A brief history of the solar diameter measurements since immemorial days: which relevant astrophysics?

« Une brève histoire de la mesure du diamètre solaire au cours des âges: quelle finalité astrophysique? »

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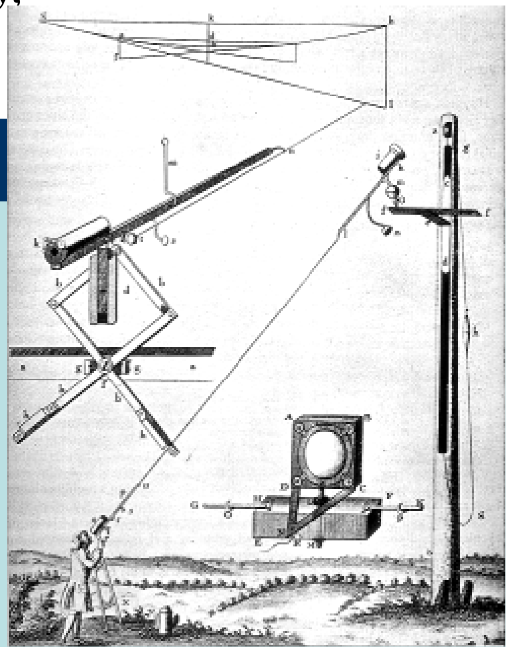

Pescara - August 2012

A fundamental astrophysical quantity: The Solar Diameter

→ Size of stars refers to the Sun's size. Ex: R (Aldebaran - α Tauri) is 44,2 R (Sun)

→ Solar physics: a change in solar size is indicative of a change in the potential energy which could be driven by such means.

→ Solar luminosity: a change in solar size carries along luminosity changes

- To first order $L = \sigma T^4$, hence $\Delta L/L = \Delta R/R + 4\,\Delta T/T$

- Accurately:

(Eddington law)

Need to measure simultaneously ΔL and ΔT to deduce ΔR

→ Precise limb shape (curvature) changes over latitudes and in time signs aspherical thermal structure:

- Better solar structure modeling and so, better solar forecasting

→ Temporal solar size variations imply a dynamical gravitational moment:

- Constraint gravitational theories

A fundamental astrophysical quantity: The Solar Diameter

$\Delta L/L = \Delta R/R + 4\,\Delta T/T$

- If $\Delta T = 0$ over the solar cycle (Livingston, immutable Sun) $\Delta R/R = \Delta L/L = 0.1\%$

  and **ΔR = 9,60 mas**

- If $\Delta T = 1.2$°C over the solar cycle (max) see Penza et al, PSPT (Roma)

  $\Delta R/R = 0.1 - 4 * (1.2/5500) \rightarrow \Delta R/R = 0.127\ \%$

  ΔR= 0.127*960''/100 = 0.0122 '' or **1.22 mas**

  Far from the astrolabe's measurements !!

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- To first order $L = \sigma T^4$, hence $\Delta L/L = \Delta R/R + 4\,\Delta T/T$
- Accurately: $$L^* \equiv 2\pi \int_0^{\pi} r^2 F_r(r,\theta,t) sin\theta d\theta$$ (Eddington law)

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A fundamental astrophysical quantity: The Solar Diameter

- **Is the Sun a slowly variable star ?**

  → **still a conundrum** (at least up to a very recent date)

To try to answer:

- What is a solar diameter ?
- What has been done in the past ?
- What is currently done ?
- Can we perform relevant astrophysics ?

What is a solar diameter ?

- **Several definitions**: all are allowed and are conventional

  When speaking about a possible variability, be sure that one speaks about the **same** diameter.

- **Physical definition**: the diameter is the place of the points where

  T (or P, or ρ, or ϕ...) = cste

  - the specified level of the constant defines the limb; for instance $\tau = 1$

  Pro: the "edge" is defined by a physical parameter

  Con: in general a model is required

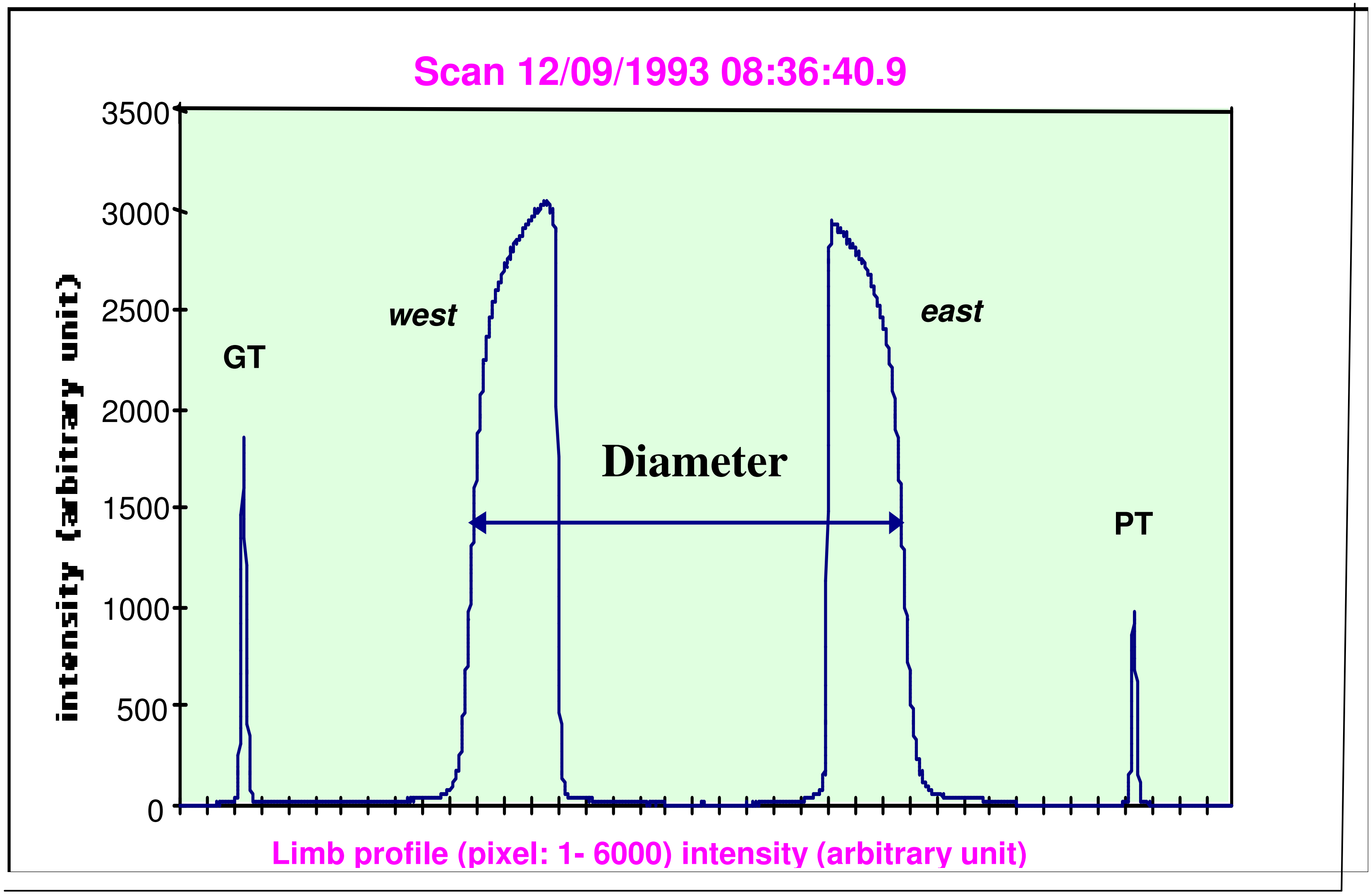
- **Observational definition:**

  Limb contact point with a fixed reference, for example the local meridian line

  Inflection point of the intensity profile

- **--> 2 methods of measurement:**
  - angular measurement
  - time measurement (clock)

Exemple d'observation (héliomètre du Pic du Midi)



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- **Observational definition:**
  Limb contact point of the limb with a fixed reference, for example the local meridian line
  Inflection point of the intensity profile

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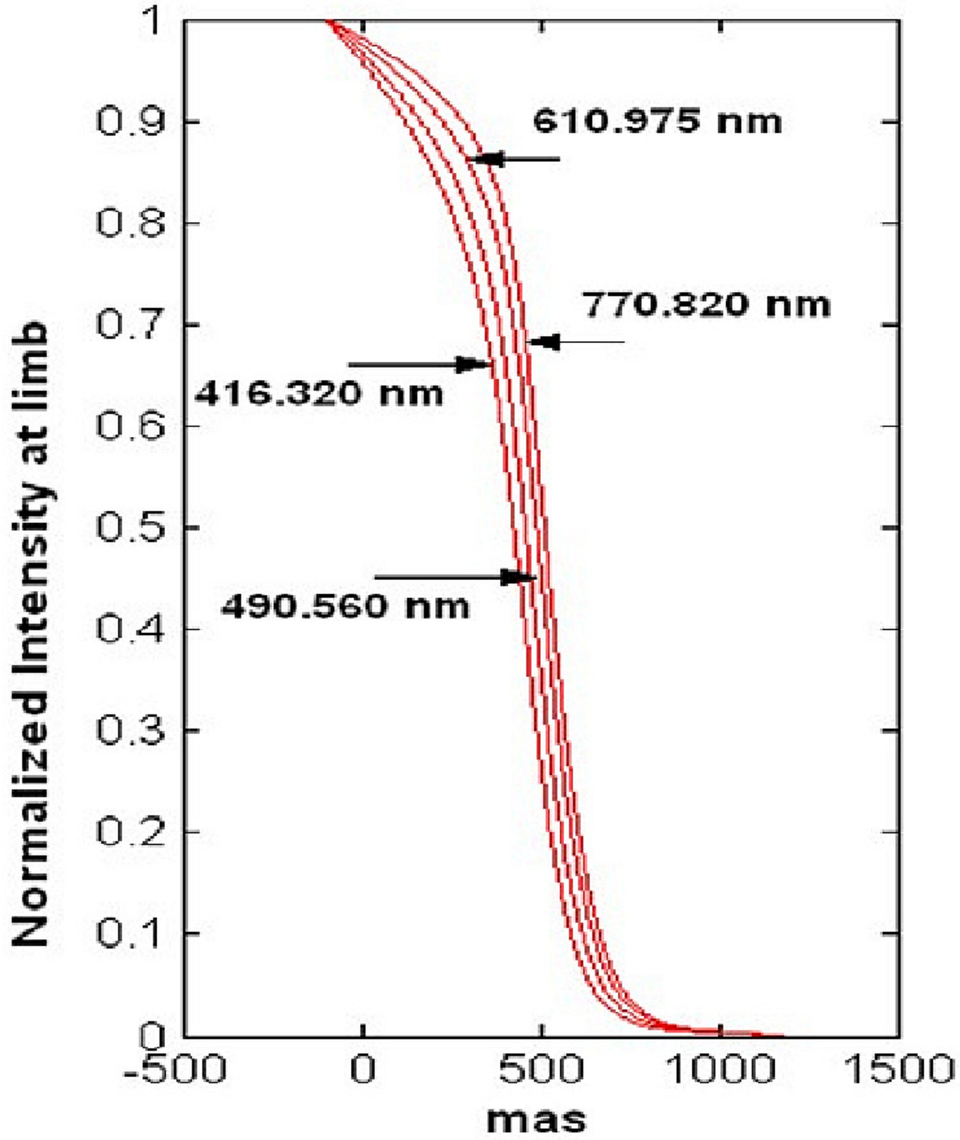
What is a solar diameter?

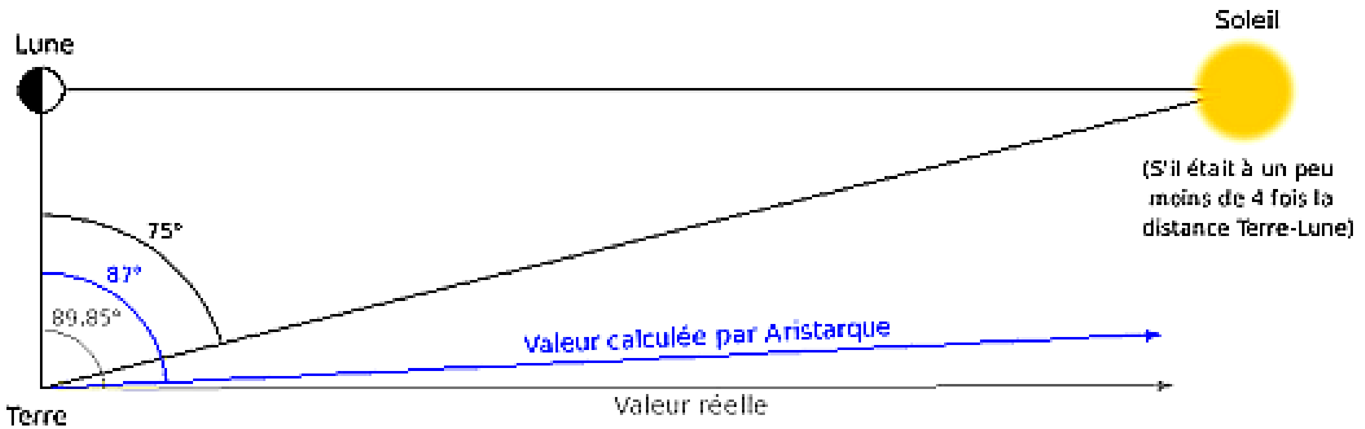
Shift of the inflection point



A great deal of human efforts in the past

- **Aristarchus of Samos (circa 310 - 230 BC)**
  brilliant geometric procedure: 720 th part of the zodiacal circle (360°/720)
  --> R = 900 second of arc ('')

- **Archimedes: 287 - 212 BC:**
  between 164 et 200 th part of the right angle
  → R between 810'' et 988'' (27'00 et 32''56)



Représentation du XVIIe siècle d'Aristarque de Samos tirée de l'atlas céleste d'Andreas Cellarius

- Hence, why to go further?

See: *D. Engels, 1985, American J. Phil., Vol. 106, 3, 298–311*

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- **Any astronomical book**
  (ex: Allen, Astrophysical Quantities, Springer ed., 2001)

  R_{Sun} = 959.63 second of arc or 15'59.63" $D_{Sun} \cong$ 32' (31'59"26)

  Or 6.95080 ± 0.00026 10^{10} cm

  as 1 second of arc on the Sun: ≅ 725 Km

- Hence, why to go further?

Archimède
Domenico Fetti, 1620, Musée Alte Meister, Dresde (Allemagne)

A great deal of human efforts in the past

- **Aristarchus of Samos (circa 310 - 230 BC)**
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  --> R = 900 second of arc (’’)

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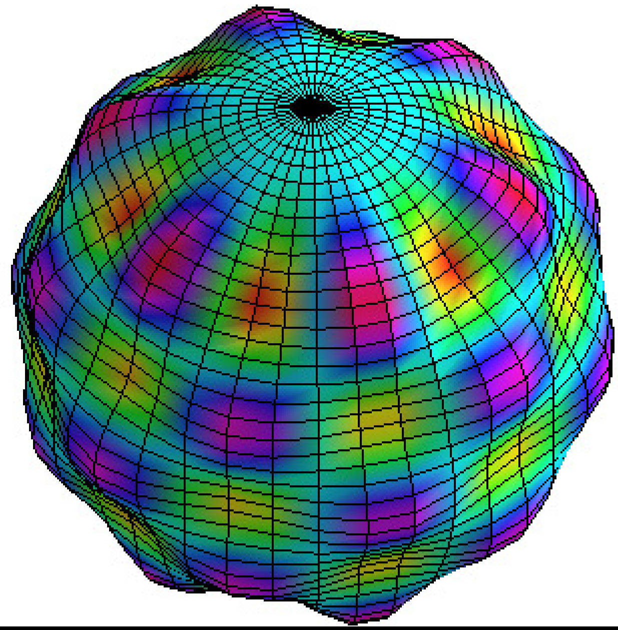
  R_{Sun} = 959.63 second of arc or 15’59.63” $D_{Sun} \cong$ 32’ (31’59’’26)

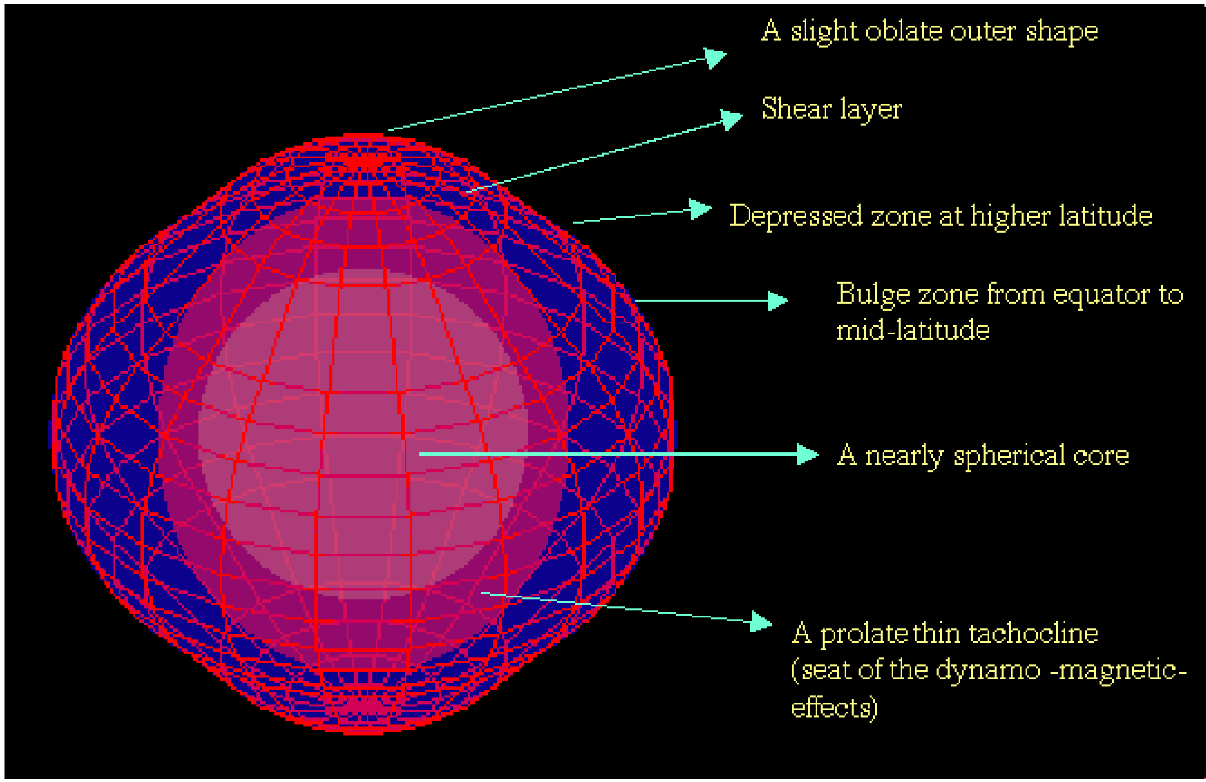
  Or **6.95080 ± 0.00026 10^{10} cm** at 1 AU

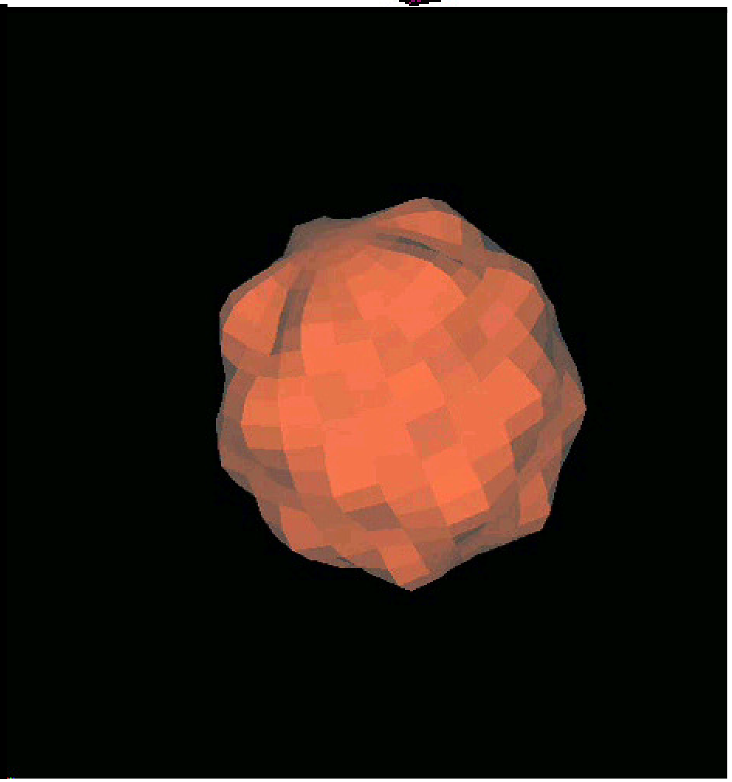
  as 1 second of arc on the Sun: ≅ 725 Km

- Hence, why to go further?

- Because the Sun is not perfectly spherical …







Solar diameter measurements: history

• **Gabriel Mouton : (1618 - 28/09/1694)** **French clergyman**

Is probably the first person who measure accurately the solar diameter,

Lyons (F), in 1661.

Published in his most famous work

"*Observationes diametrorum solis et lunae apparentium*" in 1670.

Mean value:

R = 960.67"

http://www.gap-system.org/~history/Biographies/Mouton.html

Solar diameter measurements: history

- Jean PICARD

(21-07-1620 -- 12-07-1682)

Professor of Astronomy at the "Collège Royal" in Paris, appointed in 1655. Elected "Académie des Sciences" (Paris) in 1666.

Can be credited as the « father » of modern solar astrometry: measurements made « by eye and ear » are at 0.5'' of accuracy.

- **Work was pursued by his student Philippe de la Hire (1640-1718).**

Jean PICARD (1620 - 1682)

http://www.cosmovisions.com/Picard.htm Site CNES

March 18, 1640, Paris
April 21, 1718, Paris
http://en.wikipedia.org/wiki/Philippe_de_La_Hire

Solar diameter measurements: history

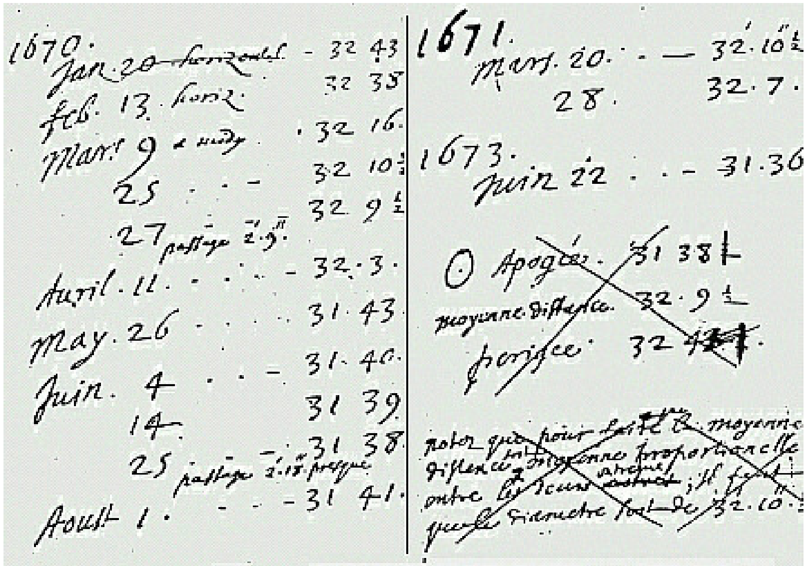
- Jean PICARD (1620-1682)

Manuscripts kept at the « Bibliothèque de Paris » published in 1741 by P.C. Le Monnier in « Histoire Céleste » (Paris)

R = 964.5''

Corrections: -2.1 '' (O' Dell & Van Helden, Nature, 1987, 330, 631)

R = 962.4''



- *La dernière page de la partie consacrée aux diamètres du Soleil dans le premier manuscrit Picard (page 23).* Manuscrit D-1. 14, Bibliothèque de l'Observatoire de Paris).

ANNÉE 1675. Janvier.	TEMPS de la PENDULE.	TEMPS VRAI ou Apparent.	ANNÉE M. DC LXXV.	HAUTEURS observées pour régler la Pendule, & pour les Réfractions.
	H. M. S.	*H. M. S.*		*D. M. S.*
le 11. au matin.	9 11 41 9 14 44		Le *Soleil*... Le diametre du *Soleil* a paſſé au Méridien en 2′ 21″.	8 40 0 9 0 0

Fig. 5. Example of an observation made by J. Picard, transcribed by P.C. Le Monnier in 1741 in his book *Histoire Céleste ou Recueil des observations astronomiques faites par ordre du Roy.*

Solar diameter measurements: history

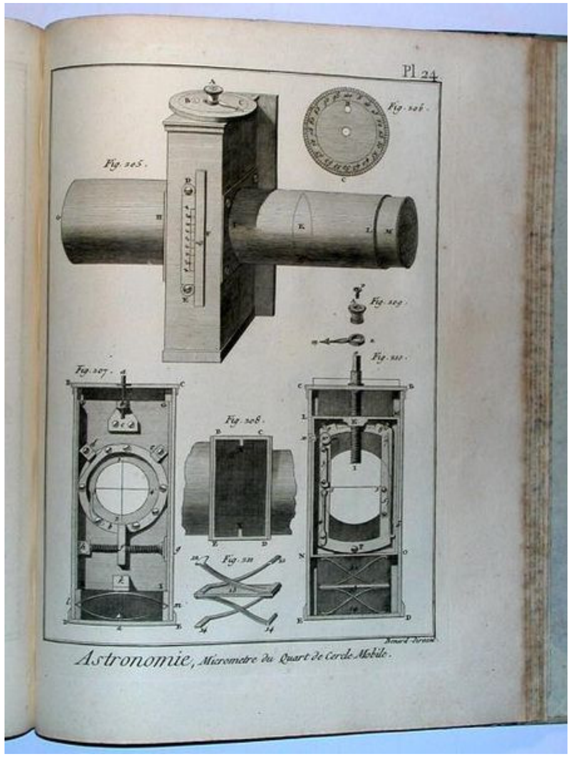
- **Measurements were pursued by a lot of other astronomers, among them**

Adrien Auzout (1622-1691)

Gascoigne (1612-1644)

Etienne Villiard (1671)

Etc…



Solar diameter determined by many means:

Transit Time Measurements:

- Micrometers
- Meridian circles
- Passages of Mercury or Venus
- Sun eclipses
- Solar astrolabes

Angular measurements

- Heliometers
- Spectroscopy
- SOHO, RHESSI, SDO, PICARD (space)

And by different schools:

- Iranian
- French
- Italian
- German
- British and American…

Some historical measurements

Table 1. Summary of efforts (observations) made from Antiquity to the beginning of the XXth century, to estimate the solar radius (in second of arc)[†].

Author(s) & publication date	Year of observation	Method	Radius (in ″)	
Aristarchus	c. 270 BC	Sunset timing	900	
Archimedes[1]	c. 230–280 BC	Moveable disk on rod	815–988	
Ptolemy	c. 130	Parallactic instrument: also called Ptolemaic ruler	936	(constant)
Al Battani	c. 880	Parallactic rulers	974	
Ibn-al-Shatir	c. 1350	Polar-axis sundial	885.0–969.6	(apogee to perigee)
Mäslin	1577	Meridian transit time	967	
Tycho-Brahe[2]	1591	Pinhole instrument	900–931	(apogee to perigee)
Scheiner	1620	Heliotropium telescopium Projection	1500	
Gascoigne	1640	Eyepiece micrometer	963	
Mutas	1644	Calibrated Castelli Projection	961	
Riccioli	1651	Review of existing data	900–973.2	
Cassini	1656	Gnomon shadows (Upper and lower limbs)	947	
Mouton[3]	1659–1661	Meridian transit time	960.67	
Picard	1666–1670 and 1673–1681	Meridian transit time	964.64	
La Hire	1683–1684	Meridian transit time	963.60	
Eimmart	1694	R(Sun)/R(Moon) during solar eclipse	967	
Auzout	1729	Heliometer	948.5	
Bradley	1753	Mural quadrants (altitude of limbs)	961.5	
Bouger	1753 (June, 22)	Heliometer	969.3	
Delisle	1756	Mercury transit	961.7	
Mayer	1758	Transit time	960.46	

Notes: [1] 1/164 and 1/200 of the right angle. [2] Reduced by J. Kepler, published in 1604. [3] Diameter: 32′3,12 as given by Secchi [1877]. See Figure 9. See also corrections made by Toulmonde [1997]. [4] See text, Section 5, for other estimates. [†] References not listed in the Bibliography come from Wittman [1989; 1998].

Some historical measurements

Table 1. Continued.

Author(s) & publication date	Year of observation	Method	Radius (in ″)	
Bessel	1832	Mercury transit	960.38	
	& 1869	idem	959.86	
Lalande[4]	1760	Heliometer	961.05	
Du Séjour	1764	Solar eclipse	960.3	
Messier	1766	Solar eclipse (August, 16)	942.75	
Lalande	1769	Venus transit	958.0	
Gauss	1820	Transit time	961.17	
Chevalier	1912	Photographic plates	960.0	
Sadžakov & Dačić	1975–1986	Meridian telescope	961.1	
Auwers (1891)	1874 & 1882	Venus transits	**959.63**	
Poor (1905)	1870–1894	Photographic plates	959.63 ± 0.05	
Ambronn (1905)	1890–1902	Heliometer	958.94 ± 0.015	
Wittmann (1977)[1]	1836–1975	Heliometer drift scans	960.0 ± 0.09	
Laclare[2]	1975	Solar astrolabe (Calern, F)	959.88 ± 0.07	
Wittmnan (1980)	1976	Photoelectic drift scans	960.52	
Sofia et al. (1983)	1925–1979	Solar eclipses	959.36 ± 0.02	Mean
Fiala et al. (1994)	1715–1991	Solar eclipses	959.75 ± 0.06	Mean
Neckel (1995)	1981	Center to limb profiles	959.62 ± 0.03	
Akimov et al. (1993)	1981.5	Meridian transit time	959.97	
Emilio (2001)	1972–1999	Solar astrolabe (Sao Paulo, B)	959.52 ± 0.03	Visual
		idem	959.61 ± 0.05	CCD
Brown et al. (1998)	1984.7	Solar diameter monitor	958.96 ± 0.02	
Laclare et al. (1996)	1975–1994	Solar astrolabe (Calern, F)	959.42 ± 0.01	Visual
	1989–1994	idem	959.40 ± 0.01	CCD
Leister et al. (1996)	1980–1993	Solar astrolabe (Rio, B)	959.40 ± 0.05	
Yoshizawa (1994)	1989.5	Meridian Circle	959.83	
Maier et al. (1992)[3]	1990	SDS	959.57–959.64	±0.017
Noël (1995)	1990–1994	Solar astrolabe (Santiago, C)	960.230–961.075	±0.07
Sanchez et al. (1995)	1990–1992	Solar astrolabe (San Fernando, S)	958.54 ± 0.12	
Wittmann et al. (1993)	1981 & 1990–1992	Photoelectric drift scans	960.56 (mean)	±0.06

Some historical measurements

Table 1. Continued.

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Wittmann (1997)	1836–1975	Heliometer Photoelectric drift scans	960.00 ± 0.09	
Kilic et al. (1998)	1994.5	Solar astrolabe (Antalaya, T)	959.44 ± 0.05	
Toulmonde (1997)[†]	*1660–1995*	*Corrected compilation*	*960.0 ± 0.1*	
Wittmann et al. (2000)	1990–1998	Photoelectric drift scans	960.66 ± 0.03	Locarno (CH)
	1990–2000	Photoelectric drift scans	960.63 ± 0.02	Izana (SP)
Noël (2004)	1998.39 (1990–2003)	Solar astrolabe (Santiago, C)	960.42 ± 0.01	
Kuhn et al. (2004)	2003	SOHO-MDI	959.28 ± 0.15	
Emilio & Leister (2005)	1972–1997	Solar astrolabe (Sao Paulo, B)	959.52 ± 0.03	
Schou et al. (1997)	1997	Heliosismology	959.87 ± 0.01	
Jilinski et al. (1999)	1997.5	Solar astrolabe (Rio, B)	959.2 ± 0.02	
Antia et al. (1998)	1996 (over 144 days)	Heliosismology	959.34 ± 0.01	
Golbasi et al. (2001)[4]	1999.5	Solar astrolabe (Antalaya, B)	959.03 ± 0.07	
Puliaev et al. (2000)	1998.5	Solar astrolabe (Rio, B)	959.07 ± 0.02	
Sveshnikov (2002)	1631–1973	Mercury transits	959.79 ± 0.02	
Kilic et al. (2005)	2001–2003	Solar astrolabe (Antalaya, T)	959.29 ± 0.01	
Rozelot et al. (2003)	2001	Heliometer (F)	959.434 ± 0.008	
Andrei et al. (2004)[5]	1998–2001	CCD Solar astrolabe (Calern, F)	959.509 ± 0.014	
Egidi et al. (2006)	1992, 1994, 1995, 1996	SDS revisited	959.5–959.7	<0.01
Kilcik et al. (2009)[6]	2006	Solar eclipse	959.22 ± 0.04	
Morand et al. (2011)[7]	1985–2009	CCD Solar astrolabe (Calern, F)	959.48 ± 0.01	

Notes: [1] See Table I of his paper (p. 226) for other measurements. [2] Original estimate as published in Laclare (CRAS, 280, B, p. 13). See also Acta Astron., 40, 1990, 313–319. [3] According to the orientation mode. Revisited by Egidi et al., 2006 (see below). SDS: Solar Disk Sextant instrument. [4] See a complete table p. 1081. [5] and [7]. Not corrected for azimuthal refraction. [5] East-West discrepancies of $0''.631$. [6] A complete table of $R_\odot$ determined through solar eclipses is given. [†] Estimate not taken into account to determine the general mean.

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Andrei et al. (2004)[5]	1998–2001	CCD Solar astrolabe (Calern, F)	959.509 ± 0.014	
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Conclusion:

The canonical value adopted since the work of Auwers (1891), i.e. 959’’.63 +/- 0.05

(*or* $R = (6.95997 \pm 0.003610) * 10^{10}$ *cm*)

is certainly over-estimated by **0.02%.**

Solar diameter measurements: history

Secchi and Rosa : 1872, C.R. Acad Sc. Paris, 75, 606.

Found that solar diameter varies with solar activity by up to 3’’ max and is anticorrelated with activity.

In his book « The Sun », edited in 1872, Secchi wrote:

« *Serait-il absurde de se demander si les dimensions de l'astre sont absolument invariables avec le temps, si sa forme est rigoureusement sphérique et si son axe de rotation coïncide avec l'axe de figure et le centre de gravité? Nous ne le croyons pas* » (p. 210)...

« *Il faut regretter (...) qu'en ce qui concerne la mesure du diamètre solaire, bien peu d'astronomes s'occupent de ce problème* » (p. 216) .

« Would it be senseless to wonder if the sizes of the Sun are definitively immutable, if its shape is purely spherical and if its rotation axis coincide with the figure axis and the center of gravity. We do not believe that.» (p. 210)...

« It should be regrettable (…) with regard to the measurements of the solar diameter, a very few astronomers deal with this problem. » (p. 216)

Solar diameter measurements: temporal variations?

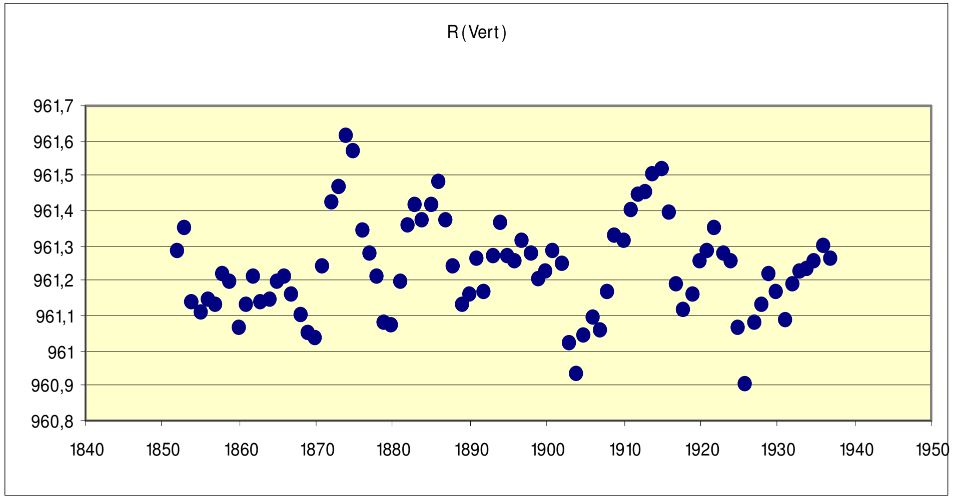
Lucio Giallanella: 1941. "Le Variazioni del diametro solare nel sessanteno 1874-1937, secondo le osservazioni eseguite neel'osservatorio del Campidoglio". Memoria presentata dall'Academico Pontificio Guiseppe Armellini nella Tornata del 30 novembre 1941. Commentationes, Vol. VI, No 25, p. 1139-1197..

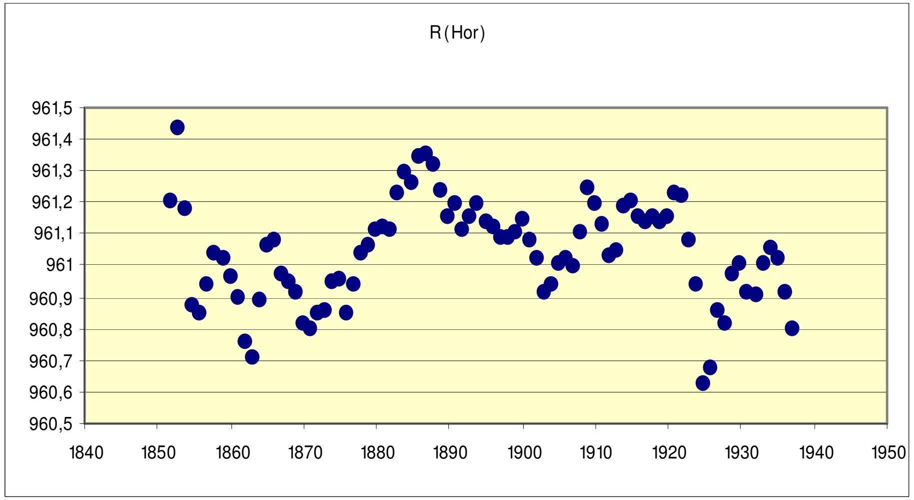
« Omnes eadem ratione (quod antea factum erat numquat) exhibentur observationes diametri solaris, AA. 1874-1937 in Specula Capitolina (Romae) peracteae per circulum meridianum ab Ertel repertum.
Auctor, plane perpensis singulorum speculatorum propriis erroribus, demonstrat valorem 961",38 radio solari, si medium sit intervallum, esse tribuendum; ostendit praeterea fluctuationes et oscillationes diametri ipsius, quarum amplitudo 1" exsuperet, periodus autem inconstans.
Perpendit denique auctor quomodo variationes apparentes diametri solaris per anni cursum, se habeant ad variationes irradiationis atmosphaericae ».

Solar diameter measurements: temporal variations?

Giannuzi, M.A.: 1953. "Riduzione delle osservazioni dei diametro solari orizzontali (1851 al 1937)". Memoria della Societa Astronomica Italiana, 305-314.
Giannuzi, M.A.: 1955. "Riduzione delle osservazioni dei diametro solari verticali (1851 al 1937)". Memoria della Societa Astronomica Italiana, 447-454.

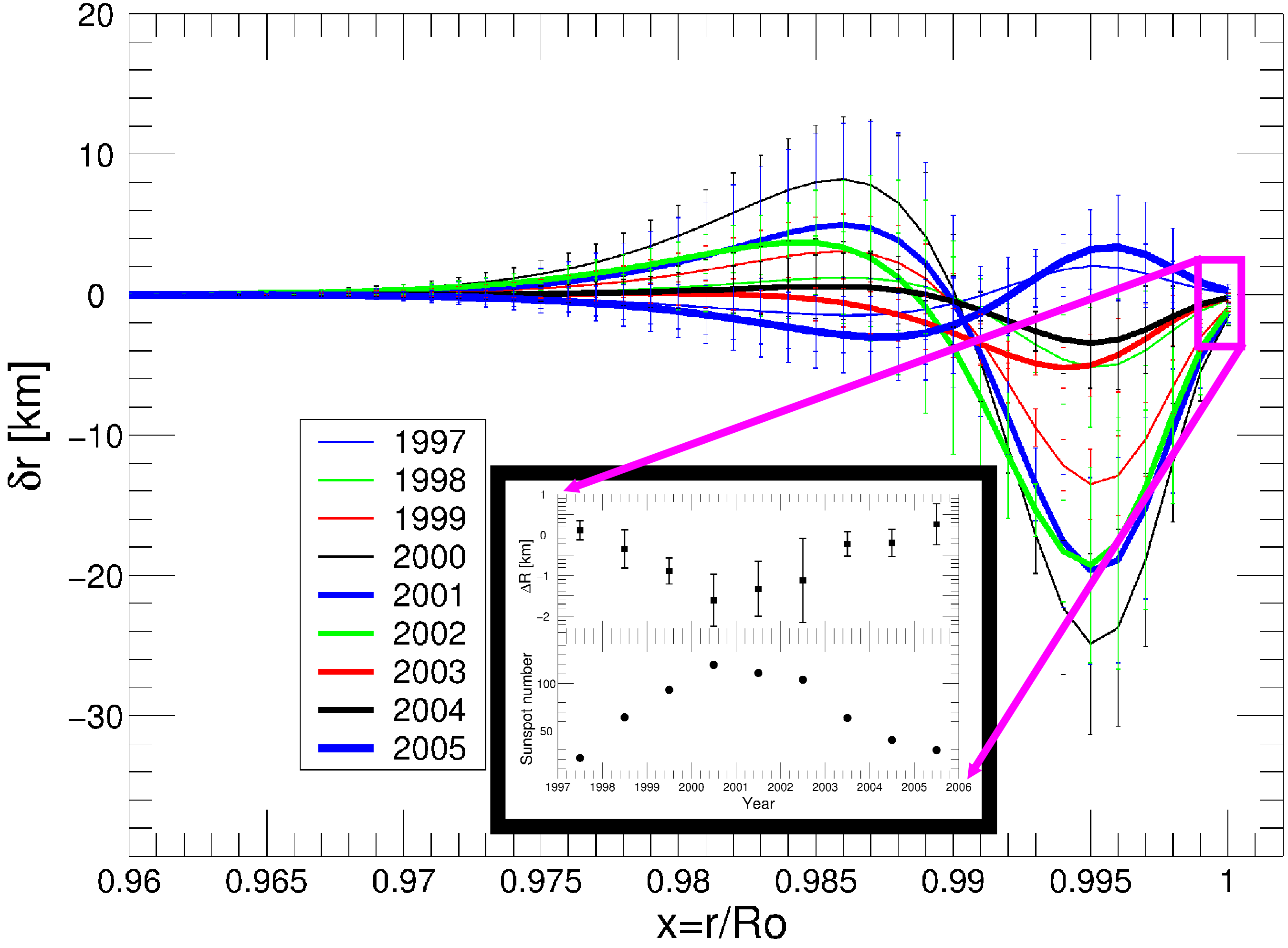
Campidoglio Observatory (Roma, I)





Giannuzi found a basic cycle of 22 to 23 yrs, of 0"1 -- 0"2 amplitude, in phase with solar activity, modulated by a shorter cycle of 7 to 8-yrs (7.5 as a mean), in phase opposition with solar activity, "given suspicion of its atmospheric origin". This periodicity is exactly three times those found in the Calern data (Laclare 1983, Laclare 1999, Laclare 2010):
7.5 yrs * 365 = 2737 /900 = 3.04.

Variation of the position of subsurface layers



Lefebvre & Kosovichev, 2005, *ApJ*, 633, L149
Lefebvre et al., 2007, *ApJ*, 658, L135

What can be done with that, otherwise than to print beautiful postcards?

1/ Accurate determination of the successive gravitational moments: J_n

For instance : $J_2 = 2.0 \pm 0.4\ 10^{-7}$

(Rozelot, Godier, Lefebvre: 2001, Sol. Phys., 198, 223 and Damiani et al. 2009, 2010, JASP, ApJ.)

2/ Constrain alternative theories of gravity and decorrelate PPN

(Review in Pireaux & Rozelot, Astro. Space Sc Rev., 2004)

3/ Global system integration: Sun + Moon + Planets)

Δr cannot exceed some 20 mas over a solar cycle

(Bois et al.: 1998, Astr. Soc. Pac., 140, 75 and Cel. Mec., 1999.)

4/ The complex question of the so-called asphericity/luminosity parameter *w*

Solar case:

Rotation expansion of the form $\omega = \omega_0 + \omega_2 \mu^2 + \ldots$

Solar shape follows from the equation of hydrostatic support,

$$\vec{\nabla} p = -\rho \vec{\nabla} \phi_{grav} + \Omega^2(r,\theta)\ \vec{s}$$

$$(R_{equator} - R_{pole}) / R_{equator} = \frac{-3}{2} J_2 + \frac{\Omega^2 R^3}{2GM}$$

p, ρ, ϕ and ω represent the pressure, density, gravitational potential and rotation rate
Ω is an ill-defined characteristic surface rotation rate related to ω

Magnetic fields and non-rotational velocity flows complicate this result…
See Fazel et al, 2008, New Astronomy,13, 65-72. Scientia iranica, 2008, 15, 144-149.

Solar limb shape distortions

- J_{2n} are dimensionless coefficients satisfying

$$\phi_{out}(r,\theta) = -\frac{GM_\odot}{r}\left[1 - \sum_{n=1}^{\infty}\left(\frac{R_\odot}{r}\right)^{2n} J_{2n} P_{2n}(\cos\theta)\right]$$

For n = 1 J_2 is the quadrupole moment

For n = 2 J_4 is the octopole moment

For n = 3 J_6 is the hexapole moment

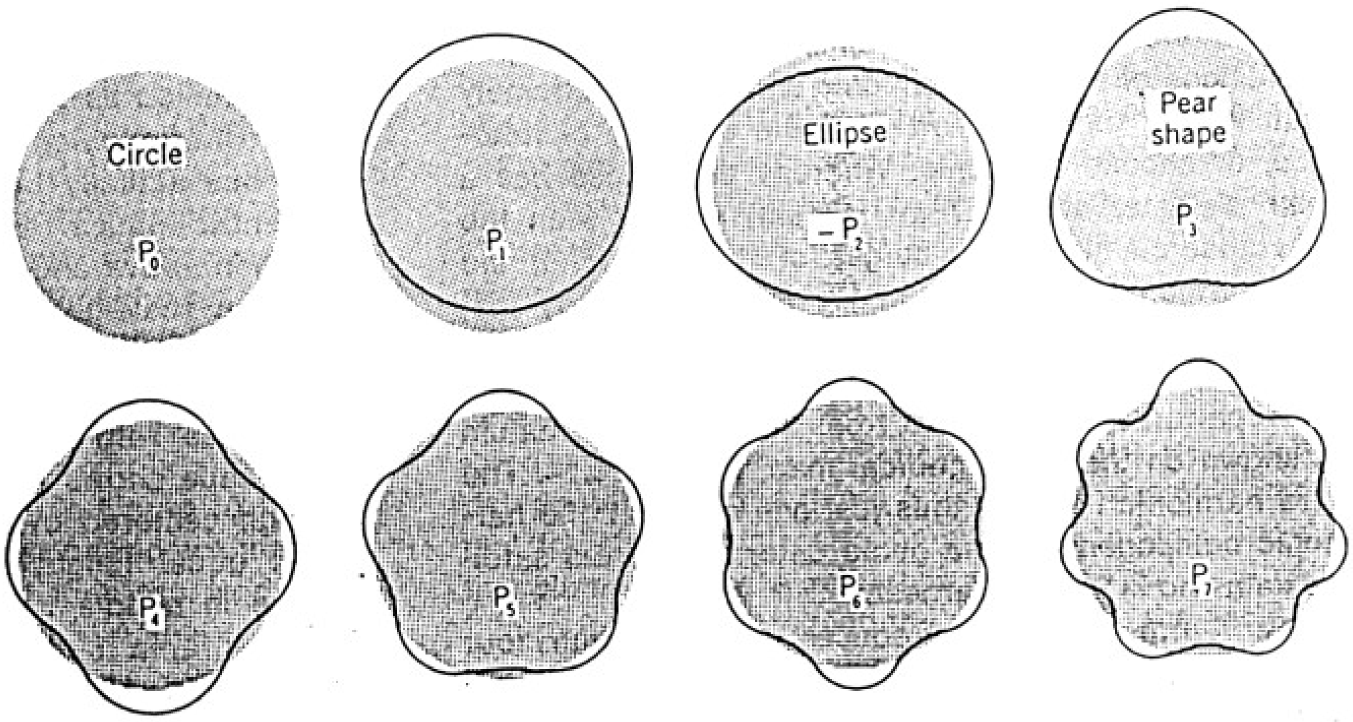
And so on…

→ J_n have a physical meaning.

They told us how much the matter deviates from a pure sphere

(Note that the axial symmetry imposes n even.)

Spherical harmonics: 2-D



N = 1 unbalance
N = 2 ellipsoid shape
N = 3 pear shape
N = 4 ….

Results

Solar limb shape distortions

References	Method	J_2	J_4	J_6	Others
Ulrich & Hawkins (1981)	SSE[1] and spots rotation law	between 10 and 15 10^{-6}	between 0.2 and 0.5 10^{-6}		
Gough (1982)	First determination of helioseismic rot. rates	36 10^{-7}			
Campbell & Moffat (1983)	Planetary orbits	(5.5 ± 1.3) 10^{-6}			
Landgraf (1992)	Astrometry of minor planets	(0.6 ± 5.8) 10^{-6}			
Lydon and Sofia (1996)	Solar Disk Sextant Experiment (SDS)	1.84 10^{-7}	9.83 10^{-7}	4 10^{-8}	J_8 = -4 10^{-9} J_{10} = -2 10^{-10}
Paternò *et al.* (1996)	SSE + empirical rotation law and SDS	2.22 10^{-7}			
Pjipers (1998)	SSE + GONG and SOI/MIDI data Ponderate value	2.14 ± 0.09 10^{-7} 2.23 ± 0.09 10^{-7} 2.18 ± 0.06 10^{-7}			
Armstrong & Kuhn (1999)	Vect. Spher. Harm. numerical error	-0.222 10^{-6} 0.002 $^{-6}$	3.84 10^{-9} 0.4 10^{-9}		
Godier & Rozelot (1999)	SSE + Kosovichev law	1.6 10^{-7}			
Roxburgh (2001)	SSE + 2 models of rotation law	2.208 10^{-7} 2.206 10^{-7}	-4.46 10^{-9} -4.44 10^{-9}	-2.80 10^{-10} -2.79 10^{-10}	J_8 = 1.49 10^{-11} J_8 = 1.48 10^{-11}
Rozelot *et al.* (2001)	Theory of Figure	$-(6.13 \pm 2.52)$ 10^{-7} Note[2]	3.4 10^{-7} Note[3]		
Rozelot & Lefebvre (2003)	Theory of Figure	- 6.52 10^{-7}	4.20 10^{-7}	-9.46 10^{-9}	J_8 = 2.94 10^{-13}

Science Objectives

RELATIVISTIC CELESTIAL MECHANICS

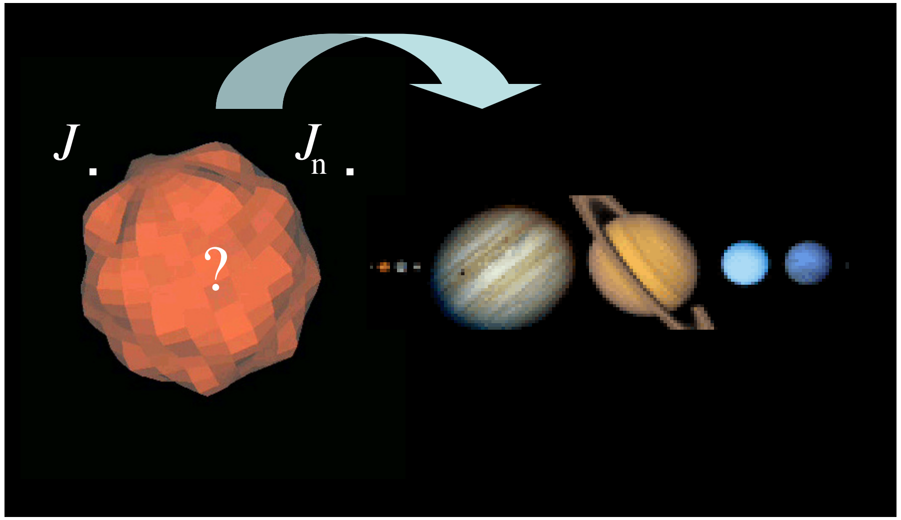
J_2 plays a role in the relativistic perihelion precession of a planet with orbital parameter (a, e, i):

$$\Delta\omega = \Delta\omega_{0\ GR} \bullet \left[+\frac{1}{3}(2 + 2\gamma - \beta) - \frac{R_\odot^2}{R\, a\,(1-e^2)} J_{2\odot}\left(3 \sin^2 i - 1\right) \right]$$

42,98 arcsec/century

Post-Newtonian parameter encoding the amount of non-linearity in the superposition law of gravitation

Through spin-orbit couplings, J_2 influences the motion (a, e, i) of solar system bodies.



A precise knowledge of J_2 is needed to set up precise ephemeris....

The predicted advance per orbit $\Delta\omega$, is then given by

$$\Delta\omega = \left[\frac{2GM}{a\,(1-e^2)}\left(2\alpha^2 + 2\alpha\gamma - \beta\right)\right] + \left[J_2 \frac{\left(3\sin^2 i - 1\right) R^2}{a^2\,(1-e^2)^2}\right] \tag{12}$$

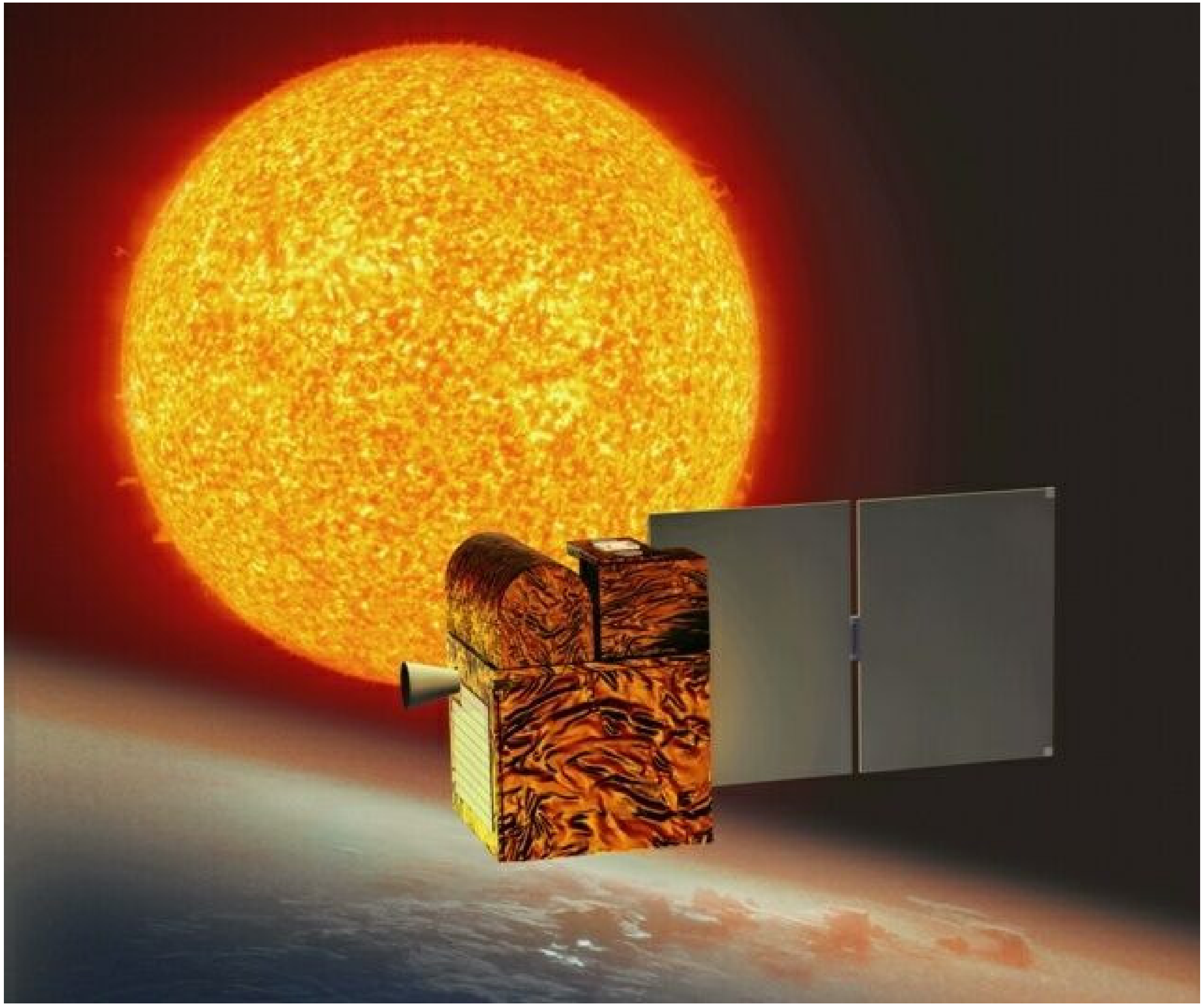
which reduces to equation (11) in pure G.R. In the case of Mercury, for instance, one obtains

$$\Delta\omega = 42.980\left[\frac{1}{3}(2+2\gamma-\beta) + 0.296\times 10^{-4}\left(\frac{J_2}{10^{-7}}\right)\right] \quad \text{in arcsec per century.} \tag{13}$$

Table 1. Ephemerids tests, starting epoch Julian day 2440400.5, carried out by removing or includin planets motion. The first column gives the number of case tests, as defined in column two. Third t fifth column provide the solution values for J_2 and Post-Newtonian parameters β, γ. Sixth to eight columns give the correlation between pairs of these three quantities. The zero inside a column mear that the value was constrained.

Test	Data	J_2 $\times 10^{-7}$	$(\beta$ -1) $\times 10^{-4}$	$(\gamma$ -1) $\times 10^{-4}$	J_2 β	J_2 γ	β γ
0	All data (nominal GR solution)	2.2 ± 0.4	0	0			
1	No Mercury data	3.6 ± 0.8	0	0			
2	No Venus data	2.2 ± 0.4	0	0			
3	No Mars data	3.1 ± 1.2	0	0			
4	No Mars ranging data	0.5 ± 0.6	0	0			
5	No Mars VLBI data	2.6 ± 0.4	0	0			
6	No early Mars data (pre–1985)	2.3 ± 0.4	0	0			
7	No late Mars data (post–1985)	2.0 ± 0.5	0	0			
8	All data (fully conservative)	3.2 ± 0.8	-0.1 ± 3.4	-2.6 ± 2.4	+ 0.45	- 0.56	+ 0.30
9	All data	3.2 ± 0.7	0	-2.5 ± 2.3		- 0.82	
10	All data	2.7 ± 0.6	1.0 ± 3.2	0	+ 0.78		

Space data collections



SOHO

RHESSI

PICARD

SDO

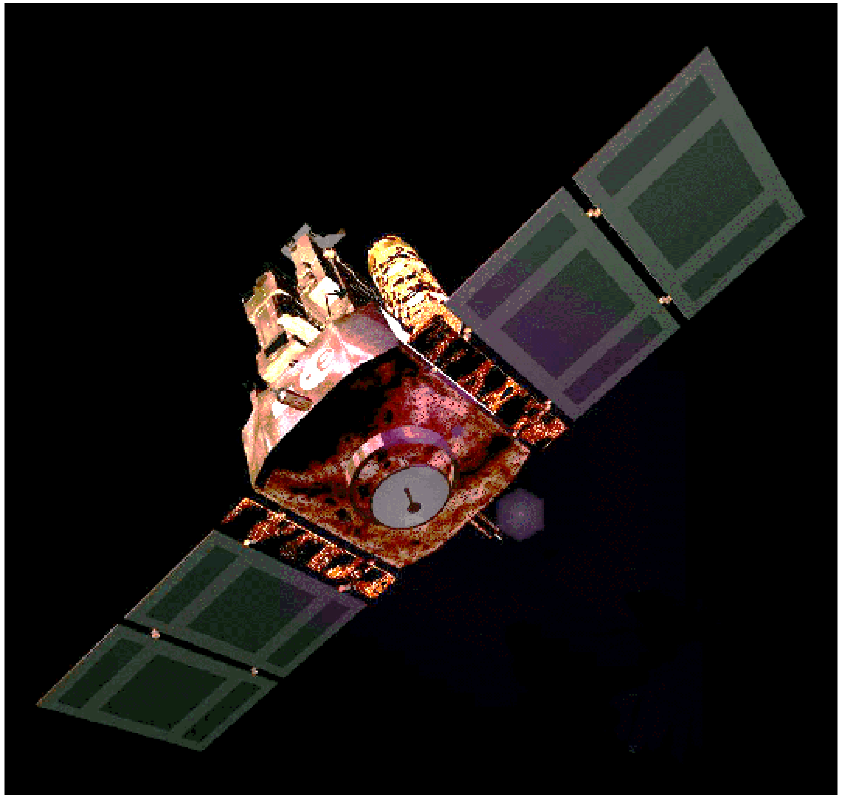
Next coming:

DynaMICCS/HIRISE

Solar astrometry from space – Solar and Heliospheric Observatory, Michelson Doppler Imager (MDI)

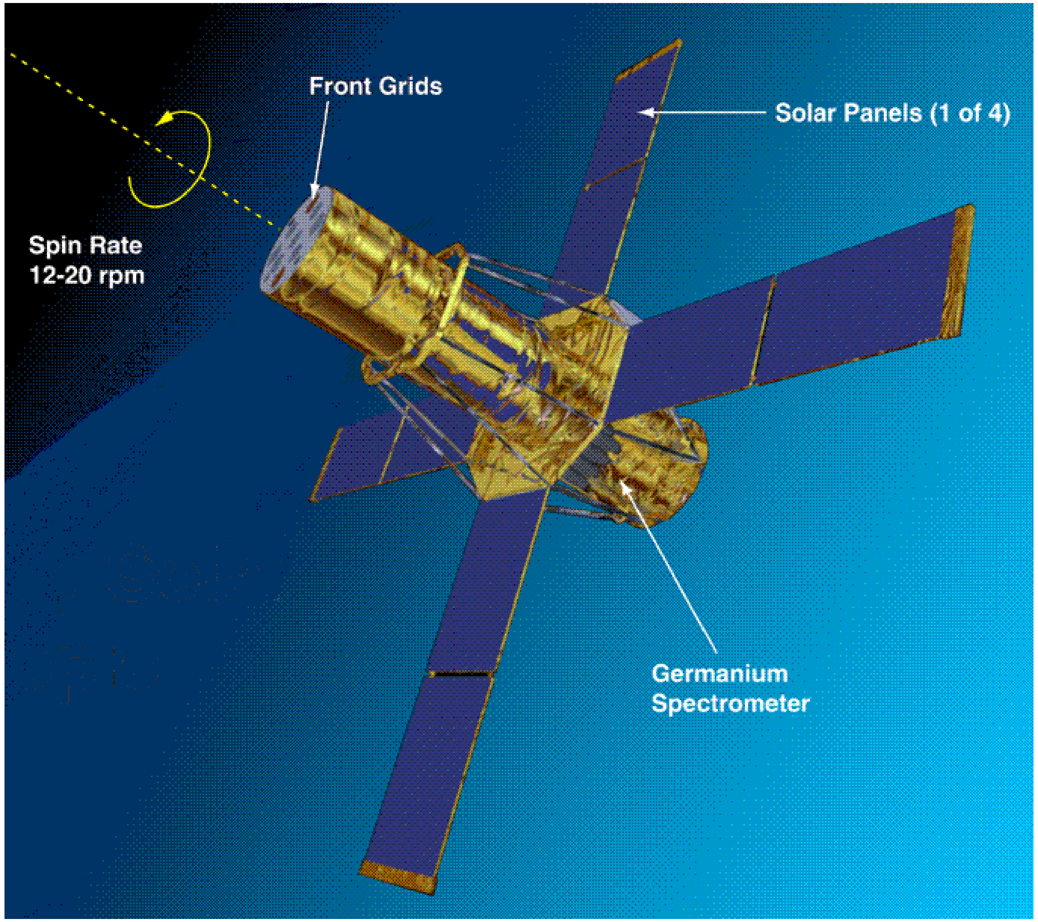
1. Satellite in "halo" orbit near L1
2. Stable solar image limb fiducial
3. MDI Imaging instrument with well defined thermal properties, .02" pointing errors

After M. Emilio, R. I. Bush, J. Kuhn, and P. Scherrer: 2007, ApJ., 660, L161–L163



R at 1 AU: 959''.28 *+/-* 0.15 (or 695 254 *+*\- 109 km)

RHESSI Press release: How Round is the Sun?

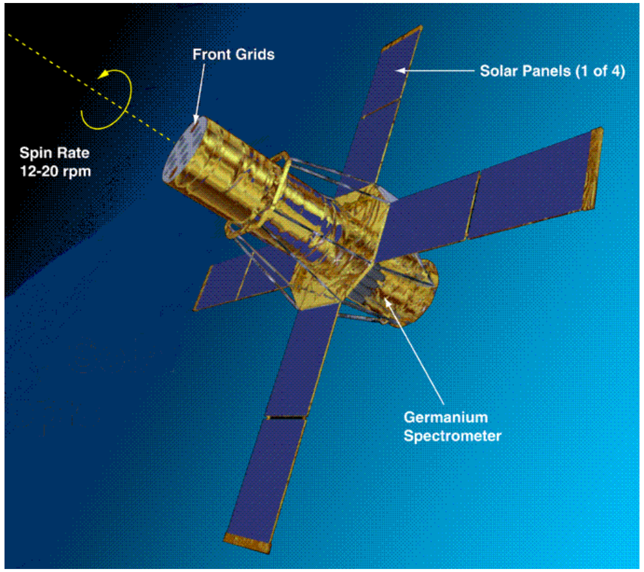


A Large Excess in Apparent Solar Oblateness Due to Surface Magnetism

Scientists using the RHESSI spacecraft have measured the roundness of the sun with unprecedented precision, and they find that it is not a perfect sphere. During years of high solar activity the sun develops a thin "cantaloupe skin" that significantly increases its apparent oblateness.

Hudson, H. and Rozelot, J.P., "History of solar oblateness", 2010.
http//sprg.ssl.berkeley.edu/~tohban/wiki/index.php/History_of_Solar_oblatenes

RHESSI Press release: How Round is the Sun?



426 The European Physical Journal H

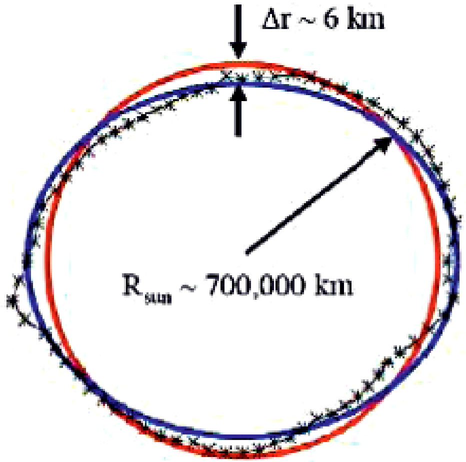
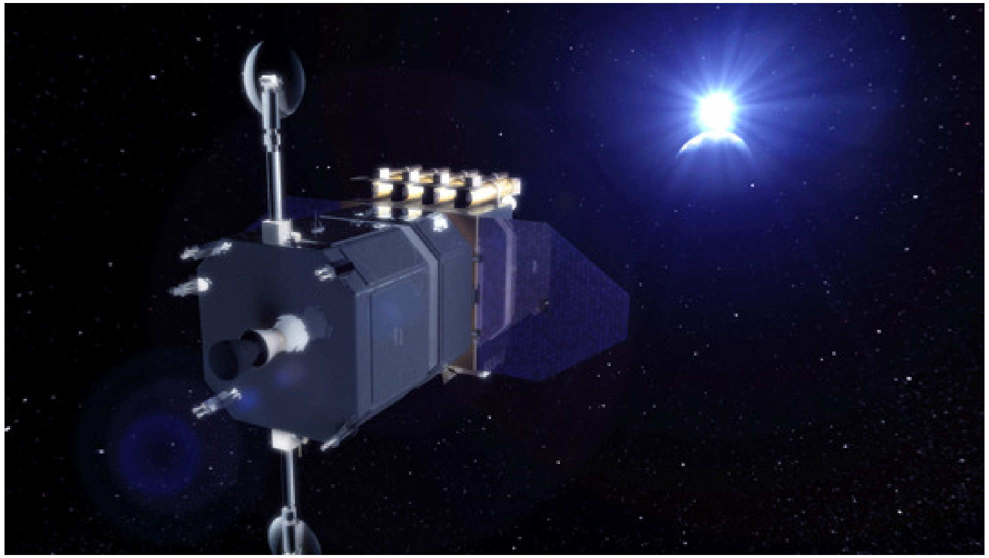


Fig. 6. Cross-section of the Sun through its rotation axis, showing its basically circular shape (red) with a small distortion induced by the rotation (blue). The radial scale has been magnified enormously as indicated. The points show actual RHESSI (see footnote 22) data [Hudson 2000].

Hudson, H. and Rozelot, J.P., "History of solar oblateness", 2010.
http//sprg.ssl.berkeley.edu/~tohban/wiki/index.php/History_of_Solar_oblatenes

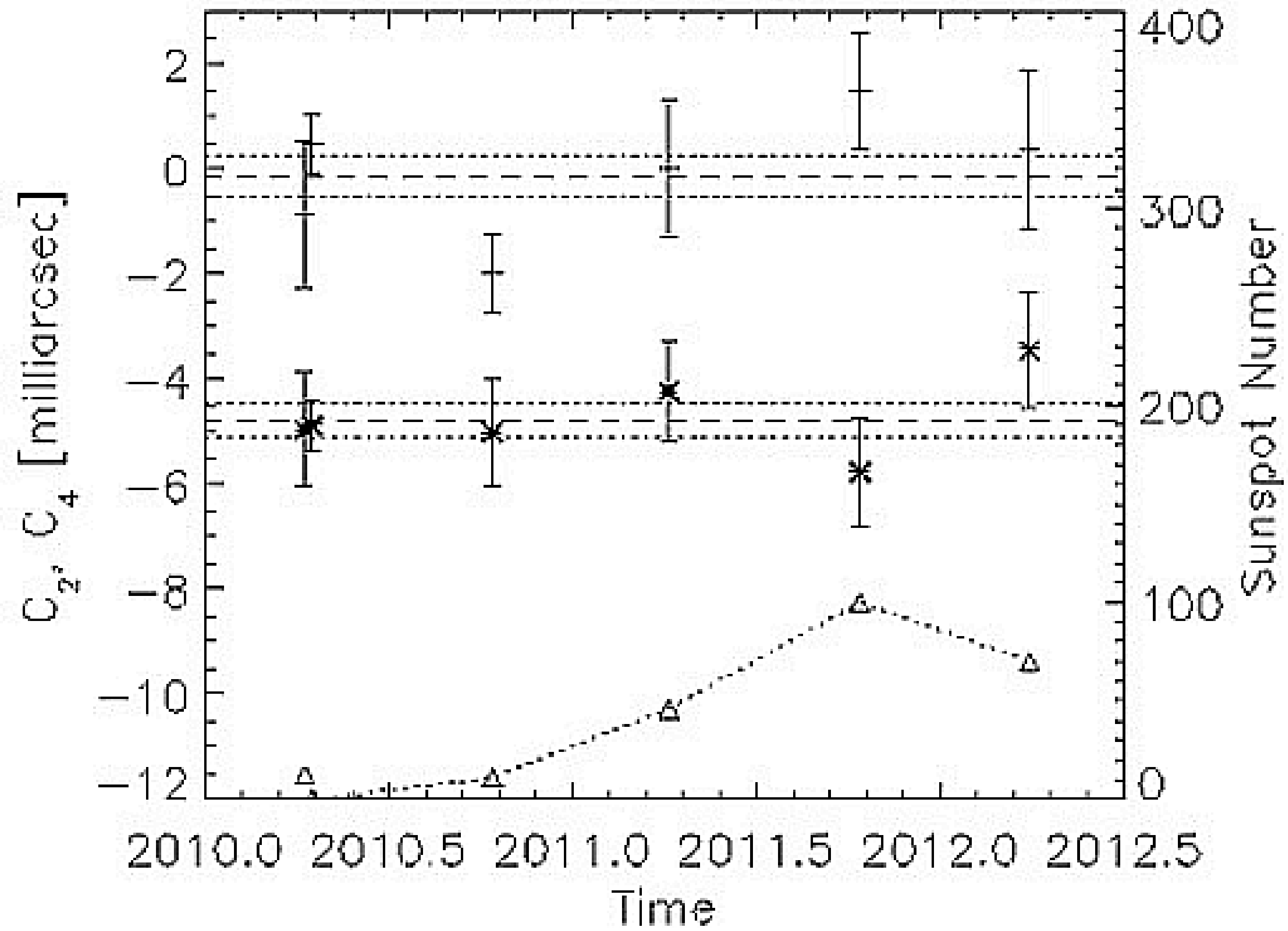
And SDO

Launched February,11, 2010



With the help of

HMI instrument



- J. R. Kuhn, R. Bush, M. Emilio, I. F. Scholl: **The Precise Solar Shape and its Variability, Science, 16th of August 2012.**

Conclusion

- The challenge opened by the Greek astronomers is about to come to its end !

Solar Eclipse, Antalaya, 2006, March, 29

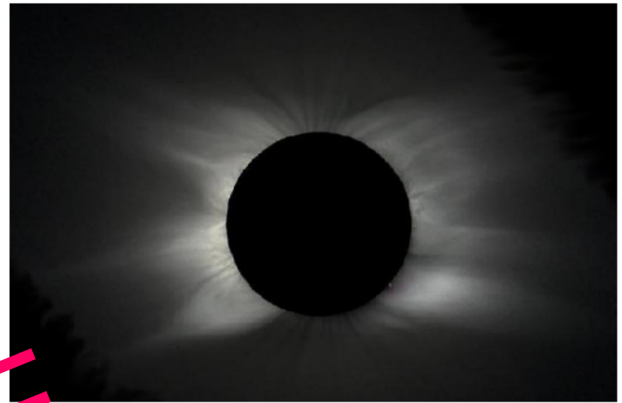


Figure 2. Total solar Eclipse of March 29, 2006, 10:55:42 TU, seen on the observation site located at Kum[illegible] (on the sea-side, between Side and Çolaklý), near Antalya (Turkey). Geographic coordinates are: 36° 47' 11.11" N and 31° 22' 41.72" E. The image shows very well the polar regions with plumes, indicating the good meteorological conditions which permitted to record accurately the second and fourth contacts. A small group of spots were just lying near the equator. Photograph by V. Desnoux.

GRAZIE

R = 959.22 ± 0.04 at 1 A.U.

A. Kilcik, C. Sigismondi, J.P. Rozelot, K. Guhl: 2009, Sol. Phys., Vol. 257, Issue 2, pp.237-250

La question du paramètre *w*

- 95 % de l'irradiance totale peut être expliquée par la modélisation des taches et facules solaire.

  --> 5% restant?

- due aux changements abrupts de la forme de l'enveloppe

  OUI: Rozelot, Sofia, Pap... NON: Fröhlich, (+ referees anonymes...)

- Rapport: $w = \partial (\ln R) / \partial (\ln L)$

- Theorétiquement (Sofia, Spruit, Deadborne, Brown…):

  $7.5\ 10^{-2}$ to $8\ 10^{-4}$ sign ?

  observations: $6.7\ 10^{-2}$ to 0.8

- *Comment mesurer w en toute confiance*?

--> Espace: satellites dédiés

MESURE DE W = δr/r / δL/L

r et L désignant le rayon et la luminosité solaire respectivement.
Les modèles solaires et les observations permettent de déterminer W.

Valeur	Auteurs	Moyens
2.10^{-4}	Spruit, 1992	Théorie
$- 8\ 10^{-4}$	Gilliland, 1980	Observations
$5\ 10^{-3}$	Dearborn et Blake, 1980	Théorie
$7.5\ 10^{-2}$	Sofia et al, 1979	Théorie
> 0 ou <0	Lydon et Sofia, 1995	Théorie
- 0.2	CERGA	Observations
<0	Sofia et al., 1994	Observations
<0	Sofia, 2001	Observations
1.2	Noël, 2002	Observations

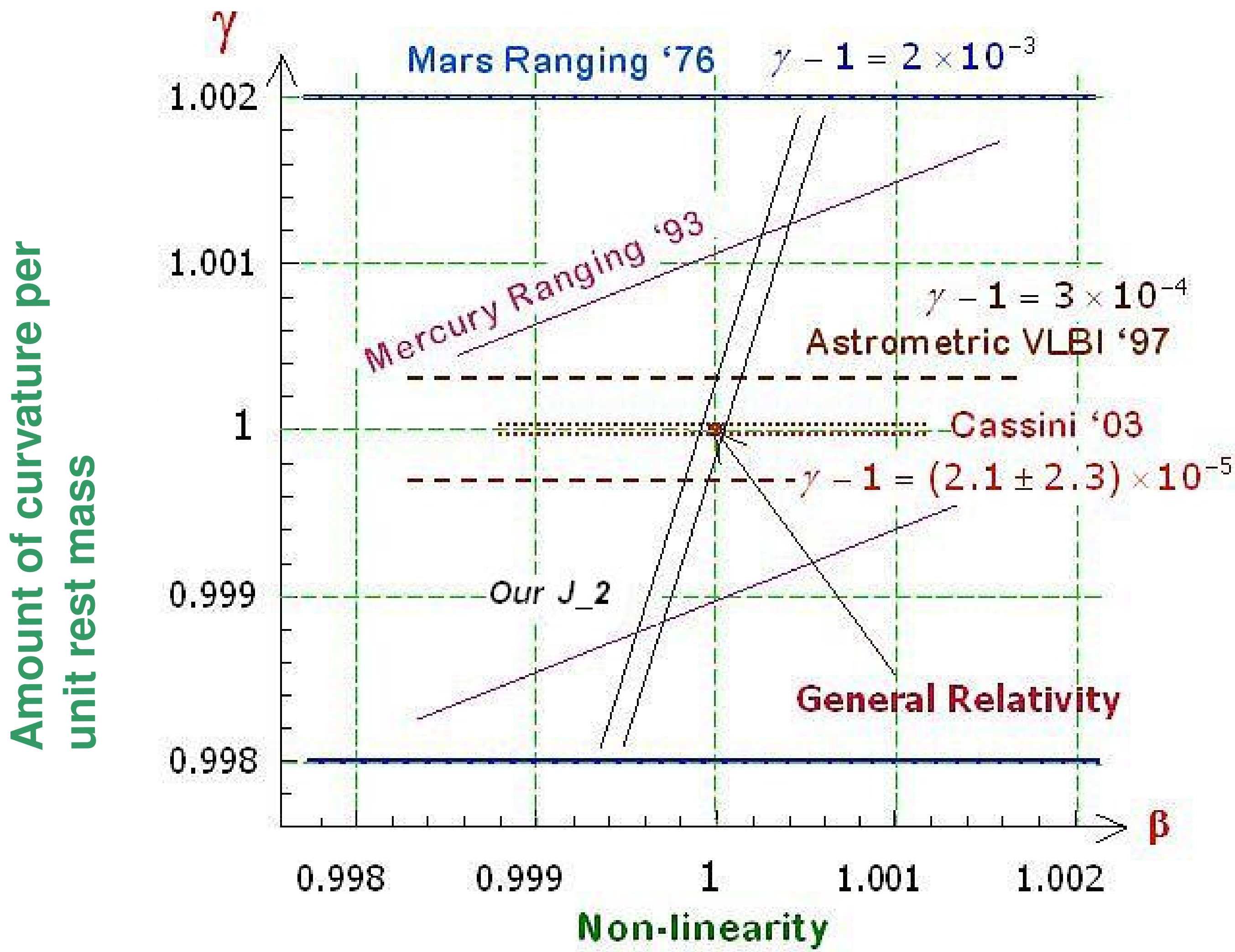
RESULTS FROM SOLAR ECLIPSE OBSERVATIONS

Date	Eclipse Type	No. Obs	Correction to Solar Radius[1]	Correction to Lunar Ecliptic Long	Correction to Lunar Ecliptic Lat
			(All in seconds of arc)		
1715 May 3	Total	3	$+.48 \pm .2$		
1925 Jan. 24	Total	8	$+.51 \pm .08$		
1976 Oct. 23	Total	43	$+.04 \pm .07$	$+.65 \pm .10$	$-.45 \pm .09$
1979 Feb. 26	Total	47	$-.11 \pm .05$	$+.52 \pm .09$	$+.25 \pm .05$
1980 Feb. 16	Total	232	$-.03 \pm .03$	$+.32 \pm .03$	$+.07 \pm .04$
1981 Feb. 4	Annular	153	$-.02 \pm .03$	$+.02 \pm .05$	$-.02 \pm .04$
1983 June 11	Total	201	$+.09 \pm .02$	$+.65 \pm .03$	$-.19 \pm .02$
1984 May 30[2]	Annular	51	$+.23 \pm .04$	$+1.01 \pm .05$	$-.47 \pm .06$
1984 May 30[3]	Annular	51	$+.09 \pm .04$	$-.12 \pm .06$	$-.03 \pm .06$
1987 Sep. 23[4]	Annular	123	$-.11 \pm .03$	$+.57 \pm .09$	$+.02 \pm .02$

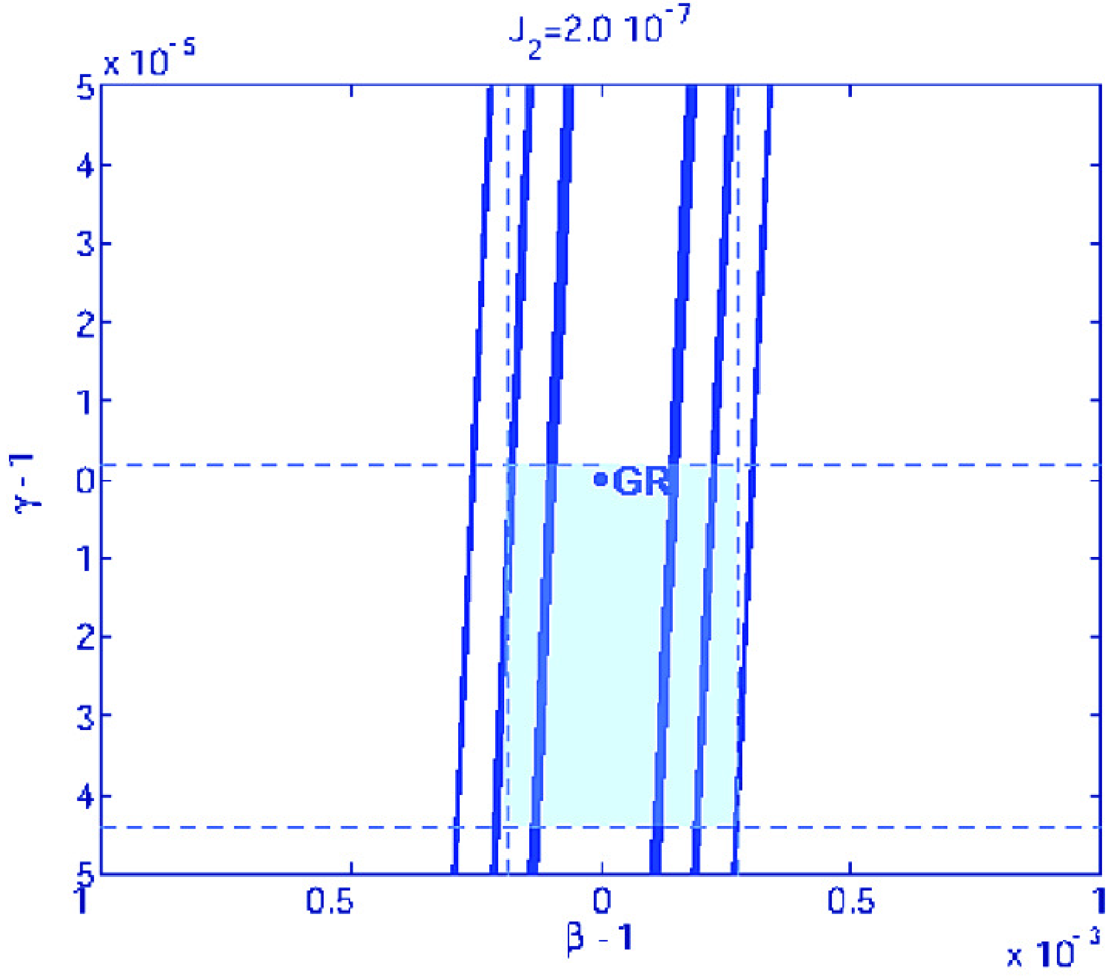
Notes.
1: Standard value 959.63 seconds of arc.
2: Old analysis, Dunham site (Fiala *et al.*, 1985).
3: New analysis, Dunham site, with LE200/DE200 ephemerides.
4: Shanghai Observatory expeditions to Funing and Tenchang, China (Wan *et al.*, 1989).

Théories alternatives possibles à la Relativité Générale?

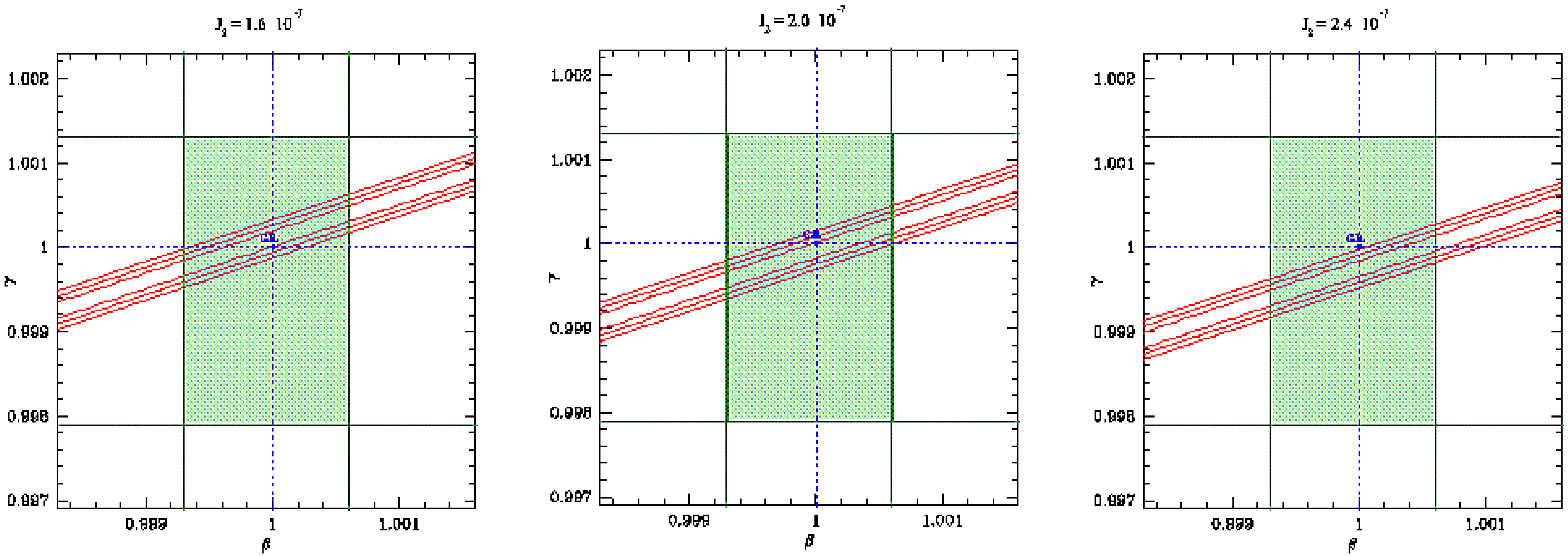
$$\Delta\omega = \left[\frac{2GM}{a\left(1-e^2\right)}\left(2\alpha^2+2\alpha\gamma-\beta\right)\right]+\left[J_2\frac{\left(3\sin^2 i-1\right)R^2}{a^2\left(1-e^2\right)^2}\right]$$



Théories alternatives possibles à la Relativité Générale?



Astrophysical relevance



There is room for Alternative gravitational Theories
Space Missions: Beppi-Colombo, Gaia…

Pireaux & Rozelot, 2003, Adv. Sp. Res.