SOLAR-RADIUS VARIATIONS OVER A SOLAR CYCLE OBSERVED WITH THE TOKYO PHOTOELECTRIC MERIDIAN CIRCLE

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Abstract. As the Sun shows the well-known magnetic activity of eleven-year period, many other interesting observational features of the Sun have been examined in connection with the solar cycle. The diameter of the Sun is one of these interesting observable quantities. The apparent radius of the Sun has been observed regularly since 1985 with the Tokyo Photoelectric Meridian Circle (Tokyo PMC) at Mitaka. Here, we show the average value of the solar radii observed by us. We also show that the annual-mean values of the observed radii take the smallest value near the solar-cycle maximum, in 1989 and 1990, and the largest ones around the solar-cycle minimum, in 1986 and 1994. The average peak-to-peak shift of the annual-mean solar radius for the solar cycle is $\Delta R_{\odot}/R_{\odot} \sim 1.2 \times 10^{-4}$, which is close to the relative change of the frequency of the 5-minute p-mode solar oscillation within one solar cycle.

1. Observations and Definition of the Solar Radius

The objective lens of the Tokyo PMC (Yoshizawa *et al.*, 1994) has a diameter of 200 mm and a focal length of 2576 mm, that is 12.5 μm correspond to $1'$ on the focal plane. The effective central wavelength of the optics (objective lens plus interference filter) and the photon counting system (photomultiplier tube) is $\lambda_O = 550\,\mathrm{nm}$ with a transmission band width of $\Delta\lambda = 60\,\mathrm{nm}$ (FWHM). Four pinholes (each of diameter $2''\!.5$) are arranged on a scanning slit plate in the focal plane, and the pinholes transit consecutively the western and eastern limbs of the Sun at six different points (nominal position angles of the six points are: 45°, 104°, 135°, 225°, 284°,

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315°; *cf.* Yoshizawa and Yasuda, 1982). During the meridian transit of the Sun the slit plate is forced to oscillate so as to cross over the solar limbs back and forth several times, following the mean diurnal motion of the Sun. The radius of the Sun of one day is determined by using about 45 pinhole crossings observed at six parts of the solar limbs. Note that, owing to the regular annual changes of the direction of the heliographic north pole at the instant of the Sun's meridian transit, almost all parts of the solar limbs, except the polar regions, are expected to be viewed with our pinholes in one year.

As the Sun is a gaseous body, limb positions vary depending on its definition. Some authors studied to provide such a robust definition of the solar limb that is little influenced by seeing effect (Hill *et al.*, 1975, Brown, 1982). Here, we define the limb with the use of a numerical filter to be convolved with a time series of photon countrates $\{D_j\}$ obtained during the transit of a pinhole across a solar limb (sampling interval is 50 msec). Let $\{I_j\}$ (j=1, 2, ...) be the cummulative count for the time series, i.e., $I_j = I_{j-1} + D_j$. A pseudo second derivative of $\{Dj\}$ defined in the interval of $\pm JB$ samplings around the j-th sampling is given by

$$S_j = I_{j+JB} - I_{j-JB} - 2(I_{j+\frac{JB}{2}} - I_{j-\frac{JB}{2}}).$$

Then, the limb position is defined as the place where the requirement $S_j = 0$ is fulfilled. The length of the numerical filter ($= 2JB$) is fixed to 16 samplings, which corresponds to 24′.

It is an easy task to evaluate the amount of the systematic bias (difference from the true position) of the limb position defined by setting $S_j = 0$ under a given seeing condition. It is confirmed that for the chosen filter length (24′) the bias in the radius takes almost a constant value ($=-0''.94$) for the seeing size 3′ to 5′, which are the typical values at the site of the Tokyo PMC in daytime. This constant bias was added to all of the observations of this article. The influences of the differential atmospheric refraction and the variation of the scale of the telescope were corrected to individual observations. The final values denoted below as $R_\odot$ stand for the apparent solar radii reduced to the values at 1 AU distance.

2. Results

The total number of observations of the solar radius used in the analyses for this article is 755, obtained between October 1985 and December 1994. The mean value of the radius calculated from all the 755 observations is

$$\overline{R}_\odot = 959''.83 \quad \text{(rms residual of single observation} = 0''.36).$$

It is noted that the average rms residual of one-day observations within a month around the corresponding monthly mean is of about 0″.33, which is

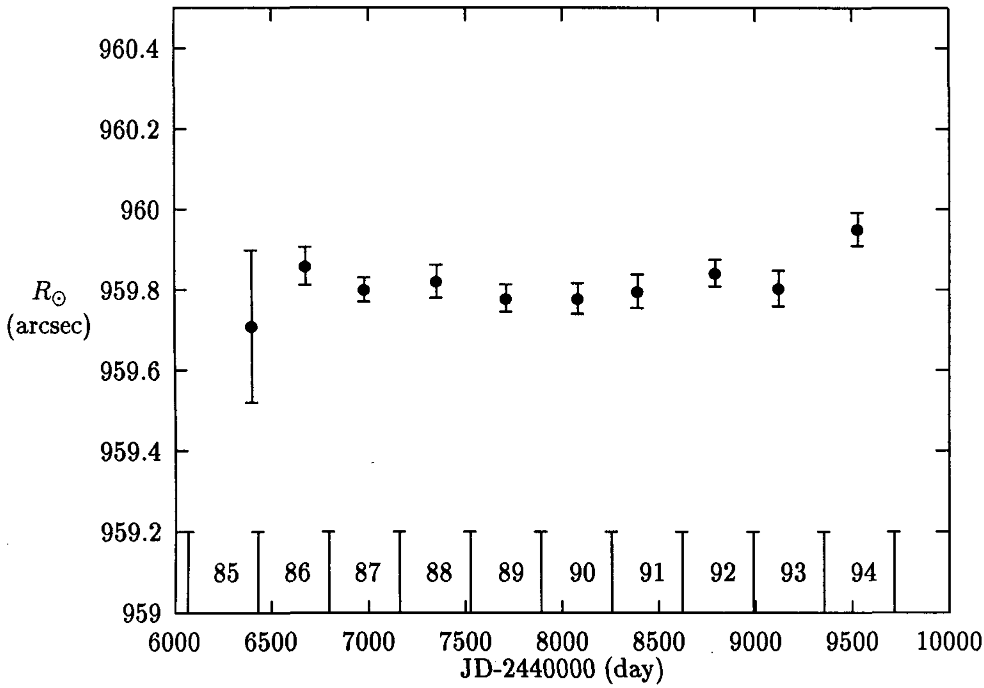

Figure 1. Time variation of the annual-mean solar radii observed with the Tokyo PMC for 1985 through 1994, reduced to the values at 1 AU distance. The effective central wavelength of the observations is $\lambda_o = 550\,\mathrm{nm}$. The error bars represent the mean errors calculated from the rms residuals of the daily observations within each year.

thought to be a measure of the standard deviation of the random component of a single one-day observation. Our value of the mean solar radius is slightly ($\sim 0\overset{''}{.}2$) larger than the IAU 1976 value of $959\overset{''}{.}64$. The standard deviation of the residuals of $0\overset{''}{.}36$ implies that the formal mean error of the derived $\overline{R}_\odot$ is of about $0\overset{''}{.}01$.

The annual-mean values of the observed solar radii are plotted in Figure 1 for each year of the recent nine years. It is seen from Figure 1 that the solar radius varies systematically over a period comparable to a solar cycle, and the minimum value ($959\overset{''}{.}78 \pm 0\overset{''}{.}04$) is reached in 1989 and 1990, near the maximum phase of the 22$^{\mathrm{nd}}$ solar cycle. On the contrary, the two largest annual-mean radii are observed in 1986 ($959\overset{''}{.}86 \pm 0\overset{''}{.}05$) and 1994 ($959\overset{''}{.}95 \pm 0\overset{''}{.}04$), when the solar activity is near the minimum phase.

In order to examine the shorter-period variabilities in the observed solar radii, the power spectrum distribution of the solar radii $R_\odot$ is derived by using the Maximum Entropy Method (or All Poles method) (Press *et al.*, 1986) for the whole data set of 755 points. Then, the most significant term is found to be the 913-day periodicity with an amplitude of about $0''.05$, which corresponds to about 35 km at the Sun. Another term to be noticed is the 8.3-yr variation with an amplitude of about $0''.04$. This longest term is supposed to be related to the systematic variation shown in Figure 1 nearly over a solar cycle. Unfortunately, our present data set covers the duration only a bit longer than nine years. Therefore, the exact value of the period of the longest term does not have much meaning at present. A few other periodic terms are identified in the power spectrum distribution that have the length of period close to one of the Sun-spot activity cycles (Delache *et al.*, 1985), e.g. 580 days and 230 days, but their amplitudes are all smaller than $0''.03$. Disappointingly, the uncertainties of the calculated periods and amplitudes are large, because of the relatively large random errors of single observations ($\approx 0''.33$), and therefore the reality of the terms with these smaller amplitudes is marginal. In any case, it is concluded that no significant systematic time variations exist in the observed solar radii that have an amplitude larger than $0''.1$ in the sense of standard deviation (or $0''.3$ in the peak-to-peak sense) and the periodicity of the order of one year.

3. Comparison with Other Observations

Now we compare our results with other observations. A series of measurements of the solar diameter has been carried on regularly at CERGA, Grasse, since 1978 with a Danjon (visual) astrolabe. From these observations several interesting long-period oscillations are reported (Delache *et al.*, 1985; Débarbat and Laclare, 1990). The most conspicuous oscillation among the reported ones is the variation of a 1000-day periodicity with an amplitude in radius of about $0''.15$ (Débarbat and Laclare, 1990). The period of 913 days found in this paper is not very much different from their value (970 days). However, the amplitude of our 913-day variation is three times smaller than their value. In CERGA's monthly-average diagrams the reported 1000-day periodicity seems to be explicit in 1980 to 1982, just after the maximum phase of the solar cycle 21. But, during a few years after the minimum of the cycle 22, say from 1986 to 1988, the observed radii keep a rather stationary value (Ribes *et al.*, 1991, Débarbat and Laclare, 1990). In our data set too we could observe a similar behavior ; larger variations after a solar cycle maximum. One implication is that the amplitude of the 900-day or 1000-day variation depends on the phase within a solar cycle, in the sense that the amplitude is larger just after the activity maximum, when the solar radius is smaller than the average value, than in the period just after the activity minimum, when the radius is larger than the average.

At the High Altitude Observatory, Boulder, the measurements of the solar diameter started in 1981 with the *ad hoc* instrument called the Solar Diameter Monitor (SDM) (Brown *et al.*, 1982). The SDM is a photoelectric meridian transit instrument. The SDM's seeing-independent definition of the solar limb position (Brown, 1982), similar to the finite Fourier transform definition (Hill *et al.*, 1975), has good properties in order to make the defined limb position insensitive to the atmospheric seeing and scattering. The day-to-day scatter of SDM radii over a few months is reported to be of about 0."23 (Ribes *et al.*, 1991), which is about 50% better than our rms scatter of daily observations over a month. The horizontal SDM radii show less variability than those of CERGA, and there is no evident periodic variation larger than 5×10^{-5}, or 0."05, for time scales of a year (Ribes *et al.*, 1991), although a slight hint of a periodic variation of the order of 1000 days is noticed in the SDM's monthly means. Anyway, our results given above are not inconsistent with the SDM's. It would be an interesting work to combine the SDM and Tokyo PMC data together to study any meaningful periodicities in the observed solar radii with the amplitude of a few hundreds of an arcsec or more.

4. Discussion

Finally, we compare our results with the frequency shift of low-l p-mode 5-minute solar oscillation. It is well known that the basic frequency (3 mHz) of the 5-min solar oscillation changes with time by about a fraction of 10^{-4} within one solar cycle, probably owing to the changes in the structure of the Sun (Gelly *et al.*, 1988; Libbrecht and Woodard, 1990; Pallé *et al.*, 1989; Delache *et al.*, 1993). Gelly *et al.* (1988) showed by using ACRIM data that the frequency shift of $\delta\nu = \nu_{80} - \nu_{85/86} = +0.368\ \mu$Hz at ν=3 mHz between 1980 and 1985/86, i.e., the fraction of the frequency change between the solar maximum and solar minimum is $\delta\nu/\nu \approx 1.2 \times 10^{-4}$. At the Big Bear Solar Observatory (Libbrecht and Woodard, 1990) it is confirmed that $\nu_{88} - \nu_{86} = +0.18\ \mu$Hz(l=0 to 10) at ν=3 mHz, which means $\delta\nu/\nu \approx 6 \times 10^{-5}$. The variation of the frequency shift for a longer period $\delta\nu = \nu_{yy} - \nu_{86}$ vs. time yy at ν=3 mHz is given in Pallé *et al.* (1989) and Delache *et al.* (1985), and the peak-to-peak amplitude of about 0.4 μHz between the solar maximum and minimum is shown.

Our result is summarized as follows: The minimum $\overline{R}_{\odot,\mathrm{annual}}$ is observed in 1989–1990 (at the solar maximum), and

$$\overline{R}_{\odot,88} - \overline{R}_{\odot,86} = -0.''04 \ (|\Delta R_\odot/R_\odot| \approx 4 \times 10^{-5}),$$

$$\overline{R}_{\odot,90} - \overline{R}_{\odot,86} = -0.''08 \ (|\Delta R_\odot/R_\odot| \approx 8 \times 10^{-5}).$$

Although it is not clear at present what kind of physical relationship exists between the solar-radius variation and the frequency shift of the low-l acoustic mode oscillations at 3 mHz, the similarity in phase (actually 180° anti-phase) and relative amplitude is worth to be examined in detail. Libbrecht and Woodard (1990) suggest that the most significant solar-cycle changes in the Sun's structure are near the surface. From the above comparisons we suggest here only the following approximate numerical relation found between the relative amplitudes of the two interesting solar parameters:

$$\left(\frac{\delta\nu}{\nu}\right)_{\text{at 3 mHz}} \approx -\frac{3}{2} \cdot \frac{\Delta R_\odot}{R_\odot}.$$

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