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Solar cycle dependence of the apparent radius of the Sun

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Abstract. Visual astrometric observations of the Sun covering the second and first part of solar cycles 22 and 23 respectively, have been carried out during the last 13 years with the Danjon astrolabe of Santiago, Chile. These observations give, among other solar parameters, an absolute value of the Sun's apparent radius. We report here the results obtained from 4092 homogeneous radius measurements at 30° and 60° zenith distances. The data set shows at both zenith distances a significant radius variation in phase with magnetic activity. Moreover, the observations at 30°, which are less affected by atmospheric noise, give a significantly higher correlation coefficient between radius variation and sunspot numbers. Other investigations of solar radius variations during the last decades based on different observing techniques, as well as two analyses of historical data, are commented. Most of them show also positive correlations between radius variation and solar activity. With the noted exception of Calern, France, the results obtained at other astrolabe stations during recent years are in agreement with Santiago. The discrepancy between Calern and Santiago and its probable cause are discussed.

Key words. astrometry – Sun: general

1. Introduction

The standard model predicts very slow changes in the structure of the Sun as the hydrogen is converted to helium in the solar core. These changes should be reflected in a secular increase of the radius of the Sun of the order of a few parts in 10^{11} per year. Since such change is not detectable within human time scales, any observed variation of the solar radius would imply important constraints on the standard model (Ribes et al. 1991). However, eventual variations of the solar radius are not only important for solar physics, they are also of fundamental importance for the research of terrestrial climate. Theoretical predictions indicate that radius variations should produce significant changes in the solar luminosity, which is the primary force driving atmospheric circulation (Sofia et al. 1979). Luminosity variations as small as 0.3%, should have measurable effects on the climate (Gilliland 1980; Haigh 1996). If a link could be established between solar changes and their effects on the climate, this unique result should be sufficient to justify all the effort dedicated to this research. This is a real motivation to develop programs of solar radius measurements. Their results should be a strong contribution to guide theoretical research (Ribes et al. 1991). Scientific theories ultimately should be judged on the basis of empirical data.

The history of solar radius measurements so far has given inconclusive results. Therefore, the existence of variations in the apparent size of the Sun during the solar cycle is still a matter of controversy. While some results show no systematic variations in time of the solar radius (Brown & Christensen-Dalsgaard 1998; Wittmann 2003), other results show variations that are either correlated or anticorrelated with solar activity (Gilliland 1981). This lack of agreement could be due to the fact that the reported effects are only slightly larger than the errors of measurement (Newkirk 1983). On the other hand, analysis based on non homogeneous data sets can produce quite contradictory results (Basu 1998; Noël 2002).

2. Solar radius measurements with a modified Danjon astrolabe

Here we present significant empirical evidence that shows that the apparent radius of the Sun would vary in phase with solar magnetic actvity. This evidence is based on 4092 homogeneous radius measurements made over 13 years with a visual Danjon astrolabe at the National Astronomical Observatory of Universidad de Chile at Cerro Calán, Santiago. Since 1965 this astrolabe has been operated under a joint collaboration in Astrometry between the European Southern Observatory (ESO) and Universidad de Chile (Blaauw 1991). This collaboration has made important contributions to astrometry at the Southern Hemisphere (Anguita & Noël 1969; Fricke 1972; Schwan 1989; Noël & Débarbat 1990). They reflect the fairly good conditions of the observing site in Chile and the intrinsic capacity of the Danjon astrolabe for astrometric research.

The Impersonal Danjon Astrolabe developed at the Paris Observatory by Danjon (1960) was used extensively in astrometry with first-rate results (Eichhorn 1974). The observing principle is based on the Method of Equal Altitudes (Débarbat & Guinot 1970), which consists of timing the east and west transit of a star across a small circle of fixed altitude or almucantar that is the fiducial benchmark. A great advantage of the astrolabe is

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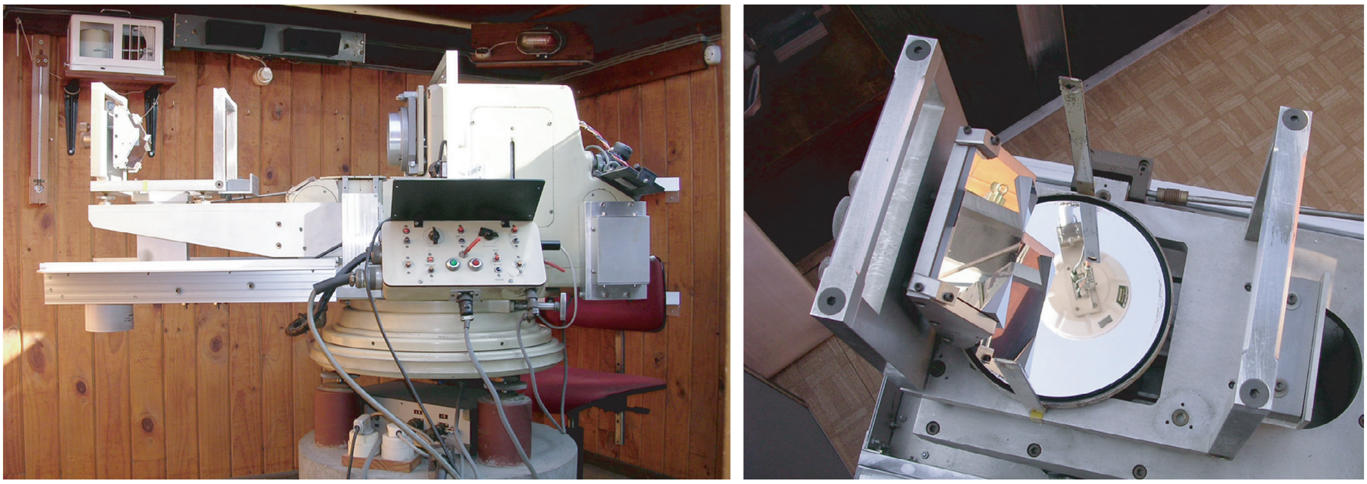

Fig. 1. Left: General view of the modified Danjon astrolabe of Santiago. The telescope is a broken refractor of 10 cm aperture and 1 m focal distance. Right: The CERVIT reflecting prism and mercury mirror that define the fixed almucantar which is the benchmark for the solar drift. The prism angle is the only instrumental constant whose variation would affect the observational accuracy. Its stability during the solar drift (at most 7 min) is assured by the low thermal expansion coefficient of CERVIT. Reflected on the mercury can be seen a unit that contains the antenna and receiver of a GPS timer that provides Universal Time Coordinated (UTC) for accurate timing of the solar drift.

that the bench mark is represented by the proper object that is being observed. A prism and a mercury mirror installed in front of the objective produce a reflected image of the observed star. Due to Earth rotation, direct and reflected images are in relative motion, and the almucantar transit is the instant of coincidence of both images. The fixed value of the almucantar is defined by the prism angle which is the unique instrumental constant whose variation would affect the observation's accuracy (Fig. 1). Therefore, the instrumental system of the astrolabe depends only on this angle (Danjon 1960). These advantages, combined with the method of equal altitudes, avoid important errors inherent to other astrometric instruments (Fricke 1972).

After modification, the Danjon astrolabe has been used also in solar astrometry (Laclare 1983; Delmas 2003). The qualites of the instrument and of the method of equal altitudes, allow measurement of the solar radius with significant advantages over other ground based techniques. Since these advantages have been described elsewhere (Noël 1999, 2003), we give here only a summary.

What is directly measured with the astrolabe is not the angle subtended by the solar diameter, but the time taken by the drift-scan of the solar image through the fix almucantar. Therefore, the calibration standard is the Earth rotation rate which is known with sufficient precision. It is claimed that the drift-scan technique is still the most accurately calibrated method for ground-based angular measurements (Wittmann 1997). The instrumental system must be stable only during the few minutes between the transits of opposite solar borders. An eventual drift of the focal distance during this short lapse can be accurately controlled. This is a prime advantage, since long-term stability of the instrumental system is the most stringent requirement of other methods for measuring the solar diameter (Brown et al. 1982). Since astrolabe observations are made at a constant altitude, the results are free of differential refraction, and according to the reduction method, eventual spurious effects in atmospheric refraction are cancelled (Noël 2003).

The special properties of the Danjon astrolabe that rendered it an important instrument in stellar astrometry make it now a very accurate instrument for solar metrology. Its accuracy relies on its fairly simple and quite compact instrumental solution for applying the method of equal altitudes (Fig. 1).

With the assistance of the astrolabe groups of the Paris Observatory and of the Station du Calern, Obervatoire de la Côte d'Azur (OCA), France, and of the mechanical and optical workshop of ESO, Chile, the astrolabe of Santiago was modified in 1989 in order to develop a program of solar astrometry. The new optical configuration is similar to that adopted by Thomas (1967) in the astrolabe of Herstmonceux. The transparent prism was replaced by two reflecting prisms made of CERVIT that allow observations at 30° and 60° zenith distances. The low thermal expansion coefficient of CERVIT provides a far more stable instrumental reference than that defined by the original glass prism. Moreover, disturbing effects inherent to transparent prisms do not exist in reflecting prisms (Kovalevsky 1990). Since both prisms can be interchanged in a few minutes, the Sun can be observed at both zenith distances during the same day. A solar filter made of transparent CERVIT is installed in front of the objective in a fixed position independent of the observing zenith distance. The bandwith of solar filter plus astrolabe optics is 200 nm centered at 540 nm approximately. For a description of the instrument, the program of solar astrometry at Santiago and the reduction method, see Chollet & Noël (1993) or Noël (2003).

3. Observational results obtained at Santiago

A total of 4383 measurements of the apparent solar radius have been obtained with the Danjon astrolabe of Santiago between April 27, 1990 and April 30, 2003. During this time, no modifications have been introduced in the instrument nor in the

Table 1. Mean values of the solar radius ($R_{\odot}$) obtained from astrolabe observations at Santiago according to the observational zenith distance ($z_{\odot}$) and to east and west almucantar transits. n is the number of measurements.

$z_{\odot}$	$R_{\odot}('')$		$\sigma('')$	n
30° East:	960.41 ±	0.02	0.49	796
30° West:	960.44	0.02	0.45	739
30° E&W:	960.42	0.01	0.47	1535
60° East:	960.36	0.02	0.59	1521
60° West:	960.45	0.01	0.49	1327
60° E&W:	960.40	0.01	0.55	2848
TOTAL:	**960.41**	**0.01**	**0.53**	**4383**

observing technique and reduction method, and since all the observations were made by the same observer, the results are homogeneous.

Table 1 gives the mean values of the solar radius according to the observed zenith distance and according to east and west transits. There is no significant dependence on the zenith distance of the mean values. This is quite important concerning systematic effects of instrumental and/or atmospheric origin. Since the prism angle is the only instrumental constant of the astrolabe as is explained above, results obtained at different zenith distances can be considered as given by different instruments. Therefore, the atmospheric artifacts that could exist in the results of Santiago should be small. Otherwise, they would affect the results obtained at different zenith distances in almost the same way. This last eventuality is, in our view, quite improbable. However, Table 1 shows a small but slightly significant difference between east and west mean values in the same sense at both zenith distances. The dispersion is also slightly different, being higher for east observations, specially at 60° zenith distance. This is consistent with the quality of the solar images observed at Santiago. In general the solar borders are slightly more agitated during the east than during the west transits. We presume that this difference comes from temperature gradients in the atmosphere which should be higher during the morning. Moreover, since the high mountain range of Los Andes is to the east and close to the Observatory, it could be also a source of atmospheric noise in that direction. Obviously, bad seeing should affect more those results obtained at higher zenith distances, as it is apparent in our case.

To avoid a bias of this effect in a research of variations in time of the solar radius, we have used those values obtained from least squares solutions that involve an east and a west observation made during the same day (see Noël 2003). In our total of 4383 solar observations, there are 2046 daily pairs of east and west observations, from which the least squares solution gives the same number of observed radius values. Therefore, 93% of the whole number of observations were as used in our analysis of solar radius variation. This does not means that the remaining 7% were useless or abnormal; we did this only to have a balanced number of east and west observations. The observed solar radii are plotted in Fig. 2 as a function of time for 30° and 60° zenith distances. σ is the average of the standard deviation given by the least squares solution, and the figure in brackets is the number of daily results. Both data sets show a coherent variation in time even though they were obtained at different zenith distances and therefore, with respect to different instrumental bench marks.

Since the radius variation seen in Fig. 2 follows approximately the variation of solar activity, we compare in Fig. 3 the monthly means of sunspot numbers provided by Brussels World Data Center for Sunspot Index (SIDC) and monthly means of solar radii combining the measurements at both zenith distances given in Fig. 2. The smoothing curves are Vondrak's fits with the same smoothing parameter for radius and sunspots (Vondrak 1969).

The similarity of both smoothing curves suggest a causal connection between radius variations and solar activity. Moreover, further evidence in this sense is given by the correlations between sunspot numbers and radius according to the zenith distance of observation. Asuming a linear dependence between radius and sunspot numbers, Fig. 4 gives the linear correlations between both data sets for both zenith distances. The correlation coefficients (r), 0.70 ± 0.04 and 0.83 ± 0.04 for 60° and 30° respectively, are highly significant. However, as one should expect if radius and solar activity are causally related, the measurements at 30° that according to Table 1 and Fig. 2 are more accurate, give a significantly higher correlation coefficient.

4. Other results of solar radius measurements

Elsewhere we have shown that with the exception of the astrolabe of Calern, the solar radius measurement with Danjon astrolabes during the last years show variations in time that are in agreement with the astrolabe of Santiago (Noël 2002). However, solar radius measurements based on different observing techniques have been also obtained during this lapse. Before giving a brief review of these results, let us look briefly into two analyses of solar radius measurements made over the last 300 years.

According to Basu (1998), quite contradictory results have been given so far by the analysis of solar radius measurements over the last three centuries. Correlated as well as anticorrelated variations of the solar radius with solar activity have been equally reported from those analyses. The reason appears to be the inhomogeneity of the data used in the investigations. From a homogenised data base covering observations over more than three centuries, Basu (1998) found a statiscally significant relationship between solar radius and sunspot numbers in the sense that to higher levels of solar activity corresponds a larger diameter of the Sun. Obviously this suggest the possibility that both should be causally connected. However, the author says that further investigations as well as more solar radius measurements with modern techniques and instrumentation are necessary.

A data base of more than 4500 contact time observations of Mercury's transits across the solar disk between 1631 and 1973 was created by the Institute of Applied Astronomy of the Russian Academy of Sciences (Sveshnikov 2002). Besides its large number of observations, the data contain information on the observing sites, observers, instruments, and observation

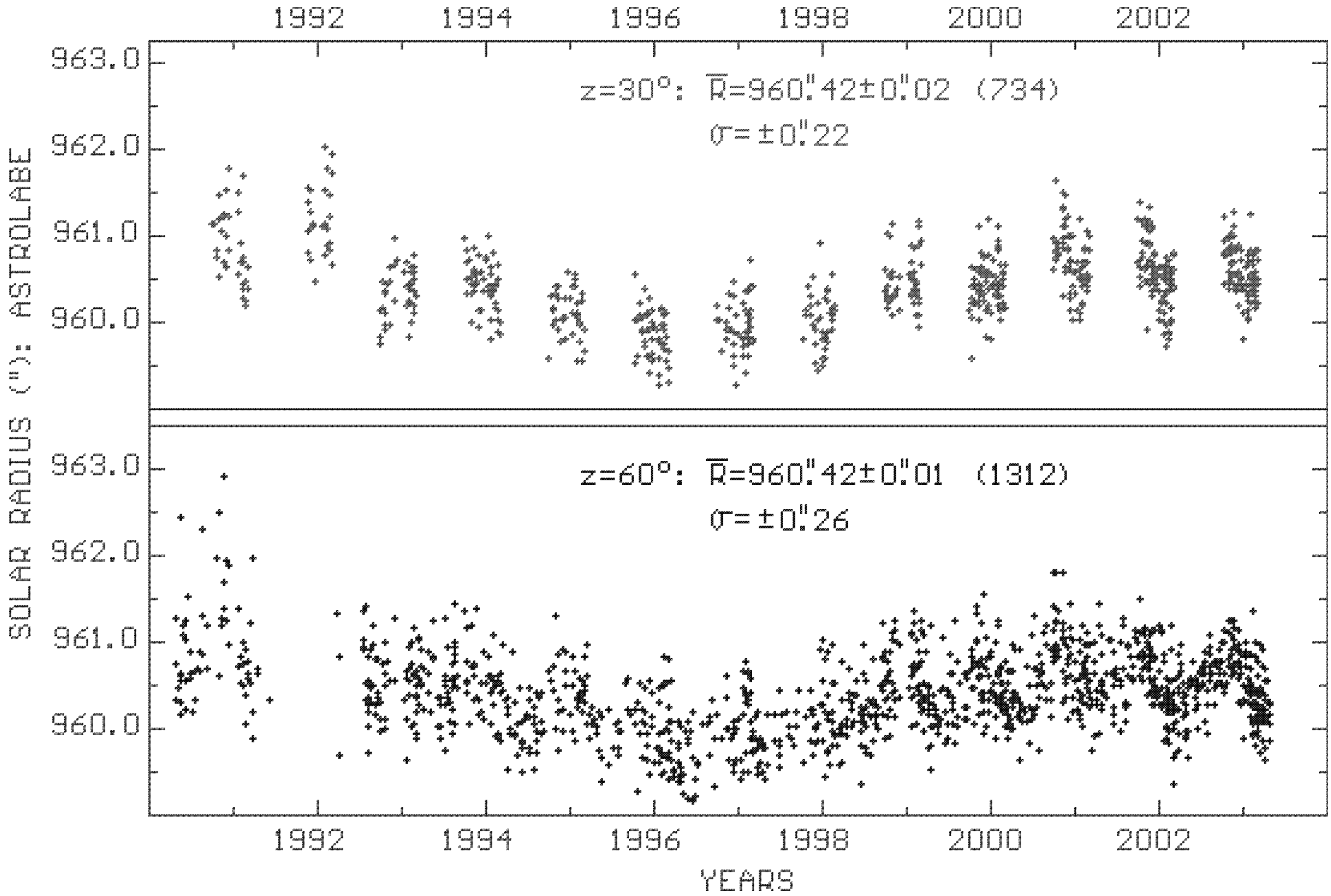

Fig. 2. Solar radius measurements obtained with the astrolabe of Santiago at 30° and 60° zenith distances between May 1990 and April 2003. Each point represents a radius value deduced from a least **squares** solution of east and west observations of the solar borders made during the same day and reduced to the unit of distance (Noël 2003). σ is the average of the standard deviations given by the least square solutions and the figure in brackets is the number of radius measurements. From Santiago (Lat. = −33°.4), the Sun is observable all year round at 60° zenith distance and from October 6 until March 7 at 30°.

techniques and conditions. Analyzing the inner contact times of Mercury transits during that period, Sveshnikov (2002) found variations of the solar radius with periods of 80 and 11 years, and with amplitudes of 0.″24 ± 0.″05 and 0.″08 ± 0.″02 respectively. The analysis shows also a positive correlation between solar radius and sunspot numbers.

One of the most extended time series of radius measurements with a technique quite different to that of the astrolabe was obtained by Ulrich & Bertello (1995) with the magnetograph of the Mount Wilson Observatory by means of a method developed by LaBonte & Howard (1981). The results, which are by-products of full-disk magnetograms obtained daily at that observatory, cover the period 1982–1994, and show a significant radius variation in phase with solar activity. The radius value is derived from photoelectric scans of the Sun's image using the 525 nm radiation of neutral iron and weighting equally all portions of the solar disk. This is almost equivalent to our radius measurements since the heliographic latitude of the contact points of the solar border observed at Santiago varies during the year between ±5° and ±85° (Noël 1999). In Fig. 5 are plotted monthly means of sunspot numbers as given by SIDC, and annual averages of the deviations from the mean of the solar radius as observed at Mount Wilson and Santiago. The radius of each circle represents the mean error of the annual average.

Accurate solar radius measurements from space have been obtained by Emilio et al. (2000) with the Michelson Doppler Imager (MDI) instrument (Scherrer et al. 1995) on board the Solar and Heliospheric Observatory (SOHO). In a three year experiment designed to detect solar diameter fluctuations the authors found, after removing temperature effects induced by the annual variation of the distance Sun–SOHO, that the Sun's radius varies over time approximately in a linear way with sunspot number (see also Gough 2001).

Radio observations of the Sun also have given evidence of radius variations in phase with solar activity. By means of the large dish of the Itapetinga Radio Observatory, Sao Paulo, Brazil, Costa et al. (1999) obtained during the period 1991–1993 maps of the whole Sun at 48 GHz that allow solar limb determinations with unprecedented precision. From a large sample of these maps, an apparent decrease of the measured radius as the solar cycle declines was found. A very good correlation was found between radius and solar irradiance variations (Costa et al. 1999).

The results that we have reviewed are consistent with the visual results of the astrolabe of Santiago. However, there are

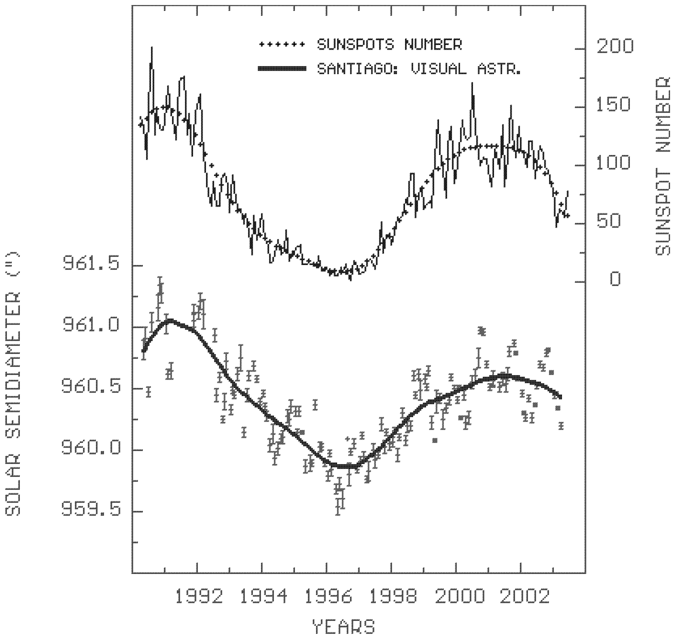

Fig. 3. Monthly means of sunspot numbers given by SIDC and of solar radius measurements made with the Danjon astrolabe of Santiago. The smoothing curves are Vondrak's fits with the same smoothing parameter for sunspots and radius (Vondrak 1969). The monthly means of solar radius were computed combining the daily results at 30° and 60° zenith distances given in Fig. 2.

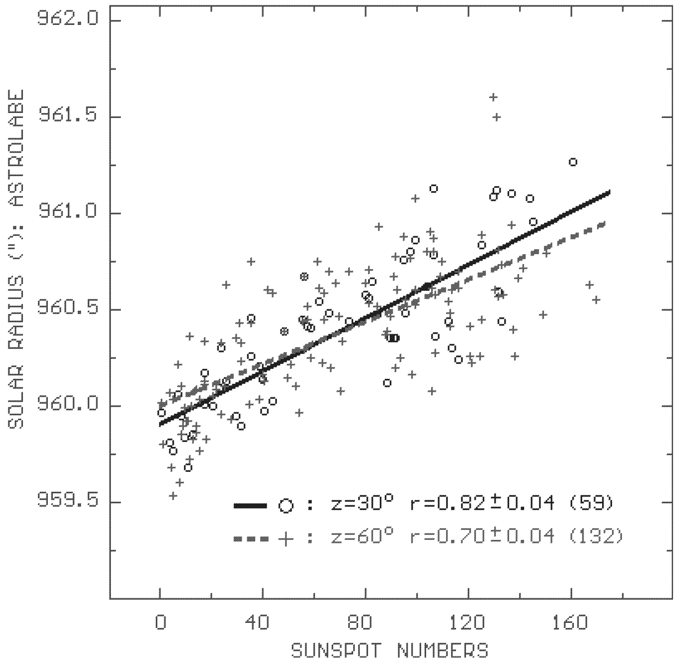

Fig. 4. Linear correlations between monthly means of sunspot numbers and of apparent solar radius observed with the astrolabe of Santiago at 60° and 30° zenith distances (z). The higher correlation coefficient (r) given by the radius measurements at 30° which are less affected by atmospheric noise, can be considered as an additional evidence that solar activity and radius variations would be causally related.

three long term time series of solar radius measurements obtained during the last 25 years that contradict our results. One is the series of visual results obtained with the modified Danjon astrolabe of Calern (Laclare et al. 1996; Pap et al. 1991) that will be discussed in the next section, and the other two were obtained by Brown & Christensen-Dalsgaard (1998) and by Wittmann (2003) and Wittmann & Bianda (2001).

Measurements of the photospheric radius of the Sun were obtained by Brown & Christensen-Dalsgaard (1998) between 1981 and 1987 with the Solar Diameter Monitor (Brown et al. 1992). This instrument is a transit telescope that allows at local noon a meridian drift of the solar image across a fixed photoelectric detector package. The results did not show significant variations of the observed diameter during the observational period. The authors claim that it is plausible that previously inferred variations in the solar diameter with solar actvity are in fact reflections of variations in the limb-darkening slope. According to Gough (2001) these measurements of the photospheric radius are perhaps one of the more reliable investigations in the long history of attempts to measure the Sun's radius from the ground.

However, bearing in mind that the Solar Diameter Monitor is essentially a meridian transit instrument, it must be considered that visual or photoelectric results obtained with this kind of instrument depends largely on the stability of the instrumental system which is defined by parameters that are not easily controlled, especially in the quite critical enviromental conditions that prevail during solar observations (Fricke 1972; Eichhorn 1974). Probably this is reflected in the rather large number of results that were discarded in the analysis of radius variations by Brown & Christensen-Dalsgaard (1998).

Although the authors do not give details on their selection criteria, discarding of almost 44% of the original measurements seems rather large and contrasts strongly with the behaviour of the results given by the astrolabe of Santiago. None of our original results needed to be discarded in our research of solar radius variations (see Sect. 5). In our view, this contrast could reflect the difference between the bahaviour of a very simple and quite compact metrological system like that of the Danjon astrolabe as can be seen in Fig. 1 (see also Danjon 1960; Noël 2003) and a far more complicate and less compact instrument such as the Solar Diameter Monitor (see Brown et al. 1982).

The other long-term series of solar radius measurements whose results do not show significant radius variations was obtained by Wittmann (2003) between 1972 and 2002 and by Bianda (Wittmann & Bianda 2001) between 1990 and 1998. Using two almost identical 45 cm Gregory-Coudé telescopes at Locarno (Switzerland) and at Izaña (Tenerife), Wittmann measured the solar radius by means of visual and photoelectric drift scan techniques. The method, based on a calibrated time measurement, provides about 30 solar radii per day. A total of 10 996 visual timing measurements were made on 320 observing days, and 1373 photoelectric recordings were made on 117 observing days. No fluctuations in excess of about $\pm 0\farcs05$ was found, neither long-term nor short-term (Wittmann 2003). Observing with the same telescope at Locarno and with the same method as Wittmann (2003), Bianda made 2470 visual measurements of the solar radius from 1990 to 1998.

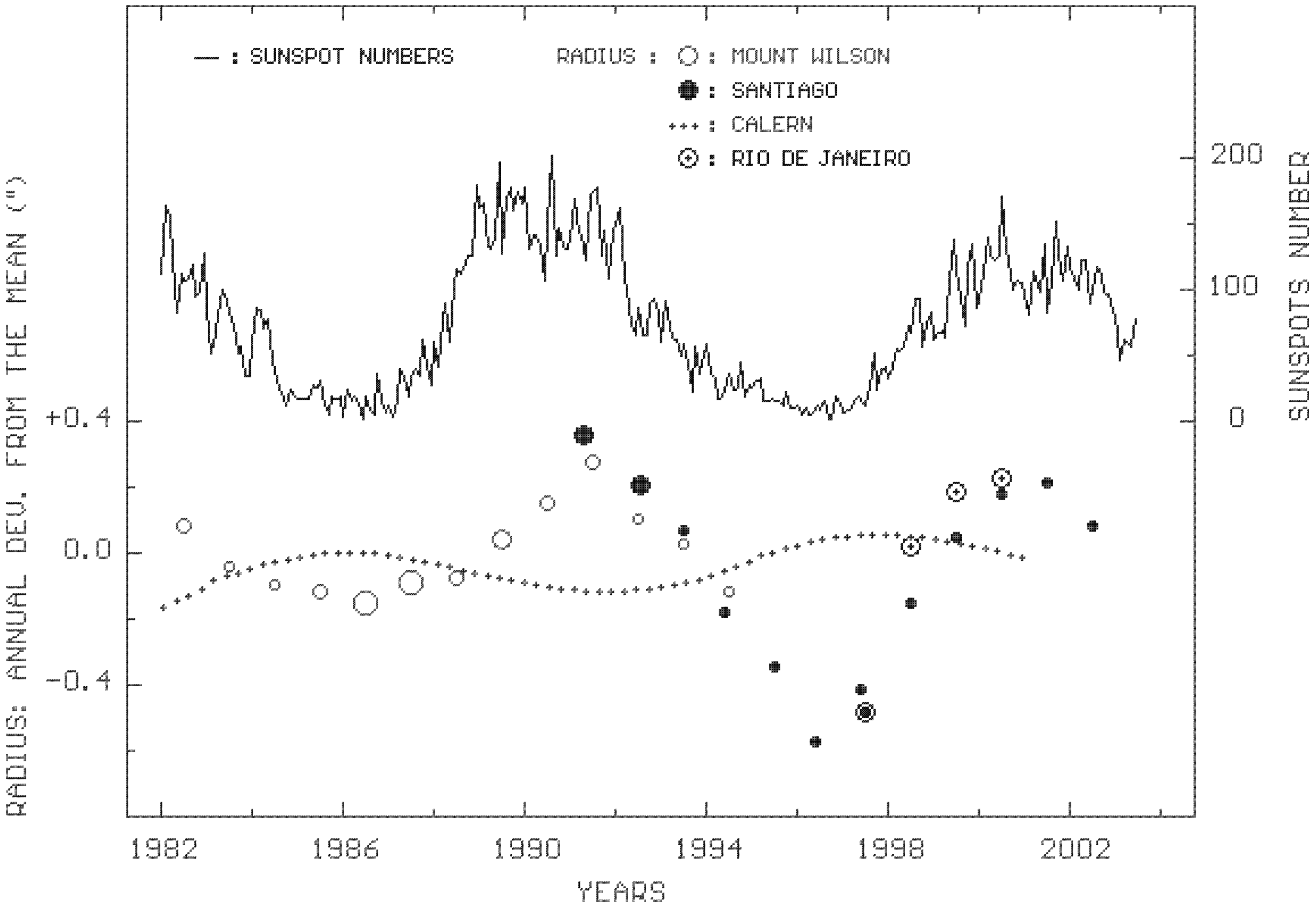

Fig. 5. Variations of sunspot numbers and solar radius between 1982 and 2002. The sunspot numbers are monthly averages obtained from the home page of SIDC. The circles are annual deviations from the mean solar radius obtained with the solar magnetograph at Mount Wilson Observatory (1982–1994), with the visual astrolabe of Santiago (1991–2002) and with the CCD astrolabe of Rio de Janeiro (1997–2000). The diameters of the circles are of the order of the mean error of the annual values. The values for Mount Wilson were adapted from Fig. 1 of Ulrich & Bertello (1995). The pointed curve is a numerical fit applied to the individual radius measurements obtained by Laclare with the visual astrolabe of Calern. It was adapted from Fig. 1 of Delmas & Laclare (2002). The discrepancy between the visual astrolabes of Calern and Santiago is discussed in the text. The values of Rio de Janeiro were deduced from the radius measurements published by Jilinski et al. (1999), Puliaev et al. (2000) and Penna et al. (2002), after eliminating internal inconsistences of the original data (for details see Noël 2002).

His results do not show significant differences with respect to those of Wittmann (Wittmann & Bianda 2001).

5. On the discrepant results of the astrolabes of Calern and Santiago

Elsewhere we have commented on the discrepancy shown in Fig. 5 between the visual astrolabes of Calern and Santiago concerning variations in time of the solar radius (Noël 2002). Whereas the observations of Santiago show a significant radius variation in phase with solar activity, those of Calern show a marginal variation and in opposite phase (Laclare et al. 1996; Pap et al. 2001; Delmas 2003).

Bearing in mind that both astrolabes are almost identical instruments, with practically the same wide bandpass centered at 540 nm and that at both sites the observations were made by one observer, this discrepancy is striking and quite disconcerting. However, even more disconcerting is the fact that in spite of this strong disagreement in large radius variations, both astrolabes give quite consistent results concerning small variations of the solar radius along the solar border (Noël 1999). Figure 6 shows the deviations from the mean of the apparent radius as a function of its heliographic inclination, observed at Calern and Santiago. The heliographic inclination (angle from the solar equator) of the observed radius varies during the year between 15° and 90° at Calern and between 6° and 84° at Santiago. Figure 7 gives the linear correlation with its correlation coeficient between the deviations from the mean radius along the common zone of the solar border observable from both sites. From the similarity of the results shown in Fig. 6 and the significant correlation coefficient given in Fig. 7, one should conclude that the results of Calern and Santiago show the real shape of the solar border. For a detailed description and discussion of these results, see Noël (1999).

The unexpected discrepance between the results of Calern and Santiago is impossible or at least very difficult to explain, unless the results of Calern are being filtered to avoid large variations of the observed solar radius. This supposition is

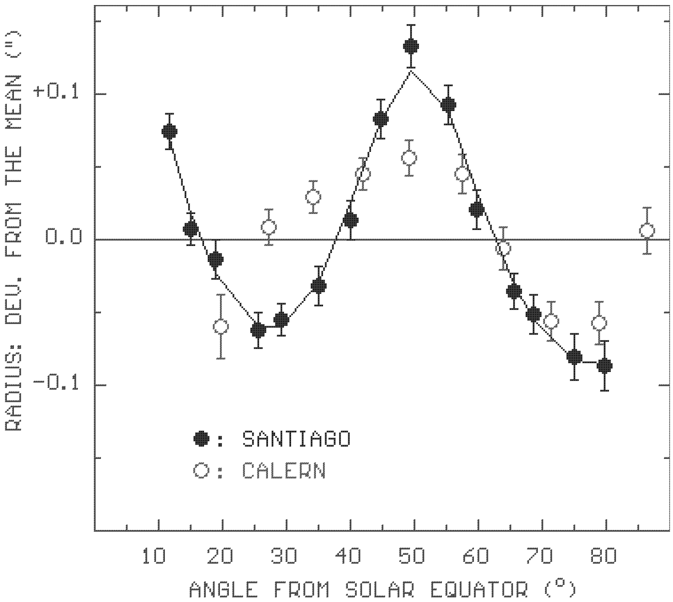

Fig. 6. Deviations from the mean of the solar radius according to its angle from the equator (heliographic inclination) as observed with the visual astrolabes of Calern and Santiago (Noël 1999). The smoothing curve is a Vondrak fit (Vondrak 1969) applied to the results of Santiago to reduce them to the values of heliographic inclination of Calern results (see Fig. 7).

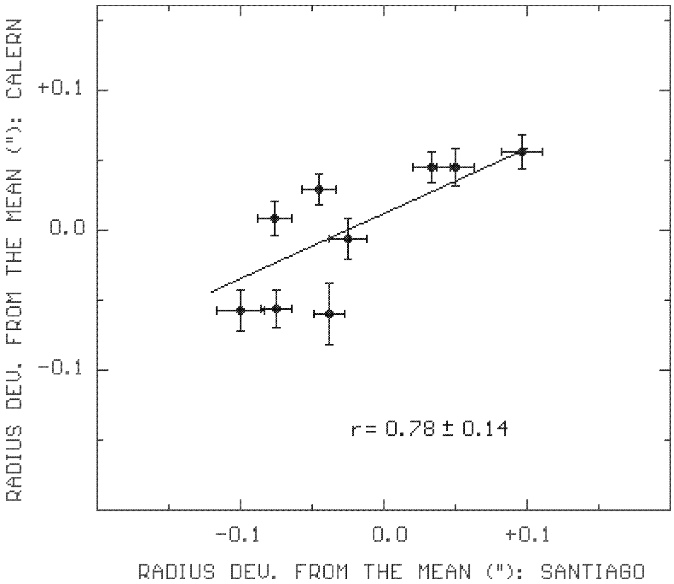

Fig. 7. Linear correlation with its correlation coefficient (r) between the results of Calern and Santiago given in Fig. 6. The results are those obtained from the common zone of the solar border observable from both sites (see text and Fig. 6).

consistent with the claim of Laclare et al. (1999) that solar radius variations, if any, can only be of small amplitude.

This assertion is contradictory to the observed variations in time of the solar radius with amplitud of the order of 0$''$.5 reported by Laclare in 1983 (Laclare 1983; Delache et al. 1985). Moreover, Ribes et al. (1991) with Laclare as coauthor, invoked a solar cause for those radius variations. Although at the present time there are no theoretical explanations for such large changes of the solar radius, there is other empirical evidence of changes occuring in the solar radius of similar orders of amplitude as those reported by Laclare (see Sofia & Li 2001).

If one considers that radius variations, if any, can only be of small amplitude, then one should consider also that results that give large radius variations must be spurious or abnormal. Obviously, a filtering of such results should have minor effects on small variations of the solar radius, but it will mask eventual large variations. This is quite apparent in the astrolabe results of Calern compared with those of Santiago (see Figs. 5 and 6).

Our explanation of the discrepance between the solar results of Calern and Santiago should be considered as tentative. Nevertheless, it is supported by the agreement with Santiago of other results of Danjon astrolabes, like those obtained with a CCD astrolabe in Rio de Janeiro shown in Fig. 5 (see also Noël 2002).

We must emphasize that we have tried to analyze the results of Santiago without preconceived models independently of previous results obtained by other authors. All our observations done in normal conditions are reduced and no result has been eliminated after reduction. Observations done in doubtful circumstances are simply not reduced. On the other hand, after our first publication (Noël 1993), all our individual radius measurements are publicly accessible at CDS.

6. Conclusions

According to Gough (2001), ground-based attempts to measure the solar radius have a long history with results of enormous disparity due to the distorting effects of the Earth's atmosphere.

Concerning periodic variations of the solar radius, there is a lack of consensus to accept its existence due to the marginal character of the reported evidence (Newkirk 1983). On the other hand, any measurable change of the solar radius would imply the action of processes that are not considered by the standard theories of the Sun (Ribes et al. 1991).

However, the results obtained during 13 years with the astrolabe of Santiago and most series of radius measurements of recent years, as well as the analysis of historical data that we have reviewed in Sect. 4, show a clear convergence towards variations in time of the solar radius in phase with magnetic activity. It is probable that the agreement shown in Fig. 5 by the radius measurements of Mount Wilson and Santiago based on quite different observing techniques, could be one of the strongest empirical pieces of evidence presented so far that show a solar cycle dependence of the apparent radius.

Only two sets of the results discussed in Sect. 4 (Brown & Christensen-Dalsgaard 1998 and Wittmann 2003) do not show significant variations of the solar radius. Concerning the results of Calern (Laclare et al. 1996), which are the only ones that show a marginal radius variation in opposite phase with solar activity, we propose that filtering of data at Calern is responsible for the discrepance between our data and that from Calern.

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