Solar and Stellar Magnetic Fields: Origins and Manifestations
Proceedings IAU Symposium No. 354, 2019
A. Kosovichev, K. Strassmeier & M. Jardine, ed.
doi:10.1017/S1743921320004068

Solar astrometry with planetary transits

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Abstract. Planetary transits are used to measure the solar radius since the beginning of the 18th century and are the most accurate direct method to measure potentially long-term variation in the solar size. Historical measures present a range of values dominated by systematic errors from different instruments and observers. Atmospheric seeing and black drop effect contribute as error sources for the precise timing of the planetary transit ground observations. Both Solar and Heliospheric Observatory (SOHO) and Solar Dynamics Observatory (SDO) made observations of planetary transits from space to derive the solar radius. The International Astronomical Union approved the resolution B3 in 2015, defining a nominal solar radius of precisely 695,700 km. In this work, we show that this value is off by more than 300 km, which is one order of magnitude higher than the error of the most recent solar radius observations.

Keywords. Sun: fundamental parameters, Sun: photosphere, Sun: activity

1. Introduction

The solar radius in theoretical models is defined as the photospheric region where optical depth is equal to the unity. In practice, helioseismic inversions determine this point using f-mode analysis, but most experiments which measure the solar radius optically use the inflection point of the Limb Darkening Function (LDF) as the definition of the solar radius. The stellar photosphere is defined as the layer from which its visible light originates, that is, where the optical depth is two-thirds in the star's continuum, since this is the average level in the atmosphere from which photons escape. Measurements of the solar radius found in literature varies from 958".54 Sánchez (1995) to 960".62 Wittmann (2003). Systematic errors among the experiments are the explanation of those differences. Planetary transits technique can only affected by second-order systematic errors and it provides an independent way to measure the plate scale. Space-based observations have the advantage of being not dependent on the Earth's Atmospheric error sources in the measurements. Emilio *et al.* (2012) measured the solar radius with the Michelson Doppler Imager (MDI) aboard the Solar and Heliospheric Observatory during the 2003 and 2006 mercury transits. The value found was 960".12 $\pm$ 0".09 (696,342 $\pm$ 65 km). In 2012 during the Venus transit the value found was 959".57 $\pm$ 0".02 (695,946 $\pm$ 15 km) with the Helioseismic and Magnetic on board the Solar Dynamics Observatory Emilio *et al.* (2015). Section 2 discusses historical and methods to measure the solar radius, including planetary transits. Section 3 compares modern measurements of the Solar Radius with International Astronomical Union Resolution B3, and finally, in section 4, we discuss why this value should be changed.

2. Historical Solar Radius Measurements

The Greeks, around 270 B.C., made the first attempts to measure the Solar radius. The value of 900" was much later compared by Auwers (1891) and Ambronn & Schur (1905) measurements, using a heliometer. We point out that the result obtained by Auwers, subtracted from "irradiation correction," was 959".63, and the standard value for more than a century. Different authors analyzed sets of measurements of the solar diameter. Among them, Gilliland (1981) studying a data set, distributed over 258 years, such as meridian observations, Mercury transit, and Solar eclipses, evidenced the existence of an 11-year modulation, in addition to a variation of 76 years, in phase, with measurements using meridian circles and Mercury transit, with amplitudes of 0".2, high even in the face of dispersion. Toulmonde (1997), analyzing measurements obtained through solar eclipses and Mercury transit, compared to astrolabes, intends that the variations found are solely due to advances in precision, and therefore due to optical effects, improved with advancement observational and instrumental techniques. This contradicts similar analyzes conducted by Ribes, Ribes & Barthalot (1987) and Gilliland (1981), which show secular variations. However, none of these authors ruled out the possibility of fluctuations on smaller time scales.

2.1. *Micrometer measurements*

Louis XIV, King of France, founded the Royal Academy of Sciences in 1666 and authorized the Paris Observatory construction, thus giving Astronomy an integral part of the programs of that academy. The Sun's study and the orbital parameters of the Earth occupied a prominent place in the scientific works of the Paris Observatory. Jean Picard, a member of the academy, dedicated an essential part of his activities to the Sun's problems. Observing the solar diameter, he determined the eccentricity of the Earth's orbit. Moreover, with the sunspot movements, Picard measured the solar rotation. After he died in 1682, his student Philippe de La Hire continued his work, having the programs observed covered the Maunder minimum period. A seasonal variation was removed from the annual average obtained at one astronomical unit for the period between 1666 and 1719. This value is 1" higher when calculated during the Maunder period. Were observed few sunspots, as expected, but Picard measurements also show a loss of speed of rotation of the Sun at the equator and a higher number of sunspots in the southern hemisphere than in the solar north.

La Hire observed, with the same instrument, for more than four solar cycles, and his observations are compared to those of Halley (1715), made during the total solar eclipse. The measurements taken from the total eclipse were more accurate than those of La Hire at the time. Thus, Ribes, Ribes & Barthalot (1987) calibrated the measures of La Hire. It was necessary to subtract approximately 3" from his measurements to correspond to the measurements made by Halley. Even so, the value found in 1683 was 962".5, which is still about 2,000 km higher than the modern values of the diameter (Ribes *et al.* (1991)).

This value corresponds to 6 times the average deviation and 20 times higher than the 11-year variation found by Laclare *et al.* (1996). Between 1680 and 1690, a decade corresponding to the end of Maunder minimum, the diameter decreases by 3", similar to the value found by Halley in 1715. Ribes *et al.* (1991) concluded that an increase in the semi-diameter occurred in the Maunder minimum period due to low solar magnetic activity. The rotation speed found was 3% slower than the current speed. Morrison, Stephenson & Parkinson (1988) affirm that careful observations of the shadow edges of the total eclipse of 1715 imply that the value of the solar radius found is essentially the same observed today. Toulmonde (1997) concluded that there is no evidence of a secular variation after revising the analysis of several measurements. The analysis by Ribes *et al.* (1989) shows an oscillation of 9.6 years. This analysis included up of 7,000 measurements made by La Hire. Other fluctuations were detected, particularly periods of the order of 2 to 3 years and 17 months. The amplitudes of the periods are in the order of two to three times the noise level. The conclusion about a possible secular variation of the solar radius from the Picard and La Hire measurements is still a matter of study in the literature.

2.2. *Meridian circles*

One of the observational programs maintained by the Royal Observatory at Greenwich was solar. Through the measurements of instants of transit of the Sun's limbs by the local meridian, and using reference stars (Cullen 1926), it was possible to obtain a reference system used at the time. This program, which included observation of planets, the moon, and small planets, was maintained on a routine basis from 1836 to 1953. Through a combination of the Sun's transit times, it was possible to obtain a series of measurements of its diameter; the first analyzes looking for periodicity were unsuccessful (Gething 1955). On the other hand, Howse (1975) obtained a variation of 0".01/year from 1890, corroborated by Eddy & Boornazian (1979) from 1836. The measurements were challenging since difficulties imposed by constant modifications introduced since 1936 in Greenwich, and the fact measures were made with a tangency in a small part of the solar limb and a reticule. It should also keep in mind that the moment of transit was interpolated by the observer between two successive beats of a pendulum, used as a time pattern, whose methodology was replaced by stopwatches from 1854. The program conducted by many observers, made the measures strongly dependent on personal equations, translated by each individual's to define the moment of tangency at the transit. There are still transit measurements made with the primary objective of measuring the size of the Sun (Auwers 1891; Gething 1955). In these cases, the primary source of error was the Earth's atmosphere.

2.3. *Mercury transits*

Observations of the time interval that the planet Mercury takes to cross the Sun resulted in one of the most accurate solar diameter measurements to detect long-term changes. Due to the particular geometry of Earth and Mercury's orbit, the passage occurs only in May or November, at a frequency of 14 times per century. The maximum duration of central transit in May is ∼8h and in November ∼6h. The precision for the solar diameter is of the order of 0".1. However, due to an observation difficulty in discerning Mercury's contact instant with the Sun's limb, the average deviation of observations for each transit is typically between 0".5, and 1" on ground observations. In total, there are four instants of contact between the limbs of the Sun and Mercury. There are two contacts with Mercury for each solar limb, one internally and one externally. The contact observations (t1 and t4) in which Mercury appears ultimately outside the limb of the Sun are said to be external. The internal contacts (t2, t3) are much more defined than the external ones (Parkinson, Morrison & Stephenson (1980)) and are used to measure solar diameter variations (Fig. 1). More than 2,000 contact measures in 30 transits of Mercury, distributed over the past 250 years, were collected by Morrison and Ward (Morrison & Ward 1975a,b), and analyzed by Parkinson, Morrison & Stephenson (1980). These measures, collected mainly to determine the variations in the Earth's rotation rate and the relativistic advance of Mercury's orbit's perihelion, allow a combination of the diameters of the Sun and Mercury to be obtained, through the angular separation between these objects. Looking those transit measurements from 1723 through 1973, Parkinson, found a decrease of 0".14 $\pm$ 0".08 (in agreement with Shapiro's (1980) variation of 0."15/sec) and a periodic variation of eight years with an amplitude of 0".24 $\pm$ 0".08, besides a sub-harmonic of approximately twenty years. The long term variations are consistent with Bush, Emilio & Kuhn (2010) null result and upper limit to secular variations obtained from Michelson

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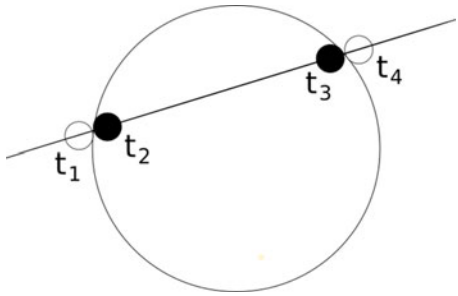

Figure 1. Planetary transit

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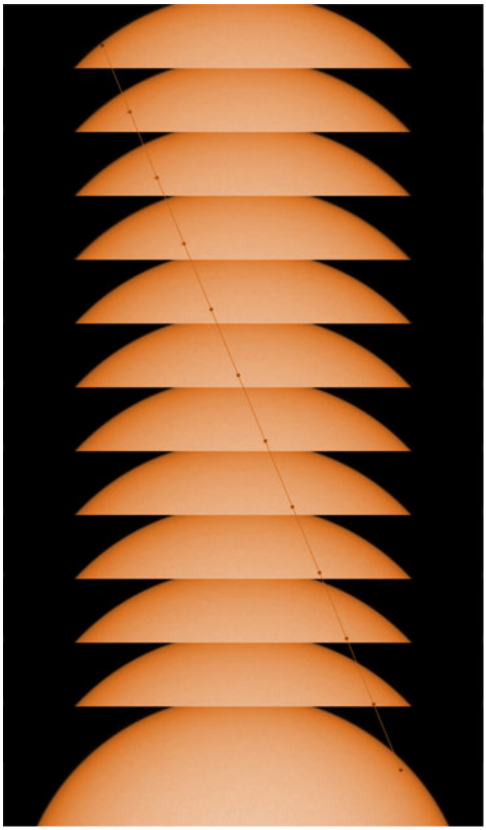

Figure 2. Composite image of Mercury transit 2003 May observed with Michelson Doppler Imager (MDI) aboard the Solar and Heliospheric Observatory with a 28-minute cadence

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Doppler Imager (MDI) imagery of 0".12 per century. Sveshnikov (2002), analyzing 4500 archival contact-timings between 1631 and 1973, found that the secular decrease did not exceed 0".06 ± 0".03. Our group made the first analysis with high-quality images outside the Earth's atmosphere of Mercury transits to obtain the solar radius (Fig. 2). The value found of 960".12 ± 0."09 is consistent with earlier MDI absolute radius measurements after taking into account systematic corrections and a calibration error in the 2004 optical distortion measurements (Emilio *et al.* (2012)). Within our accuracy, no variation of the solar radius was observed over three years between the 2003 and 2006 transits.

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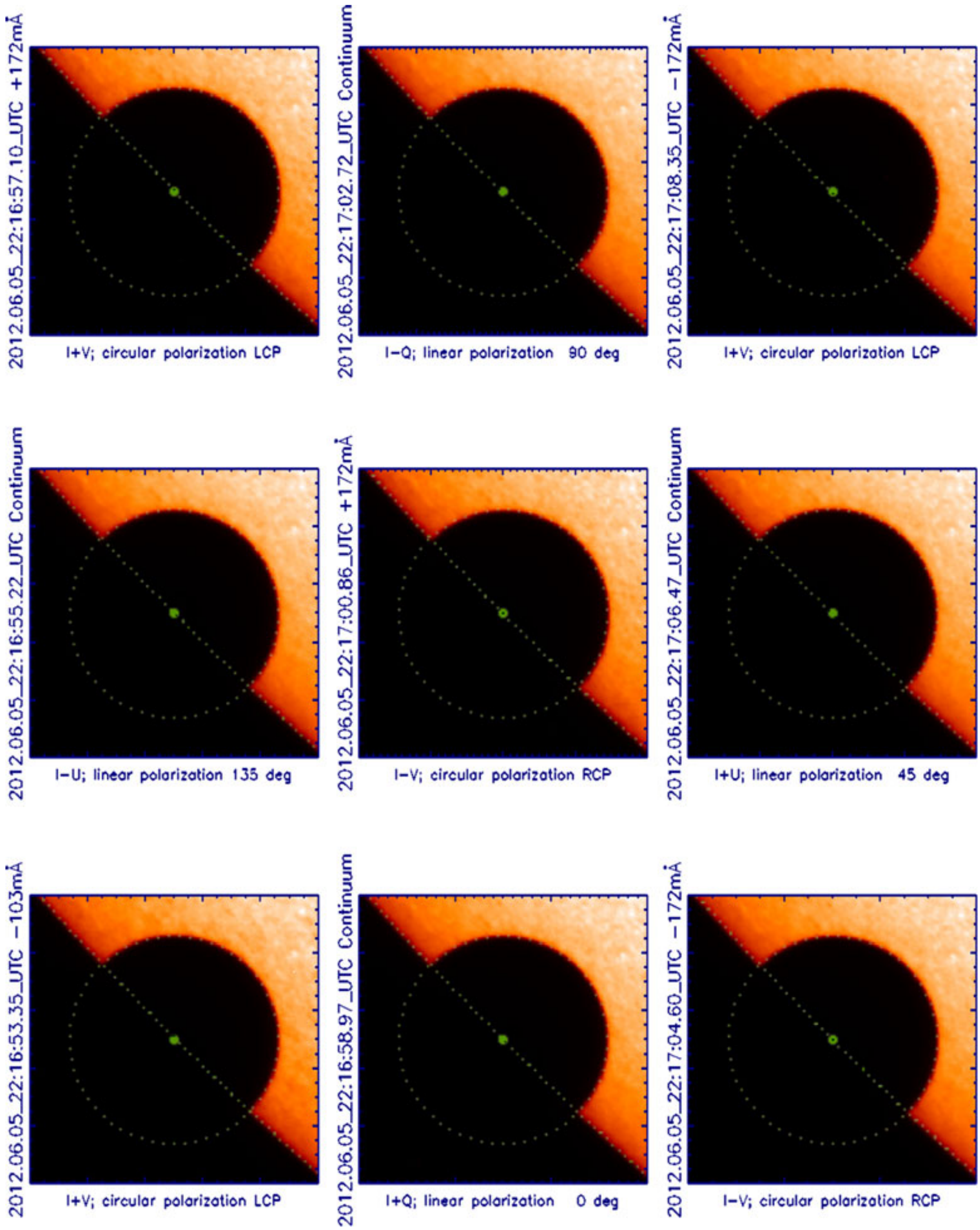

Figure 3. Venus 2012 transit ingress from HMI/SDO.

2.4. *Venus transit*

Transits of Venus occur in pairs of transits eight years apart separated by long gaps of 121.5 years and 105.5 years. They were used historically to estimate the size of the solar system. Besides Venus's apparent size being bigger than Mercury, his atmosphere brings another factor of difficulty in making precise measurements. The 2012 Venus transit was observed by the Helioseismic and Magnetic Imager (HMI) (Figs. 3 and 4) aboard the Solar Dynamics Observatory (SDO) in seven wavelengths across the Fe *I* absorption line at 6173 Å (Emilio *et al.* 2015). After applying a correction for the instrumental point

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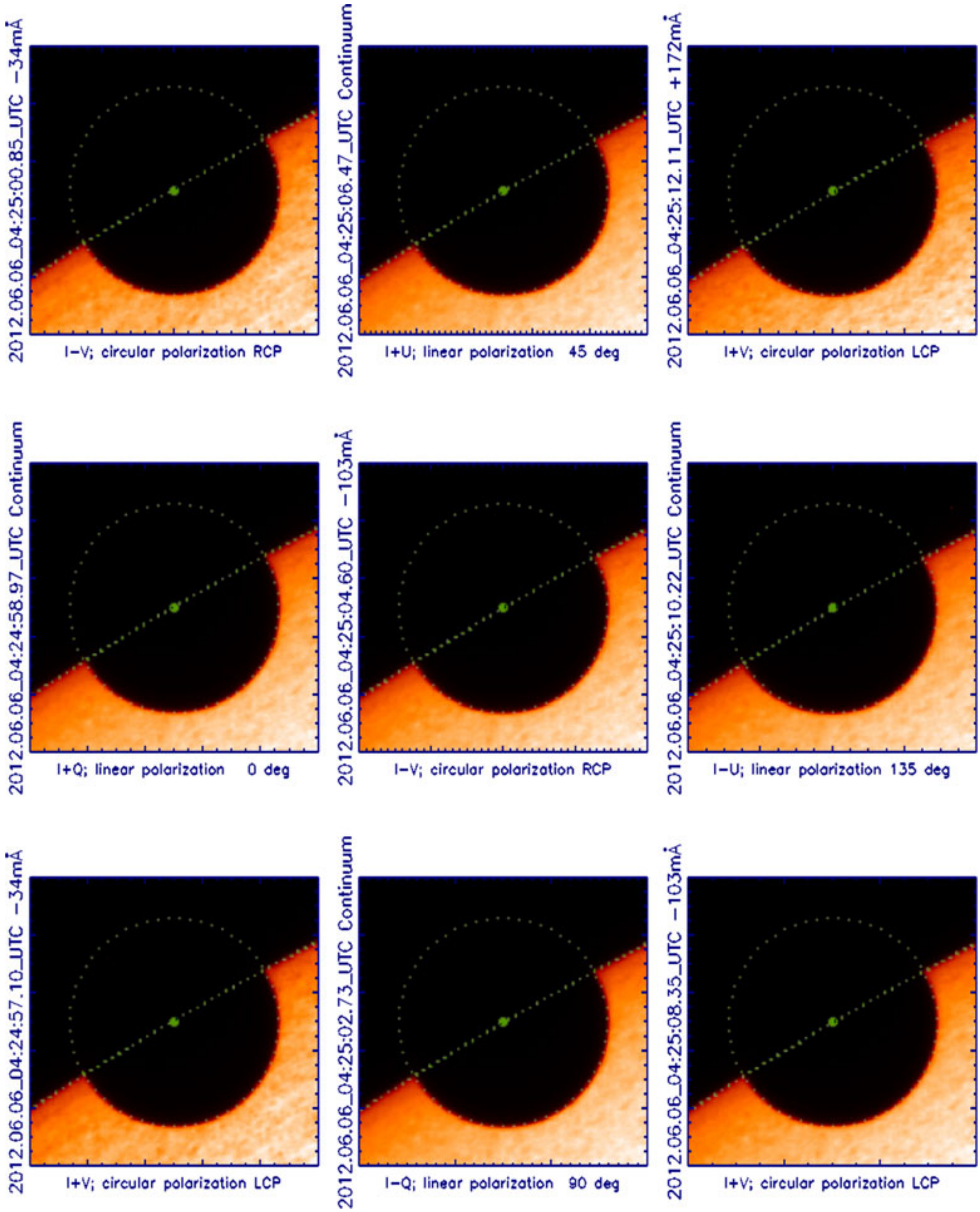

Figure 4. Venus 2012 transit egress from HMI/SDO.

spread function (PSF) of the HMI images, the value found at 1 AU was 959".57 ± 0".02 (695,946 ± 15 km). Inside the Fe *I* it was possible to measure the heights of the line formation. The difference in the solar radius determined from measurements near the line core and in the continuum wing was 0".23 (167 km).

2.5. *Solar Eclipses*

An alternative method to detect possible changes in the solar diameter comes from eclipses. The admitted accuracy of these measures, assuming the Moon's profile is known,

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is 0".2. In practice, the measure derives from the time interval between the Sun's light's disappearance and reappearance, seen in the Moon's irregular limb (Parkinson, Morrison & Stephenson 1980). The dataset includes the 1715 solar eclipse observed by Halley, the eclipses occurred between 1842 and 1925, and the photographs obtained in 1966. In addition to the average values of 959".63 for the Sun and 932".58 for the Moon, the corrections of the Moon's profile irregularities were taken into account (Watts 1963). The profile of the Moon, as seen from Earth, is irregular enough that it cannot be used immediately as an intermediate reference surface. It is even necessary to know the shape of the lunar limb so that we can remove from the observational residues that part due to the selenographic irregularities of the marginal zone of the Moon. For the average value of the Sun's radius, a correction of 0".22 $\pm$ 0".20 was found. Parkinson, Morrison & Stephenson (1980) still obtained, through linear regression, a secular variation of 0".08 $\pm$ 0".07. More recently Lamy *et al.* (2015) using synthetic light curves calculated from high-accuracy ephemerides and lunar-limb profiles constructed from the topographic model of the Moon provided by the Kaguya lunar space mission found the value of 959".99 $\pm$ 0".06 (696,246 $\pm$ 45 km). The value corresponds to an average of four solar eclipses between 2010 to 2015.

2.6. *Drift Scans*

In 1951, Pettit proposed an observational method for determining the solar diameter based on the monochrome photometric curves of the Sun's limb (Wittmann 1973, 1977, 1980). The experiment consists of scanning the solar disk in both directions, east-west, and north-south, using two photodiodes. The difference in signals allows the keep the telescope Zeiss, ($\phi = 5.0$ cm and $f_{eff} = 273.9$ cm) positioned with a precision of 1" while the attitude of the telescope can be changed both in straight ascension and in declination. The scan spans 208", and 6144 equidistant points characterize the measurements. Each point of intensity relative to the Sun's center is obtained photoelectrically every 63 μs. An average of every 64 readings is calculated and recorded (equivalent to about 0".06 in resolution), followed by the observation moment. The limb darkening functions are drawn for each scan, and the respective inflection points are obtained. An astrometric reduction follows to determine the diameter. Wittmann (1973) used this method and determined the diameter using a telescope at the Locarno observatory (Lat.:+46°10'41" and Lon.: −8°47'22" and altitude 2409 m). The first results of the semi-diameter found in 1972 (Wittmann (1973)) were 960".24 $\pm$ 0".16 in 5011.5 Å and 966".9 $\pm$ 0".4 in H$\alpha \pm 5$ Å. Wittmann, Alge & Bianda (1991) used yet another identical telescope using the technique described above in different locations. The telescope was a Gregory Coudé (D = 45 cm; f = 25 m). The accuracy for an isolated measurement was 1" in Izaña (latitude 46°10'40".6 N; longitude 8°47'22".9 and altitude 506 m) and 1".7 in Locarno. These values correspond to the seeing 1" of the respective sites. The average diameter found from the 1122 observations made in 1990 (472 in Izaña and 650 in Locarno) was 960".56 $\pm$ 0".04. The value is comparable to the 1773 observations made in 1981 (Wittmann, Alge & Bianda 1991) of 960.32 $\pm$ 0".02. Wittmann, Alge & Bianda (1991) found no evidence of variations in the semi-diameter greater than $\pm$ 0".3 in these observations. Wittmann, Alge & Bianda (1993) attribute a variation in phase with the solar cycle comparing the measurements made in Izaña and Locarno between 1991 and 1993 with the observations made in 1981. The variation in 10 years was 0".4. Such amplitude is twice as large as the variation found with astrolabes (Laclare *et al.* (1996); Emilio & Leister (2005)). After modifying the data acquisition system, introducing a CCD, Wittmann (1997) revised his study on the variation of the radius with the solar cycle. In other papers, Wittmann (Wittmann (1997); Wittmann & Bianda (2000)) does not attribute any variation in the solar semi-diameter higher than 0".05 with the solar cycle and considered that the variation of 0".4 was of instrumental origin to the interruptions in the observations.

2.7. *Balloon Measurements*

The Solar Disk Sextant (SDS) is an instrument developed by Sofia and collaborators to make measurements in a balloon, that allow obtaining the solar diameter, from the separation between two images of the Sun. The SDS is composed of a wedge approximately 1000" (Sofia, Heaps & Twigg (1994)), placed in front of the Cassegrain telescope objective, with a focal length of 20.5 m, producing two separate Solar images. The distance between the center of two consecutive images of the Sun produced by the instrument is given by $D = 2WF$, where W is the angle of the wedge, and F is the focal length of the telescope. Linear CCDs are placed along the solar limb, and in this way, the position of the center of the Sun's image is calculated. The solar radius is then calculated by $S = (D - d)/F$, where d is the separation between the images. The instrument is placed onboard a balloon at an altitude of 36 km. This method's advantage is that a small amount (the separation of the solar limb) is measured instead of the solar diameter. This technique increases the precision of the measurements compared to those that measure the solar diameter directly. An essential measured quantity is the separation of the images, located close to the optical axis, whose performance is optimized. The instrumental scale can be calibrated, as long as the focal distance is fixed. The distance between the two images is measured with each observation. The SDS instrument principle requires that the wedge angle remains constant. In this way, it is possible to separate the instrumental effects from variations in the solar diameter. The telescope can rotate around its axis, allowing observation at different heliographic latitudes. The deviation from the mean for any measurement is 0".2, and the instrument's sensitivity is 1 to 2 mas. Sofia, Heaps & Twigg (1994) found no significant variation in the solar radius. Therefore Sofia *et al.* (2013) found a variation of 200 ± 20 mas through 1992 to 2011, not in phase with the solar activity cycle.

2.8. *Santa Catalina Laboratories for experimental Relativity by Astrometry (SCLERA)*

SCLERA is a photometric technique that Brown and collaborators proposed using a modified meridian circle (Brown, Stebbins & Hill (1978); Brown & Christensen-Dalsgaard (1998)). From August 1981 to December 1986, an observational campaign was carried out with this instrument mounted in the mountains of Santa Carolina, north of Tucson (USA), on a site at 2609 meters above sea level. Through a filter centered close to 800 nm and with an amplitude of 10 nm, the Sun's horizontal diameter was obtained by combining the transit moments of the limbs by a series of linear CCD detectors. The scan was performed with a frequency of 32 Hz. A real-time algorithm to find the edge is used, and several other quantities are measured together with seeing and parameters to calculate refraction. The algorithm used to determine the limb was the finite Fourier transform (FFTD) described by Hill & Stebbins (1975). The process involves converting LDFs with theoretical curves. Theoretical curves are made up of a set of non-zero weighting functions only for a specific window of length a. The length of the window determines how much of the solar limb's darkening curve is involved in defining the edge (Hill & Stebbins (1975)). The edge is then defined as the center of that window in which the convolution is canceled. The FFTD has two crucial characteristics: The first is to eliminate the first-order contribution of seeing in determining the limb for a given length of the scattering point function. The position of the tip points of the limbs is highly sensitive to the variability of the seeing for each day; the second characteristic is that the FFTD depends on a free parameter called window length a.

Brown & Christensen-Dalsgaard (1998) found the solar diameter to be $1919''.359 \pm 0''.018$ at one astronomical unit using 550 measurements. The authors argue that this is not the correct diameter but an observational quantity constructed in a way independent of the vertical temperature gradient of the upper photosphere. The value obtained depends on the radiation transfer in the solar atmosphere and on the behavior of the FFTD limb definition. Physical models of the solar atmosphere are applied to obtain the diameter correction and calculate the intensity as a function of the distance from the solar center, and the brightness distribution profile identified with the edge by the FTTD. After applying two models to the solar atmosphere and correcting the diameter value, the authors obtained an average value of 958".96 ± 0".04. The authors found no significant variation in the solar radius over time.

2.9. *Solar diameter measurements in the spectral line of neutral iron 525 nm*

The Sun's diameter was also measured in the line of the neutral iron 525 nm (Ulrich & Bertello (1995)). A telescope located in Monte Wilson (USA) was used to make the measurements. The Sun's apparent radius was defined as the average distance between the image center and the point where its intensity falls at 25% of its value. A portion of the Sun's image is directed to a spectrograph in which the position of the image determined by a guide system placed close to the focal plane. A magnetogram is constructed by scanning the image over the spectrograph entry opening in alternating directions, with the scanning direction being adjusted, per day, perpendicular to the solar polar axis. The image is initially positioned randomly away from the poles, and successive scans construct each magnetogram in the main direction. Each scan line begins and ends at a fixed distance, away from the solar disk. The intensity of the disk is used to determine the scattering of light. During each scan, the acquisition system reads the intensity and the circular polarization in two spectral bands. An automatic control also keeps the opposite wings of the spectral line at 525.0 nm illuminated. The limb's position is determined during the reduction process and differs from that found in the visible. The reason is the neutral iron line formed close to the limb position where the temperature is minimal instead of the photosphere. The presence of faculae from active regions will influence the determination of the limb defined in this way. There are other corrections due to the effects of light scattering and atmospheric refraction. After these corrections, the residuals of the medium radius are obtained. Ulrich & Bertello (1995) measurements of the solar ray were made between 1982 and 1994. The residues show a direct correlation with magnetic activity with an amplitude of approximately 0".2. Since the iron 525 nm line formed in a high height of the solar atmosphere, the variation found is probably a solar atmosphere's change due to the magnetic activity.

2.10. *Helioseismic Radius*

The f modes propagate mostly on the surface, and their frequencies are independent of the stratification of the solar interior. The f modes depend mainly on global factors such as mass and radius. With precise measurements of frequencies in mode f, it is possible to determine the solar radius (Schou *et al.* (1997); Tripathy & Antia (1999)). The dispersion relation of the f modes given by (Tripathy & Antia 1999) is:

$$w^2 \sim gk = GM\frac{\sqrt{l(l+1)}}{R^3}$$

Where:
g is the acceleration of gravity on the surface;
k is horizontal wave number;
G is the gravitational constant;
l is the degree of the mode;

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R is the Solar radius;
M is the Solar mass.

In practice, there are significant differences in the frequencies of this asymptotic estimate. The reason is that these modes have their maximum amplitudes in layers just below the solar surface, which corresponds to a smaller radius. Moreover, this is because the speed associated with self-functions drops exponentially with increasing depth, and density increases quickly. As a result, the density of kinetic energy increases, and the height scale of density becomes comparable to the height scale of speed. Antia (1998) estimated the solar ray through the f modes using measurements made by the GONG network at 959".34 ± 0".01. Dziembowski *et al.* (2000) found no variation in the heliossismological radius correlated with the number of spots, using data from the MDI-SOHO. However, Antia *et al.* (2000) using measurements from the GONG network between 1995 and 1998 and found changes in frequencies of mode f with solar activity. A new analysis was made by Dziembowski *et al.* (2001). This time they took into account the complete data from MDI-SOHO since 1996, whose results did not confirm the correlation with solar activity.

2.11. *Astrolabes*

The most significant disadvantage is that the star catalogs made with the astrolabe are not absolute because it is not possible to fix the equinox's position and the equator of the reference frame. Classically, the orbital parameters of the Earth contribute to obtaining the spatial orientation of the reference system, in addition to the observations of planets, those of the Sun, whose attempts until 1973 (Benevides *et al.* (1979)), had not been made due to the impossibility of knowing the instantaneous zenith distance , due to the variability of the transmission prism angle. In parallel, in 1974, Laclare (1975) modified the CERGA astrolabe with the same objective. An equilateral prism was replaced by Vitro-ceramic prisms, with low dilation, allowing observation at various zenith distances (Laclare (1983)). The solar semi-diameter was a secondary measurement. The importance of this measure grew over time until it became the main objective of solar astrolabes. One of the astrolabe advantages, compared with the meridian circle, is that the instrument allows the Sun's observation twice a day with a single prism (once in the east and once in the west). The astrolabe had a unique advantage for observing the solar diameter. Its measurements are not affected by errors in atmospheric refraction (the error is second-order). An error in determining a limb's position in a given zenith distance cancels the error of the opposite limb since the radius is found by the difference between the zenith distances of the upper and lower limb of the solar disk. The only error source is caused by a change in atmospheric properties between the two contacts. However, the measure is subject to errors due to seeing and the definition of the inflection point.

2.12. *Satellites*

Ground-based measurements limit the solar radius observations by seeing effects. Also, satellites allow observing continually with no night/day interruptions. It provides the most accurate measures of variation (if they exist) and the absolute value of the solar radius (with planetary transit observations). The first to make those observations was the Michelson Doppler Imager (MDI) instrument aboard the Solar and Heliospheric Observatory (SOHO) satellite (Emilio *et al.* (2000); Kuhn *et al.* (2014); Bush, Emilio & Kuhn (2010)). The Solar Diameter Imager and Surface Mapper (SODISM) onboard the Picard space mission was a dedicated instrument to measure the solar radius in five narrow bandpasses (Meftah *et al.* (2014)). MDI/SOHO found that fundamental changes in the solar radius synchronous with the sunspot cycle must be smaller than 23 mas peak to peak, and the average solar radius must not be changing (on average) by more than

Table 1. This table shows the difference between modern measurements of the solar radius and the IAU resolution B3 definition.

Reference	Date	Method	$R_\odot$(km)	1 σ error	Difference from IAU B3 resolution (km)
Emilio *et al.* (2012)	2003,2006	Mercury transits (MDI/SOHO)	696,345	65	645
Hauchecorne *et al.* (2014)	2012	Venus transits (SODISM)	696,149	138	449
Emilio *et al.* (2015)	2012	Venus transits (HMI/SDO)	695,946	15	246
Lamy *et al.* (2015)	2010 to 2014	Solar Eclipses	696,246	45	546

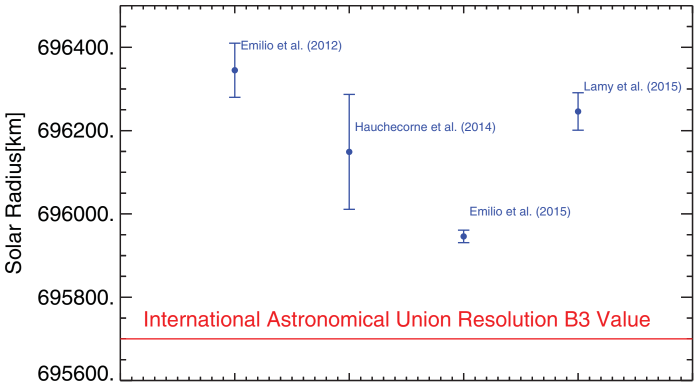

Figure 5. Modern measurements for the solar radius obtained from planetary transits and solar eclipses compared with the value adopt by the IAU B3 resolution.

1.2 mas yr^{-1} (Bush, Emilio & Kuhn (2010)). From PICARD (Meftah *et al.* (2015)), the changes in solar radius amplitudes were less than ±20 mas (±14.5 km) for the years 2010–2011 and not correlated with the solar cycle activity.

3. International Astronomical Union Resolution B3

Resolution B3 of the International Astronomical Union (IAU) defined the Solar radius as 695,700 km in 2015. This value is consistent with helioseismic determinations of the solar radius but not consistent with the most accurate measurements of the photospheric solar radius. Solar radius determined from helioseismic data is located below the photosphere. Table 1 shows some of the most modern measurements of the solar radius and Fig. 5 shows a plot of those values with the B3 resolution.

4. Discussion

Haberreiter, Schmutz & Kosovichev (2008) calculated the intensity profile of the limb the MDI continuum and the continuum for two atmosphere structures and compared the position of the inflection point with the radius at $\tau_{5000} = 1$ ($\tau_{Ross} = 2/3$). The difference between the seismic radius and the radius defined by the inflection point is 347 ± 6 km. This difference is consistent with some of the most recent measurements and IAU B3 definition of the solar radius found in table 1. The inflection point definition is closest to the adopt value used for evolutionary models defining stars' age and temperature where $\tau_{Ross} = 2/3$. Also, the inflection point definition is used for most of the experiments that measure the solar size. IAU B3 resolution for the solar radius must be raised by 300 km to agree with the solar photosphere's observations. Satellites measurements agreed that

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the upper limit of any variation of the solar radius (if any) is not bigger than 15 km with solar cycle (Bush, Emilio & Kuhn (2010); Meftah *et al.* (2015)), what is one order magnitude smaller than the 300 km IAU B3 resolution difference.

Acknowledgments

This work was partially supported by Fundação Araucária (Ed. 12/2018) and Conselho Nacional de Pesquisa (CNPq) 308871/2016-2.

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https://doi.org/10.1017/S1743921320004068 Published online by Cambridge University Press

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Discussion

Alexander Kosovichev: What Can you say about the shape of the Sun?

Marcelo Emilio: The Helioseismic and Magnetic Imager (HMI) instrument on the Solar Dynamics Observatory (SDO) spacecraft has been making periodic solar shape measurements every six months since 2011. Separate the shape signal from brightness variations in the photosphere is very difficult. Our analysis shows that the Sun's oblate shape is distinctly constant and almost entirely unaffected by the solar-cycle variability. The nominal value found by our group for the solar oblateness is significantly lower than theoretical expectations. A slower differential rotation could explain this in the outer few percents of the Sun. The higher-order (hexadecapole) term is consistent with 0.