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Heliographic latitude dependence of the apparent solar radius

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Abstract. A brief outline is given of the advantages of the drift scan method and of the Danjon astrolabe for measuring the apparent solar radius. An analysis of 2111 measurements of the apparent semidiameter of the Sun made with a modified Danjon astrolabe at Santiago, Chile, shows a significant dependence of the observed semidiameter with the heliographic latitude. These results are confirmed by similar data obtained at the northern hemisphere with the solar astrolabe of CERGA, France. On the average the results of Santiago and CERGA show a maximum value of the semidiameter around $\pm 50^\circ$ solar latitude and two minimums at $\pm 25^\circ$ and $\pm 75^\circ$. The amplitude is $0\farcs148 \pm 0\farcs030$. The results of both astrolabes show a rather clear anticorrelation with non facular temperature excess along the solar limb. The temperature data were obtained by other authors from observations made with the Princeton Solar Distortion Telescope.

Key words: astrometry – Sun: fundamental parameters

1. Introduction

The shape and size of the Sun and its eventual variations are issues of fundamental importance not only for solar physics, but also for other scientific fields. An oblate Sun should have important consequences for the dynamic of the solar system and for the applications of general relativity to celestial mechanics (Lieske & Null 1969, Dicke et al. 1985). Changes in the solar size can be related to variations of luminosity (Spruit 1991) which have been postulated as an important source of climatic changes (Sofia et al. 1979).

A great deal of work has been done in this sense in the last decades, including the development of new instrumentation for solar astrometry (Dicke & Goldenberg 1967, Oleson et al. 1974, Laclare 1975, Brown et al. 1982, Sofia et al. 1984, Chapman et al. 1989, Wittmann 1997, etc.). However, in spite of this effort and new instruments, the results obtained so far are still inconclusive. The existence of a slight oblateness in the Sun is still a matter of discussion (Rozelot & Bois 1998), and concerning solar radius variations there is no consensus to accept the evidences obtained sofar (Pecker 1994).

Probably a main factor in this controversy is the precision of the methods which have been used for measuring the apparent solar semidiameter. It has been claimed that among ground-based techniques, the drift scan method could be the best one for measuring the solar radius (Wittmann 1997, Brown et al. 1982). What is directly measured with this method, is not the angle subtended by the solar diameter, but the time which takes the drift of the image of the Sun, with respect to a fix reference in the telescope focal plane. The calibration standard for the drift rate of the solar image is the rotation of the Earth which is known with sufficient precision, and with modern chronometric techniques, measuring time intervals is more precise than measuring angles. The instrumental system must be stable only during the few minutes between both transits of the solar border. Probably this is the main advantage of the method, since the most stringent requirement of other techniques for measuring the solar diameter is a long-term stability of the instrumental system (Brown et al. 1982).

It has been claimed also that due to the capacity of the human eye to partly compensate the irregular motion of the image caused by the atmosphere, in certain circumstances, a visual drift measurement can be more accurate than a photoelectric scan drift (Toulmonde 1995, Wittmann 1997, 1998). On the other hand and according to Sofia et al. (1979), current astrometric instruments could achieve results of sufficient precision as to determine an eventual link between diameter changes of the Sun and variations of luminosity.

2. Solar observations with astrolabes

Among the current astrometric instruments, the Danjon astrolabe has been rather powerful in many fields of astrometry (Guinot 1958, Fricke 1972, Noël 1988). It works according to the method of equal altitudes (Débarbat & Guinot 1970) and after some modifications it can be adapted for solar astrometry (Laclare 1975, Chollet & Noël 1993). If the solar diameter is the only unknown of interest, the method of reduction can be greatly simplified (Laclare et al. 1996) and is equivalent to a visual drift measurement of the Sun image with respect to a fixed small circle of altitude. The solar diameter is obtained from the transit times of the solar borders through the almucantar which is fixed automatically by means of a mercury mirror and a re-

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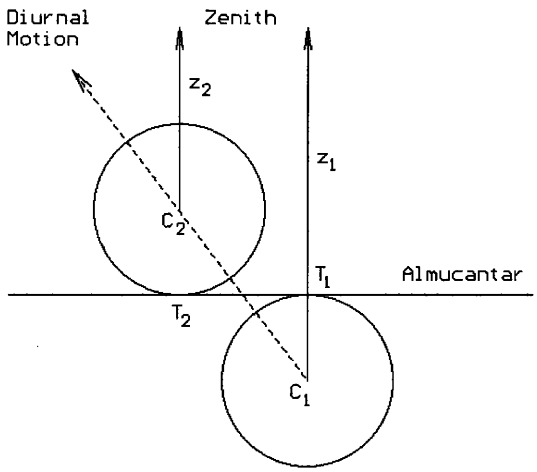

Fig. 1. Measurement principle of the Sun semidiameter with an astrolabe (see text)

flecting prism. The precision of the results depends mainly on the stabilities of the almucantar and time standard, and on an accurate computation of eventual variations of the atmospheric refraction during the few minutes taken by the drift of the solar image.

The principle of the method can be seen in Fig. 1. If t_1 and t_2 are the recorded times of the transits T_1 and T_2 respectively, of the solar borders through the almucantar, and if z_1 and z_2 are the zenith distances of the center of the Sun computed with t_1 and t_2 respectively and corrected for refraction and for some instrumental parameters (Laclare et al. 1996), then the solar diameter is given by $z_1 - z_2$. Any spurious effect in the computed refraction will not affect the result since it will be cancelled when making the difference of both zenith distances.

From Fig. 1 it is apparent also that the measured diameter will have always a vertical direction with respect to the local reference frame and that the transits of the borders of the Sun are observed always at the same zenith distance. This is a great advantage, since the results should be free from the effects of differential refraction, and an eventual effect of irradiance (Cullen 1926, Toulmonde 1995) should be constant. However, there is a further and rather important advantage. Since the heliographic inclination of the solar diameter observed with an astrolabe depends on the hour angle of the Sun, it will have an annual variation between limits defined by the zenith distance of observation and by the geographic latitude of the instrument. Therefore, if the measurements of the solar diameter have a sufficient precision it could be possible to disclose an eventual relation between the simidiameter and the heliographic latitude. In this paper we present the results of such a research, based on solar observations made with the solar astrolabe of Santiago, Chile.

3. The solar program of the astrolabe of Santiago

The modifications introduced in the Danjon astrolabe of the National Astronomical Observatory of Cerro Calán at Santiago, and the program of solar astrometry with this instrument, are described in detail elsewhere (Chollet & Noël 1993, Noël 1997).

Table 1. Apparent solar semidiameter obtained at Santiago, as a function of heliographic inclination (H.I.)

H.I.	Semidiameter		n
$11\overset{\circ}{.}9$	$960\overset{''}{.}237 \pm$	$0\overset{''}{.}030$	300
15.1	960.201	0.026	391
19.0	960.193	0.033	252
25.6	960.118	0.031	269
29.4	960.119	0.029	311
35.2	960.166	0.031	248
40.3	960.205	0.032	267
44.7	960.244	0.034	268
49.7	960.289	0.038	214
55.4	960.235	0.035	219
60.1	960.193	0.033	272
65.8	960.167	0.030	388
68.7	960.142	0.033	305
75.4	960.121	0.041	143
80.0	960.121	0.042	190
Mean:	$960\overset{''}{.}186 \pm$	$0\overset{''}{.}012$	2111

The observations are made visually at two zenithal distances, $30°$ and $60°$. Since the latitude of the astrolabe is approximately $-33\overset{\circ}{.}4$, the Sun can be observed during the whole year at $60°$ and from October 6th until March 7th at $30°$. The annual variation of the heliographic inclination of the measured semidiameters is comprised approximately, between $13°$ and $84°$ for $30°$ zenith distance and between $6°$ and $83°$ for $60°$. The observations are reduced using the equatorial coordinates and geocentric distance of the Sun given by the DE200/LE200 solar ephemeris. The solar radius adopted by this ephemeris is $959\overset{''}{.}645$ (Toulmonde 1995).

4. Results

The results presented in this paper are based on 2111 measurements of the apparent Sun semidiameter made since the beginning of the solar program of Santiago in April 27, 1990, until October 16, 1998. All the individual results of the astrolabe of Santiago, including the zenith distance residuals given by the observation of each solar border are available in electronic form at the Centre de Données Astronomiques at Strasbourg (CDS) (Noël 1998). Since the instrumental system, the observing technique and the reduction method have been kept without modifications during the whole observational period and on the other hand, all the observations were made by a unique observer, the results should be considered homogeneous.

The observed semidiameters were sorted in 15 classes of $15°$ wide of heliographic inclination with an overlap of $5°$, and a mean value was computed for each class. The results of Santiago do not show significant systematic differences between the semidiameters observed at $30°$ and $60°$ zenith distances (Noël 1997), therefore, no correction for zenith distance effect (Laclare et al. 1996) has been applied.

The results are given in Table 1 with the mean value of the solar radius obtained during the whole period of observation. In

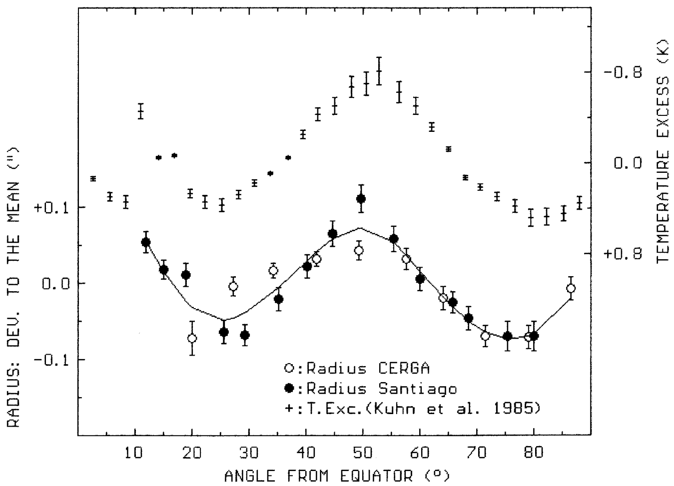

Fig. 2. Deviations to the mean of solar semidiameters observed with astrolabes and temperature excess of the solar limb as a function of heliographic inclination

Fig. 2 are plotted the deviations to the mean of the semidiameters as a function of the heliographic inclination expressed as angle from the solar equator, with similar results obtained with the solar astrolabe of the Centre d'Etudes et des Recherches Géodynamiques et Astrometriques (CERGA), France, during the period 1978–1994. The results of CERGA were obtained also visually and also by a unique observer (Laclare et al. 1996). The values of CERGA in Fig. 2 were obtained by this author from Fig. 4.8 of Vigouroux (1996). The heliographic inclination of the semidiameters observed at CERGA varies during the year between $15°$ and $90°$ (Laclare et al. 1996). The results of both astrolabes in Fig. 2 are smoothed by the method of Vondrak with a smoothing parameter equal to 1×10^{-8} (Vondrak 1969). Therefore, the solid curve represents the average of the results of CERGA and Santiago.

Non facular temperature excess of the photosphere along the solar limb were obtained by Kuhn et al. (1985) from observations made with the Princeton Solar Distortion Telescope between 1982 and 1983. The graphic values given in Fig. 5 of that paper were adapted by this author and are plotted in Fig. 2. However, for a clearer comparison with the astrolabe results the temperature scale is inverted, and the amplitude was corrected according to Kuhn et al. (1987).

5. Discusion

From Fig. 2 it is fairly clear that there is a significant dependence of the observed solar semidiameters with the heliographic inclination. However, as it was stated above, the heliographic inclination of the semidiameter observed with an astrolabe varies throughout the year. Therefore, we may wonder whether this dependence could be not well explained by a seasonal systematic effect in the astrolabe results. On the other hand, it follows from Table 1 that at Santiago each solar radius is obtained at $\sigma \approx \pm 0''.5$. Since the average value of n is 269 and since the radius variations reported in Fig. 2 are of the order of $0''.1$, they are comprised between $\sigma(\pm 0''.5)$ and $\sigma/\sqrt{n}(\pm 0''.03)$. Therefore, one could presume that at least part of the semidiameter fluctuations seen in Fig. 2 could be of statiscal origin. Nevertheless, the remarkable agreement of the results of CERGA and Santiago that can be seen in Fig. 2 would be at issue with these assumptions. Both sets of results were obtained from long series of observations made at places with quite different local topography and at different hemispheres. Furthermore, the observational periods and the precision of the results are also different (Laclare et al. 1996). There is no reason to presume that the same seasonal artifact could be affecting the observations at two sites some 12.000 km apart, or that a special behaviour of accidental errors is producing a similar distortion of the results at both observatories. Therefore, in our view, the observed dependence of the apparent solar semidiameter with the heliographic inclination presented in Table 1 and in Fig. 2, should be intrinsic to the Sun.

An interesting and rather clear anticorrelation between the deviations to the mean of the semidiameter and the temperature excess along the solar limb can be seen in Fig. 2. The temperature excess data show maximums at high latitude zones and towards the zone of active regions. Since the radius and temperature data were derived from separate and quite independent experiments based on rather different observing techniques, the accuracy of the anticorrelation suggests that both parameters should be somehow but rather closely related.

According to Pecker (1996), at least part of radius variations along the solar limb can be linked on the one hand with the "royal zones" (about $20°$-$30°$ of heliographic latitude) where the existence of spots diminish the brightness and therefore the measured radius, and on the other hand with the high latitude activity zone ($70°$-$80°$) where faculae should have an inverse effect. However, one can see in Fig. 2 that the relation between temperature and semidiameter along the solar limb, is not consistent with that assertion. On the other hand, Ribes et al. (1991) have associated temperature excesses with an equivalent displacement of the solar limb. If there is a real displacement of the limb or if higher temperatures imply a modification of the limb darkening function gradient, then the measurements of the solar radius could be affected (Vigouroux 1996).

A research is in progress at Santiago concerning a possible variation of the observed shape of the solar limb with the solar cycle. According to our data obtained so far, the bulge of the apparent limb that can be seen in Fig. 2 around $50°$ of solar latitude, is probably time independent. However, towards the zone of higher latitudes but rather specially towards the solar equator, it seems that the shape of the limb varies with the solar cycle. Apparently this is also consistent with the temperature excess along the solar limb (Kuhn et al. 1988). A report will be given once a period of observations equivalent to a solar cycle has been completed with the astrolabe of Santiago.

6. Conclusions

Since personal biases remain one of the main unknowns, the legitimacy of visual observations for measuring the solar diameter has been disputed. The personal equation is extremely difficult to estimate, as it is not known which part of the limb profile the eye is sensitive to. Furthermore, it is not possible to assure that personal bias should remain constant with time for a given observer (Ribes et al. 1991, Sinceac 1998). Therefore, the absolute value of the solar diameter obtained from visual observations can be strongly affected by personal biases. Nevertheless, for solar physics the eventual variations of the Sun semidiameter are far more interesting than its actual value (Ribes et al. 1991, Toulmonde 1995). However, to disclose from visual observations such eventual variations of the solar radius, it must be strongly stressed that only those results obtained by the same observer should be used in the analysis. This is a fairly important point, and the astrometric results presented in this paper show that visual observations with astrolabes, when they are made by a unique observer like at Santiago and CERGA, can disclose rather fine variations of the solar semidiameter.

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