminiscent of the annual temperature systematic we corrected in the astrometric data. It seems likely that the discrepancy between these two satellite results is due to uncorrected geometric solar radius fluctuations in the helioseismic analysis. This would contaminate the derived mode dispersion relation and the implied solar radius.

Sofia et al. (6) argued that solar cycle changes which affect the convective efficiency near the photosphere will have a comparatively large affect on the solar radius. Their calculated value of W≈0.075 is ruled out by these measurements, suggesting that solar cycle irradiance changes are not caused by such superficial fluctuations in the outer (superadiabatic) layers of the sun. It is possible to improve the radius detection sensitivity by more than one order of magnitude, either with a longer measurement time baseline from MDI, or with other dedicated satellite observations. In either case, it is clear that precise solar radius observations have reached a level of accuracy that particular models of solar cycle variability may be directly addressed. These new astrometric results support the view that changes deep in the solar interior are required to account for the observed irradiance variability.

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Figure Captions

Figure 1: This figure shows a family of limb darkening functions (LDFs), $I(r, \theta_i)$, for a typical image. Each 22.5 degree sector yields a LDF for that angular bin within about 6 arcsec of the limb.

Figure 2: The apparent radius change due to the SOHO satellite orbit dominates the raw radius measurement and is the upper plot in this figure. The apparent solar radius has been computed from the nominal Sun-satellite distance and subtracted from the raw data to yield the lower curve in this plot. Slow and rapid instrumental focus changes dominate these residuals.

Figure 3: The lower plot shows the MDI residual solar radius after known instrument mode focus changes are corrected. An annual radius variation of 0.1 arcsec is apparent and is due to variations in the MDI front window temperature. The measured MDI front temperature is plotted in the upper curve. It shows the annual temperature change due to the variable Sun-satellite distance and a secular variation due to degratation of the front window transparency.

Figure 4: This figure shows daily average solar radius variations after removing the MDI front window temperature contribution. The residual linear variation in the Sun's radius is 8.1 ± 0.9 milliarcsec/year. The smooth curve in this figure shows a fit to the smoothed sunspot number during this period.

Figure 5: **A** The sunspot number record during the last solar cycle is plotted

here. The smoothed sunspot function, S(t), is also shown as it was calculated from the 5 principal harmonic components of the sunspot number record. **B** This shows the CERGA solar radius data and the projected smoothed sunspot function. The amplitude of the 11 year period is about 0.1 arcsec and is in opposite phase with the solar magnetic activity (8). **C** The daily average MDI-SOHO solar radius variations over this time period had a much smaller amplitude and opposite correlation sense than CERGA.