OBSERVATIONS OF THE SOLAR LIMB SHAPE DISTORTIONS

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Abstract. Two new campaigns devoted to the observation of the solar limb distortions were made at the Pic-du-Midi Observatory, in September 2000 and September 2001, by means of the scanning heliometer. This apparatus can be used now routinely to accurately determine solar limb profiles (at two wavelengths), at any heliographic latitudes. Each measurement is made within 44 milliseconds (of time) which permits to record a limb profile together with the seeing. Scans are automatically rejected for seeing larger than 1.3 arc sec. Such conditions are essential to perform high-quality observations necessary to obtain the quadrupole term ($l = 2$) in the polynomial expansion of the radius contour $R(\psi)\ |_{\rho=\text{constant}} = R_0\left(1 + \sum_l c_l P_l(\psi)\right)$. Exceptional meteorological conditions in September 2001 (seeing of the order of 18 cm, for a 50 cm clear aperture of the refractor) enabled us to determine c_2 and c_4 (see Table I) with an accuracy of a few milli-arc-sec. Results indicate a distorted solar shape, the departures from a pure spherical body not exceeding 20 milli-arc-sec. We propose a model to interpret such results (the combination of a nearly uniform rotating core with a prolate solar tachocline and an oblate surface), which is briefly discussed. Our results are confronted to those obtained from space. We conclude that measurements of the quadrupole term from the ground are possible, but of high difficulty and can be obtained only during excellent weather conditions. The hexadecapole term should be only obtained from space. We show that an astrometric satellite would be required, whose mission would be also to accurately determine the solar rotation profiles (both surface and in depth) in order to unambiguously determine the inertia moments of the Sun through the J_n terms. Such values are also briefly discussed.

1. Introduction

In spite of its apparent simplicity, solving the accurate determination of the solar shape is perhaps today one of the most difficult problems of solar physics. At a first glance, we expect the whole figure of the Sun to be oblate, owing to centrifugal distortion by its rotation. The differentially rotating convection zone seriously complicates this crude analysis, all the more confused by non-constant values over zonal rings (sometimes called ‘cylinders’), both on the surface and in depth. Such a complex regime has been revealed by helioseismic observations. In this last case, even if the measurements are accurate from the equator to the mid-latitudes and below the photosphere, and become more and more uncertain when sounding the poles and the very near surface (Di Mauro, 2003, including many other references), it is now understood that the rotation rate is far from being uniform. In such conditions, how can the oblateness of the outer envelope be computed, as this

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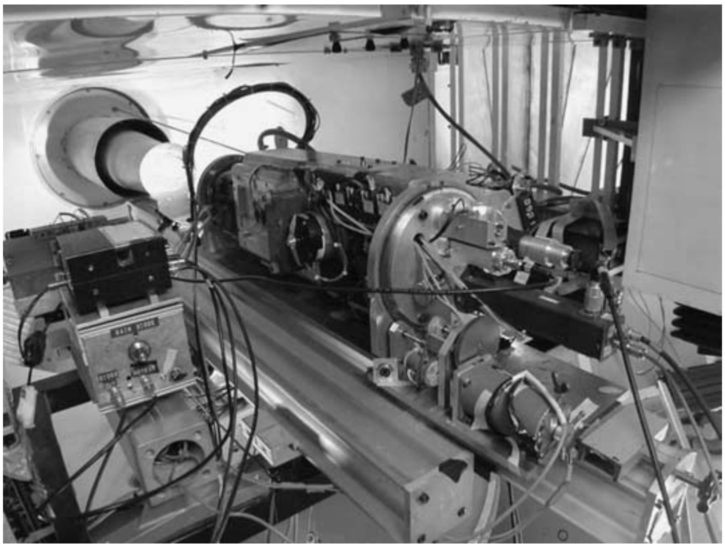

Figure 1. The scanning heliometer mounted inside the so-called 'coupole tourelle' – turret dome – at the Pic-du-Midi Observatory (F). A complete description of the apparatus can be found in Deslandes (1994, 1995).

oblateness reflects the physical conditions acting in the Sun's interior? Directly related to this question, due mainly to magnetic stresses and thermal shears, it is perfectly conceivable that the figure of the Sun must be distorted. In contrast, if it would be possible to precisely measure the solar shape by any means, then the determination of the solar multi-pole moments (oblateness to the first order) could yield constraints on the Sun's internal structure (a fact called by G. Isaak *'a new window open over the Sun's interior'*, Rozelot and Lefebvre, 2003). Unfortunately, the exact determination of the figure of the Sun is also a very difficult task; today with the progress of more and more sophisticated techniques, and awaiting the advent of dedicated space missions, attempts in this direction deserve to be made. Moreover, as it is not yet well understood if the solar shape is time dependent or not, we reactivate our solar program, initiated by J. Rösch in 1970 (Rösch and Yerle, 1983), but operational since 1996 only (Rösch *et al.*, 1996).

2. Observations at the Pic-du-Midi Observatory

The scanning heliometer (Rösch *et al.*, 1996) can be used now as a patrol instrument due to several improvements, mainly made in the electronic parts and the software of data acquisition and analysis. Let us recall that the apparatus is mounted at the Pic-du-Midi Observatory (Figure 1) inside the so-called 'coupole tourelle' (a turret dome, completely closed in order to avoid heating transfer between the inside of the dome and the outdoors, a concept which gives complete satisfaction

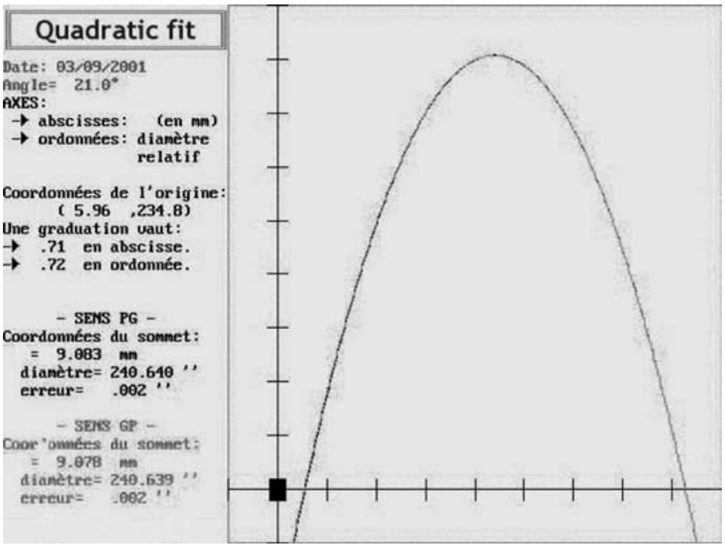

Figure 2. An example of the 'slicing process' (directly taken from the screen of the PC monitor) which consists to measure successive chords below and beyond the diameter (at a given heliographic latitude), within a 100 milliseconds of arc (mas) extent permitting to reconstruct the limb in the vicinity of the 'true' diameter. The diameter is deduced as the maximum of the parabolic fit of the data (an elliptic fit was tried, but does not increase the accuracy). The error of the position is no more than 0.002 arc sec. Two curves are plotted, one for a scan in one direction (for example west–east) and the other curve for the opposite scan (east–west scan in the example).

and that has been adopted in other sites such as the 'Themis' telescope in Canary Islands). The instrument was first designed to accurately measure the solar oblateness. Campaigns in 1993 and 1994 have permitted to settle the instrument which gave its first acceptable results: due to technical reasons, only equatorial and polar diameters were measured, leading to the determination of the visual oblateness (see preliminary results in Rozelot and Bois, 1998; a complete re-analysis is under consideration). Unfortunately, the Pic du Midi was closed between 1996 and 1997 and a technical refurbishing of our instrument has been done in 1998 and 1999, preventing observations during all that time. As results of the early observations were encouraging, the main initial goal was taken again aiming to record solar limb profiles at any heliographic latitude: thus the whole shape of the Sun can be restored. However, the data collecting process is still rather long, due to the 'slicing' procedure. This procedure can be described as follows. To be sure to measure a genuine diameter, at a given heliographic latitude, we record several successive chords below and beyond this diameter that permit to re-build the limb; the diameter is deduced as the maximum of the quadratic fit of the data (see Figure 2, with an error of the position of no more than 0.002 arc sec). Each data point is the result of 44 scans in one direction (for instance west–east) and 44 others in the other one (east–west in the quoted example; an internal system

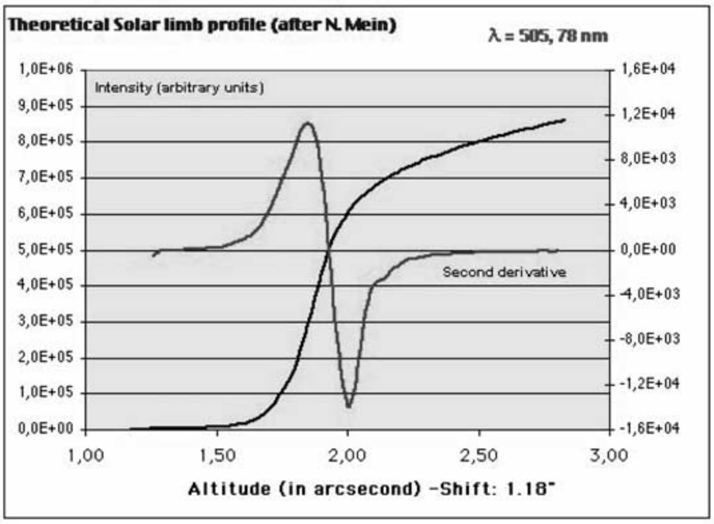

Figure 3. Theoretical solar limb profile (after N. Mein, from Meudon Observatory) – in bold, *left scale* – and its second derivative – *right scale*. This profile, computed in steps of 20 km has been interpolated to steps of 1 km by means of cubic splines and is used to determine the seeing. A short-exposure Fried function computed with increased parameters r_0 is successively convoluted with this theoretical profile to be fitted to the experimental data. The process is stopped when the adjustment is maximum ($\mathcal{R}^2 = 0.9$ or higher), thus giving the best r_0 at the time of the measurement.

– a small air-prism – permits to discriminate the two directions if necessary and allows a perfect calibration of the scan. Such a procedure does not allow to obtain daily more than about a dozen of diameters around the Sun, the outside turbulence becoming too important after noon. Indeed, our experience shows that it is pointless for our purpose to observe when atmospheric conditions are not exceptional.

The seeing is monitored for each scan and is deduced from the deconvolution by a Fried short exposure time function (Coupinot, Hecquet, and Futaully, 1990); the theoretical limb profile has been computed by N. Mein and is visible in Figure 3. It has already been shown (Loyer, 1995) that this last function can be approximated by a Gaussian which models the complete set consisting of the atmospheric function plus the transfer function of the apparatus: the fitting of the experimental data, after the convolution process, gives an adjustment coefficient $\mathcal{R}^2$ always greater than 0.9. This value is checked at each scan and the scan is rejected if $\mathcal{R}^2$ is below this threshold. Finally, knowing the seeing permits to compute the shift of the inflexion point as the profile of the image of an object progressively darkened (case of the solar limb) is shifted towards the brighter region. This shift increases with the width of the image and can reach 80 mas for a seeing x of 1.5 arc sec. The theoretical curve

$$y(\text{shift}) = 0.083x - 0.045 + 0.045\ \exp(-4.09x) \quad (y \text{ in arc sec}),$$

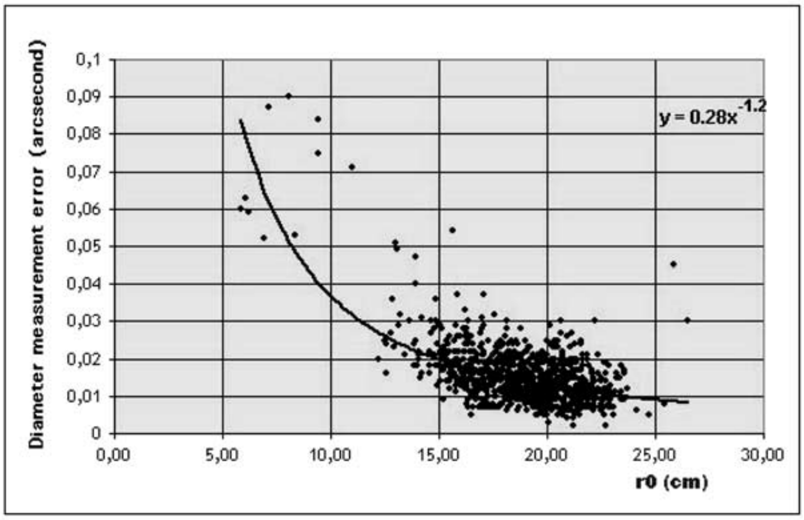

Figure 4. Error in diameter measurements as a function of the Fried parameter r_0. Exceptional weather conditions were encountered on the 3rd, 4th, 5th, and 6th of September 2001. Note that the theoretical diffraction limit of the refractor (diameter 50 cm) is $\alpha = 0.256$ arc sec. The exponent of the power curve fitting is 1.2, as exactly predicted by the theory: 6/5.

where x is the seeing, shows that a variation of $\pm$ 20% of this value, implies a shift of 50 mas. This technique is thus strictly similar to the FFTD proposed by Hill, Stebbins, and Oleson (1975). In other words, corrections by means of the above description of the shift of the inflexion point, or corrections made by applying directly the FFTD, lead to the same consistent values.

3. Observed Values and Data Analysis

From several campaigns made at the Pic-du-Midi Observatory, only two were kept for our purpose: measuring distortions of the solar shape. One campaign was done during September 2000 and the other one during September 2001. Unprecedented weather conditions were encountered in this last mission: moderate north–west wind, slight turbulence; a mean seeing of $r_0 = 18$ cm was obtained. Figure 4 shows the errors on the diameter plotted versus the seeing. The exponent of the curve fit is 1.20, to be compared to the theoretical one which is 6/5. As expected, the errors decrease with increasingly good seeing conditions. Curiously, two points have been obtained for high values of r_0 (i.e., 25.7 and 26.4 cm), which are completely out the curve fit; these two measurements are certainly erroneous for an unknown reason. Data are recorded in files together with the meteorological parameters (namely, hygrometry, pressure and temperature: these parameters are recorded outside, around 6 m from the focal point, near the refractor lens) which permits to perform the refraction corrections afterwards.

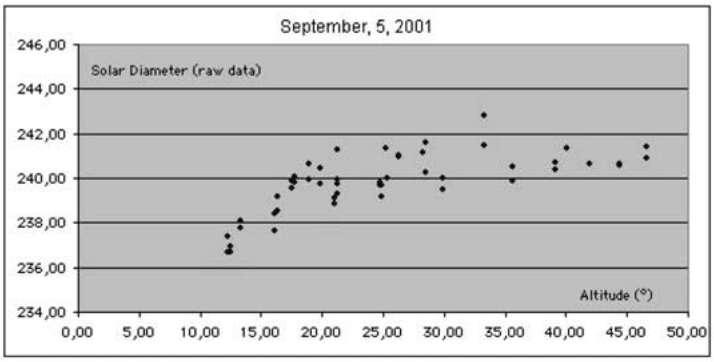

Figure 5. Raw data obtained on 5 September 2001 plotted versus the altitude; no refraction corrections have yet been applied. The instrumental constant (1661.50 arc sec) is not taken into account, as well as all other corrections such as the rotation of angle B_0. The point higher than 242 arc sec has been identified as the result of a scan through a faculae (see Figure 6). Values are for the time being semi-absolute and will become absolute when a prism will be set in front of the telescope to calibrate the distance between the two internal signals giving the reference distance of the two opposite inflexion points.

When scanning the Sun at a given heliographic latitude, the two limbs are brought together through a rhomb of well-defined and fixed-angle distance (1661.50 arc sec – this quantity acting as an instrumental constant). This time saving process permits to simultaneously record the two opposite limbs in the same file (but r_0 is computed for each profile). Raw data of the diameter plotted as a function of the zenith angle are shown in Figure 5 (the instrumental constant excluded). Note that the measurements are self consistent: the distance between the inflexion points is always accurately measured by reference to the internal calibration. However, we need to go from these semi-absolute values to absolute ones by putting a prism in front of the telescope to obtain the absolute reference. This will be done in the future. Data are then corrected to take into account the refraction effects, the angle B_0 and at last are normalized to 1 AU. As the topocentric correction is very sensitive, we used in the computations the exact longitude and latitude of the center of the dome: $\lambda = 36.4$ s east, $\phi = 42°56'12.0''$ north (and $z = 2861.0$ m).

4. Results and a Possible Model

After all corrections were made and the Sun rotated to adjust the north pole, the following results were obtained:

(1) Although fairly good meteorological conditions were encountered during the September campaign in 2000 (on the 2nd and 4th), the mean seeing was 'only' $r_0 = 14$ cm; the turbulence was not sufficiently stable to perform measurements at several heliographic latitudes. In order to save chances to observe in the best

TABLE I

Measurements of the (relative) semi-diameter of the Sun, averaged over four consecutive days in September 2001 (on the 3rd, 4th, 5th, and 6th), for six heliographic latitudes.

Position angle (°)	Semi-diameter	Error	Number of scans
0.0	959.434 arc sec	± 2.8 mas	1980
7.2	959.442 arc sec	± 3.2 mas	1320
21.7	959.444 arc sec	± 4.1 mas	1056
50.0	959.424 arc sec	± 3.3 mas	748
70.0	959.424 arc sec	± 3.0 mas	924
90.0	959.425 arc sec	± 2.9 mas	1188

atmospheric conditions, we first carried out processes at the solar equator and at the pole to determine the flatness, which was found to be

$$f = \Delta R/\overline{R} = (R_{\mathrm{eq}} - R_{\mathrm{pol}})/\overline{R} = (9.05 \ \pm \ 1.60) \times 10^{-6}$$

as an average. We also performed some measurements at other heliographic latitudes to improve the experimental procedure which is not obvious (for each measurement of the slicing process, one has to compensate both in declination and right ascension; at the equator or at the pole, one has to adjust only in one direction, which is easier). Only measurements at 45° have been kept for a further analysis.

The daily means of $\Delta R = (R_{\mathrm{eq}} - R_{\mathrm{pol}})$ in September 2001 are, respectively: 7.43 ± 4.0 mas (3 September), 8.44 ± 2.9 mas (4 September), 7.65 ± 2.9 mas (5 September), and 11.49 ± 2.1 mas (6 September).

The weighted mean value is 9.46 ± 1.41 mas.

(2) Certainly measured for the first time from the ground (7216 scans), and on four consecutive days, six solar radius measurements were obtained for six angles of position listed in Table I.

Averaging data over the four days, we found a measured oblateness of

$$\varepsilon = \frac{(R_{\mathrm{eq}} - R_{\mathrm{pol}})}{R_{\mathrm{eq}}} = (9.42 \ \pm \ 3.02) \times 10^{-6}.$$

The measured shape asphericity of the density contour of the Sun plotted versus the heliographic latitude (diamonds with their error bars) is given in Figure 7. The line curve (circles) is the representation of

$$R(\psi) \mid_{\rho=\mathrm{constant}} = R_0 \left[1 + c_2 P_2(\psi) + c_4(P_4(\psi)\right],$$

where ψ is the colatitude and P_n the Legendre polynomials of degree n. From this plot can be deduced the quadrupole term ($l = 2$) in the polynomial expansion of the radius contour as $c_2 = -(1.1 \pm 0.5) \times 10^{-5}$ (c_2 is the average of the fitted coefficients using the upper and lower points of the error bars, hence the uncertainty). The hexadecapole term ($l = 4$) is more difficult to determine. A value of $c_4 = 3.4 \times 10^{-6}$ was deduced, but any values below this threshold would adjust the data. A strict fitting of the observed values yields $c_2 = -1.32 \times 10^{-5}$ and $c_4 = +4.43 \times 10^{-6}$.

From the best Legendre's polynomial fit curve, the oblateness is

$$\varepsilon = (R_{\rm eq} - R_{\rm pol})/(R_{\rm eq}) = 1.46 \times 10^{-5}, \qquad (1)$$

a bit larger than expected from the measurements alone, whilst the theoretical curve gives $\varepsilon = 8.42 \times 10^{-6}$. The flatness is thus $f = 9.38 \times 10^{-6}$.

Finally, inspection of Figure 7 shows a well-marked asphericity. Indeed, the simple interpretation is to fit the data points by a sphere, the radius of which would be $\overline{R} = 959.432$ arc sec. This fit systematically overestimates the values at the poles and underestimates the equatorial ones. Relaxing the assumption of sphericity, the measured visual outer shape appears to be slightly bulged from around 10° to 30° and moderately depressed at higher latitudes. The global whole shape remains ellipsoidal and the departure from a spheroid does not exceed ± 10 mas, as a very upper bound. Such a result, obtained in excellent meteorological conditions (it has been shown in the past that photographic granulation obtained at the same dome at the Pic-du-Midi Observatory with the same refractor had reached the same resolution as pictures obtained with stratospheric balloons, see, for instance, Shirley and Fairbridge, 1997) needs to be confirmed by other means, especially from space. We expect that SDS experiments would be able to do that in a near future (at least as soon as flights will be again operational and we would be grateful to the scientific community to support such missions). In the future, one of the main goals of the PICARD mission, already accepted and financed by the French Space Agency CNES is to precisely measure the shape of the Sun. The launch is expected by mid 2007.

4.1. Comparison with Theoretical Computations

Armstrong and Kuhn (1999) computed the theoretical distortions of the shape of the Sun, $R(\psi)\mid_{\rho=\text{constant}} = R_0\left[1 + \sum_l c_l P_l(\psi)\right]$, through a vector harmonic solution. This theoretical curve is plotted (squares) on Figure 7 using the c_n given by the authors.

Results can be also compared with these obtained from the SOHO-MDI observations, and are listed in Table II. Data from SOHO-MDI have been obtained by Kuhn *et al.* (1998) and the shape coefficients c_n were derived by measuring small displacements in the solar limb-darkening function. At last, the complete theory of the figures permits, for the Sun, to compute the values of the c_n and can be found in Rozelot and Lefebvre (2003). If a general agreement can be found for c_2, it is not the same for c_4 and this shows that the observed outer shape of the Sun deviates from a pure sphere. In this last case, c_4 would be $c_4 = +\frac{12}{35} f^2$ (where f

TABLE II

Comparison of the shape coefficients as observed from SOHO-MDI and from the Pic-du-Midi experiments. First line of the column 'Theory': as computed using the theory of figures; second line: as computed by Armstrong and Kuhn (1999). For c_4, the mismatch between the theory and experimental data can be only explained by a better understanding of the three-dimensional solar interior rotation.

Shape coef.	SOHO-MDI	Pic-du-Midi	Theory
c_2	$-(5.27 \pm 0.38) \times 10^{-6}$	$-(1.1 \pm 0.5) \times 10^{-5}$	-7.06×10^{-6}
			-5.87×10^{-6}
c_4	$(1.3 \pm 0.51) \times 10^{-6}$	3.4×10^{-6} (or less)	3.48×10^{-11}
			0.616×10^{-6}

is the flatness) which is obviously not the case (c_4 would be 3.48×10^{-11}). The only way to interpret such a discrepancy is to say that not only the rotation velocity rate is greatly perturbed on the surface, but also within a thin sub-surface layer. The first point is known from helioseismology, for which helioseismic surface measurements are different from Doppler or other visible tracers. The second point may imply magnetic stresses or shears in a thin layer just beneath the surface, sometimes called the 'leptocline'.

5. Discussion and Comparison with Other Data

It is rather hard to deduce the oblateness f as well as the shape coefficients c_2 and c_4 from observations, either from ground or from space experiments. Several attempts have been made since the 'historical' measurements done by Dicke and Goldenberg (1967). Although the fractional difference of equatorial and polar radii obtained $(5.0 \pm 0.7) \times 10^{-5}$ at that time was certainly too great, leading to astrophysical consequences not easily acceptable, the flood of major papers that followed have shown the interest of such measurements. The debate is not closed.

All the values of the Sun's oblateness so far obtained are not yet in complete agreement, but it seems that comparative limits can be set up. Firstly, the value of f is certainly less than the upper Roche's limit for the Sun which is (5/4) m (Burša, 1986), that is to say 2.7×10^{-5} (m is $\omega^2 R^3/GM$ with classical definitions of the variables). If the Sun would rotate rigidly, the maximum value deduced from the maximum measured equatorial velocity rate is $f = 1.13 \times 10^{-5}$ and from the polar one around 6×10^{-6}. In this case, the value is less accurate as uncertainties on polar velocity rates are higher at the poles than at the equator, even using helioseismology. It results that the solar flatness lies between these values, and leads to a difference between the equatorial and polar radii of the Sun of 8.53 ($\pm$ 1.89) mas, bounded by 6.39 ($\pm$ 1.31) mas as a minimum and 10.54 ($\pm$ 0.25) mas as a

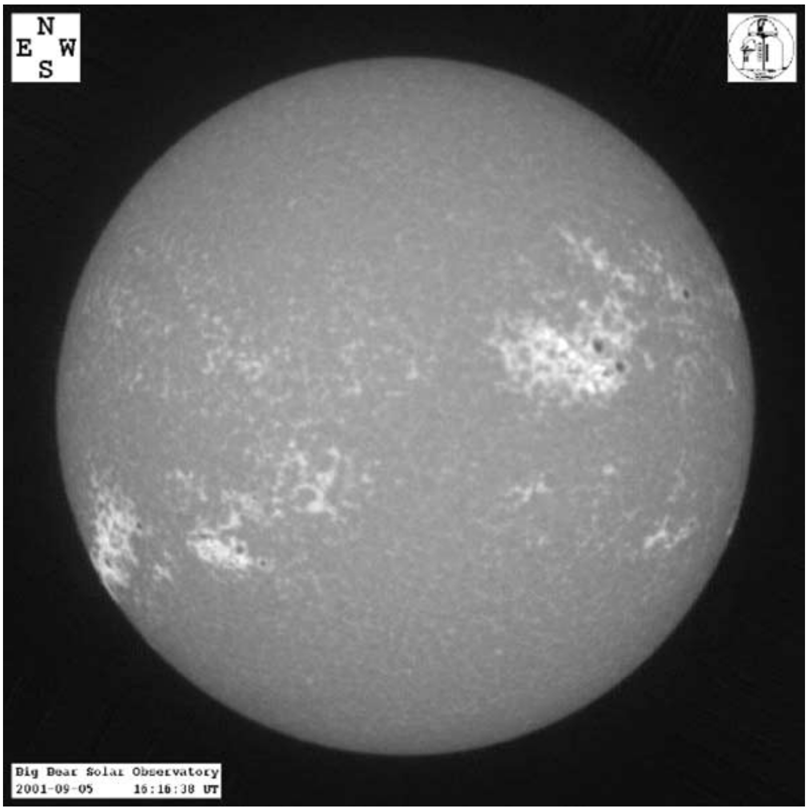

Figure 6. Image of the Sun on 6 September 2001 taken at Big Bear Observatory (web site). The faculae on the east side (left) are perfectly visible. Some scans were made through these faculae: the signal was perturbed giving a double maximum at the top of the profile. The signature of the faculae was thus perfectly identified. A similar profile, but enlarged at the bottom of the profile is obtained when scanning a spot (which was not the case here). As the profiles of the limbs are displayed on the monitor before being recorded, their sample eye-inspection permits to visualize the contamination at the solar edge. The complete identification can be made afterwards and the files contaminated by spots or faculae are removed. During the next campaign, an instrumentation called MIRESOL will be put in operation in parallel with the scanning heliometer to detect on Ca II images the Sun's activity at the limb. (See Lefebvre and Rozelot, 2001.)

maximum. Lower, as well as greater values, would imply accounting for physical mechanisms, such as shear turbulence beneath the surface, of such an order of magnitude that these mechanisms can play a significant role.

From the Solar Disk Sextant Experiment, Lydon and Sofia (1996), have determined f to be $(9.17 \pm 1.25) \times 10^{-6}$ in 1992 and $(8.77 \pm 0.99) \times 10^{-6}$ in 1994. Other values can be found in Godier and Rozelot (2000, 2001).

It is not the first time that a distorted shape of the Sun is reported in the literature. For instance, the solar diameter measurements of Noël (1999, 2003) and Reis Neto *et al.* (2003), by means of the solar astrolabe, have already shown that

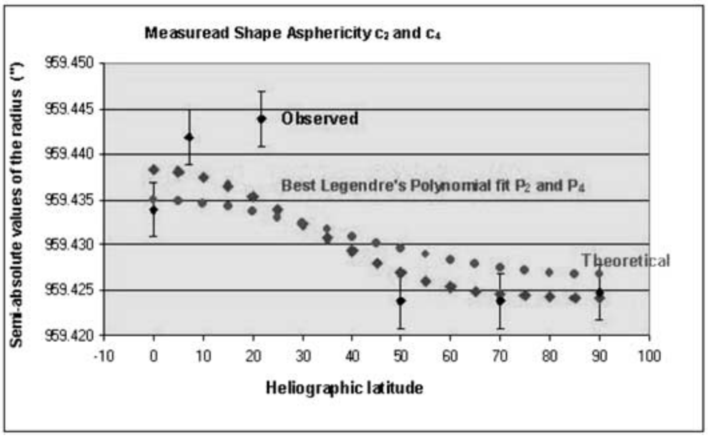

Figure 7. Measured shape asphericity c_n of the density contour of the Sun plotted versus the heliographic latitude. Observed points (*diamonds*) with their error bars show a well-marked asphericity. The theoretical curve (*squares*) has been plotted using the shape coefficients taken from Armstrong and Kuhn (1999): $c_2 = -5.87 \times 10^{-6}$ and $c_4 = 6.16 \times 10^{-7}$. As observed values are semi-absolute, the corrected measurements have been adjusted to the same scale as the theoretical ones. The best fit, given by the two first Legendre's polynomials (average of points fitting on one hand the upper error bars and on the other one the lower ones) yields $c_2 = -1.1 \times 10^{-5}$ and $c_4 = +3.4 \times 10^{-6}$. A bulge is observed which ranges from around 10° to 30° of heliographic latitude, followed by a depletion zone, with the whole shape remaining ellipsoidal. The departures from a spheroid are no more than ± 10 to 12 mas.

the solar radius is latitude dependent. Averaging semi-diameter measurements by helio-latitudes, the Brazilian team obtained an asphericity characterized by a bulge well marked around the royal zones followed by a depression before reaching the poles. Obviously, atmospheric seeing conditions in Brazil may pollute the signal coming from the Sun (if any), but the time span of three years used for sorting the data is of sufficient range to deduce significant results. Even if the data are certainly affected by the turbulence effects, it would be unlikely that similar results found by different observers at different sites, and using different techniques would not reflect a real solar effect. As already stated (and the same argument can be applied for temporal radius variations, see for instance Noël, 2003, or Wittman, 2000), only space missions would be unambiguous.

Up to now, such departures of the solar sphericity, if admitted, are not well explained and only rough explanations can be put forward. A possible one lies in the difference of temperature measured between the solar pole and the equator (Kuhn, 1998) that can be also related with the radius and the angular velocity through the 'thermal-wind' equation. Such a formalism is detailed in a separate paper (Lefebvre and Rozelot, 2003). However, if J_4 is of the order of J_2, as deduced from our observations and already obtained by Sofia, Heaps, and Twigg (1994) or Lydon and Sofia (1996), then the theory of figures of rotating bodies indicates clearly a distorted shape of the Sun. For the time being, the only way to reconcile

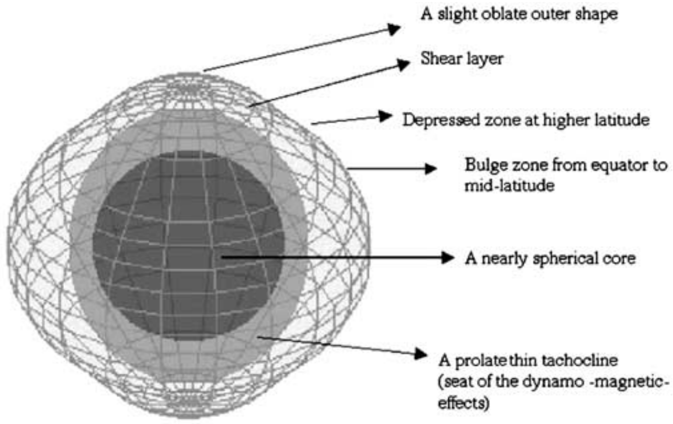

Figure 8. Schematic shape of the Sun (exaggerated view – not to scale). This crude – but realistic – theoretical model of the Sun includes a spherical solar core rotating at a nearly uniform velocity rate, a prolate solar tachocline and an oblate surface shape, both rotating at different velocities; it results mainly from latitudinal shears and thermal winds on the surface, that affect the surface which is thus corrugated. The induced gravitational moments such as J_2 (value: $(2.0 \pm 0.4) \times 10^{-7}$) and J_4 (value $(9.1 \pm 0.3) \times 10^{-7}$) explained the deviations from the best sphere, which cannot exceed an amplitude of $\sim \pm 10$ mas.

observations with the theory is to admit a model of the Sun composed of a spherical solar core rotating at a nearly uniform velocity rate, encapsulated by a prolate solar tachocline and an oblate surface shape, both rotating at different velocities. Figure 8 shows a schematic shape of the Sun, not to scale but illustrating our model. Such a configuration results mainly from latitudinal shears and thermal winds on the surface (Garaud, 2001) that affect the surface which is thus corrugated. The induced gravitational moments J_2 (value: $(2.0 \pm 0.4) \times 10^{-7}$, Pireaux and Rozelot, 2003) and J_4 (value: $(9.1 \pm 0.3) \times 10^{-7}$, Rozelot and Lefebvre, 2003 compared with 9.83×10^{-7}, Lydon and Sofia, 1996) explained the deviations from the best sphere that cannot exceed $\sim \pm 10$ mas. The analysis of hydrodynamic stability of solar tachocline latitudinal differential rotation using a shallow water model by Dikpati and Gilman (2001) leads to the same conclusion (see their Figure 1, p. 538).

6. Conclusion

Observations at the Pic-du-Midi Observatory by means of the scanning heliometer show departures from sphericity of the visual outer solar shape.

We have found that

– the mean oblateness was $(9.05 \pm 1.90) \times 10^{-6}$ in September 2000 and $(9.42 \pm 3.02) \times 10^{-6}$ in September 2001;

– the asphericities (which seem to be static, i.e., not time dependent) do not exceed ± 10 mas;

– the shape coefficient c_2 is $-(1.1 \pm 0.5) \times 10^{-5}$ and c_4 is $+3.4 \times 10^{-6}$.

This last value is inconsistent with a body purely ellipsoidal, for which c_4 would be 3.4×10^{-11};

– results are consistent with observations previously performed from space.

The mismatching between observed asphericities and theoretical ones, especially for the c_4 shape coefficient, can be explained if one takes into account the thermal wind effects. A crude theoretical model is proposed which is supported by theoretical works from other authors.

Progress on that problem will depend on improved measurements of the solar limb shape for which SDS experiments from balloon flights are greatly encouraged until the advent of dedicated space missions.

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