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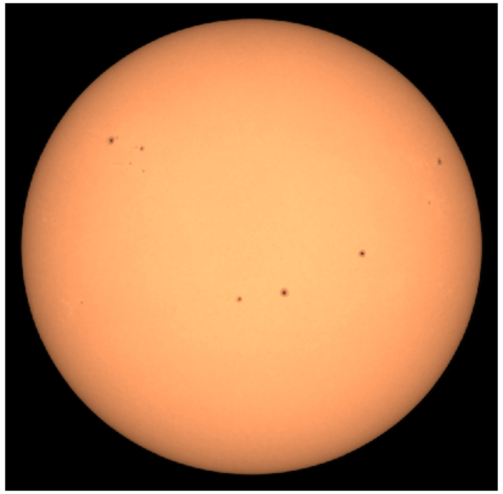

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Variations of solar oblateness with the 22 yr magnetic cycle

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The solar oblateness, a key input for models

- The **internal dynamics of the Sun**, from its depths to the most superficial layers, are manifested by disturbances on the surface of the photosphere, leading directly to small deviations from the sphericity of the Sun i.e. **the solar shape**

- The **solar shape reflects the internal state of the Sun** and the processes that take place there

Fundamental issues

- **Accurate measurements to study its variability with solar activity**

- **Long-term observations**

outline

- **Measurements and variations of solar oblateness, a brief history**
- Solar oblateness measurements with HMI/SDO
- Main results
- Conclusion

Measurements and variations of Solar oblateness, a brief history

- **1865: Newcomb** suggested that **500 milli-arcseconds** of **solar oblateness** (**Pole-Equator radius difference**) due to a rapidly rotating interior of the Sun could explain **the advance of Mercury's perihelion** (observed by **Le Verrier** in **1859**) **not predicted** by the **Newtonian gravitational theory**.

- At that time, **the solar shape** was understood via **two main theories**: **theory of gravitation** and **internal rotation of the Sun**.

- **Einstein's theory of general relativity** provided an **explanation** for the anomalous of **advance of Mercury's perihelion** but **good estimates of solar oblateness remain important for this theory** i.e. **gravitational moments of the Sun** are still relevant for **Mercury's perihelion.**

- **Many measurements** of oblateness were carried out **for several decades**, generating **other questions** about its **mean value** and **temporal variations**.

Measurements and variations of Solar oblateness, a brief history

- **1966:** The oblateness measurement of **Dicke and Goldenberg** in Princeton (New Jersey) is worth mentioning because of its high value (**41.9±3.3 mas**): it allowed them to highlight **the scalar-tensor theory of gravitation** and **the quadrupole moment of the Sun** associated with a **rapidly rotating core**.
- These results were widely criticized, but have sparked a **growing interest in the interior of the Sun**.
- **1967: Sturrok & Gilvarry** showed that a **rapid change of internal magnetic field** would **cause magnetic distortions at the surface**, resulting in **an oblateness comparable to the observations**: **The magnetic field appeared as the third major issue affecting the solar shape**.

Measurements and variations of Solar oblateness, a brief history

- **Gravitational models** and the **helioseismology** (to probe the Sun's interior to estimate both **radial profiles of latitudinal differential rotation** and the **internal magnetic field**) made it possible to **identify acceptable values for oblateness** that is **mostly induced** by the **centrifugal force on surface layers** with a **very weak contribution** from **the gravitational quadrupole moment J_2**.

- **Modern measurements** from space, balloons and ground **confirmed expected values**.

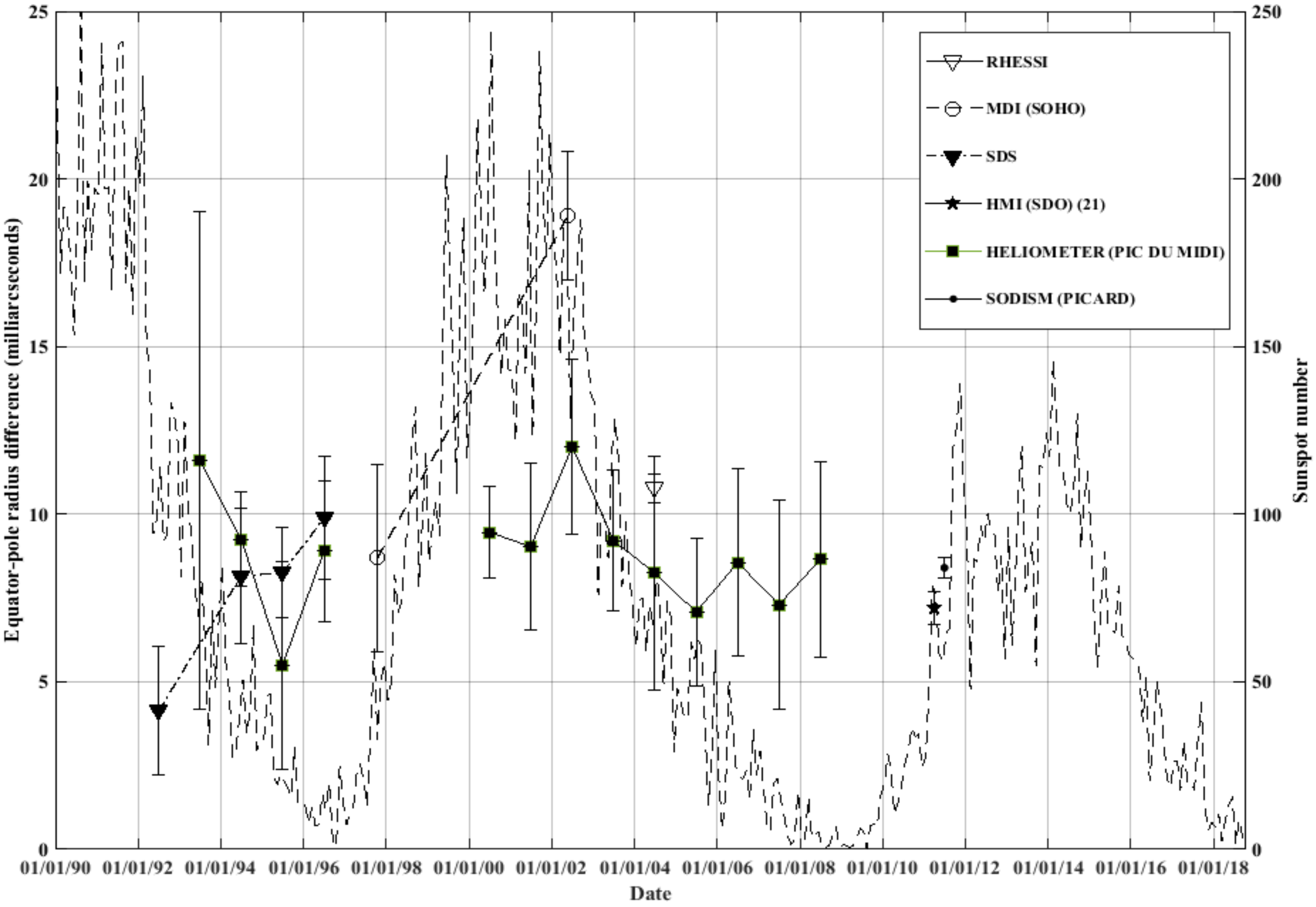
- **Temporal variations of oblateness** are just as useful for **understanding the functioning of the Sun** in relation with the **activity cycle**.

Temporal variations of solar oblateness

Time series of oblateness recorded on the ground, from balloons, and lately from space **showed variations** but they were **inconclusive**:

They are **in phase with the solar activity** (Dicke *et al.* 1987; Emilio *et al.* 2007; Rozelot *et al.* 2009; Damiani *et al.* 2011) or **in anti-phase** (Egidi *et al.* 2006; Meftah *et al.* 2016).

Kuhn *et al.* (2012) reported **no obvious variations**.



Temporal variations of solar oblateness

The **longest time series in space** was recorded with the **Helioseismic and Magnetic Imager** (HMI) **on board the Solar Dynamics Observatory** (SDO).

SDO was **launched in February 2010** just after the **beginning of Cycle 24**, and the series of HMI measurements now covers almost the entire cycle.

These measurements, therefore, are a **major asset** to being able **to explain and validate those carried out in the past**, including **reported inconsistencies**.

Presentation outline

- Measurements and variations of solar oblateness, a brief history
- **Solar oblateness measurements with HMI/SDO**
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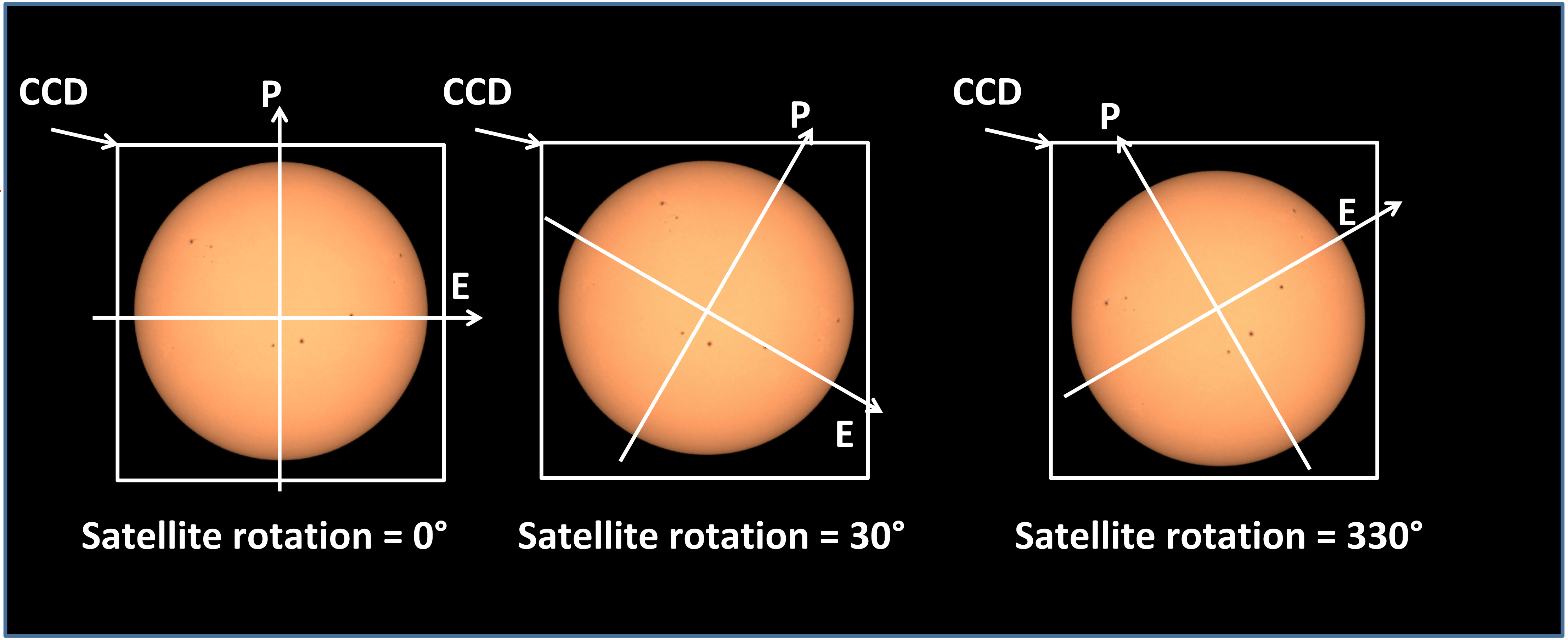
Solar oblateness measurements with HMI

- **Solar oblateness** is **obtained** from data recorded during **roll procedures** (calibration mode) of the SDO spacecraft: the **spacecraft** is **rotated around the line-of-sight of HMI** with **angular steps** of **11.25°**

Consequence of the roll: the **solar image turns** in the CCD coordinate frame.



- **The roll procedure is run twice a year and the time is around 6 hours for each one.**
- **About 330 images are recorded in the solar continuum (617.3 nm – 70 mA) during a roll sequence.**

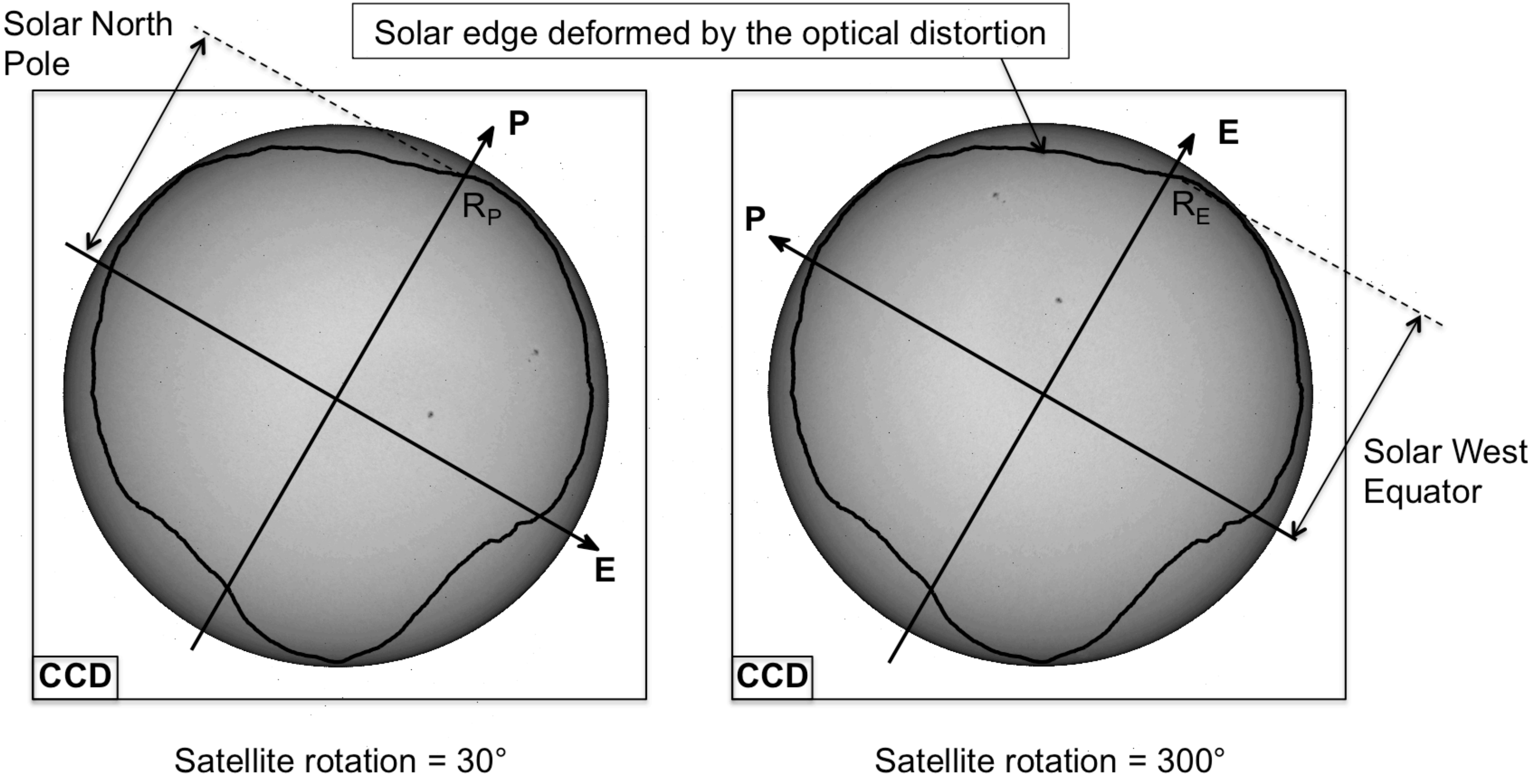
The roll procedure for solar oblateness measurements

- **Different rotation steps in a roll sequence** are considered to **avoid HMI optical effects** on oblateness calculations.

- **Solar oblateness** is **computed** from all **pairs of radius** in **different rotations** taken in **same angular orientations θ in the CCD frame**.

Solar radius for each θ of each image are then **averaged** over the roll sequence time to obtain the **mean solar shape:**

$$R(\theta) = R_{mean} + \Delta R(\theta)$$

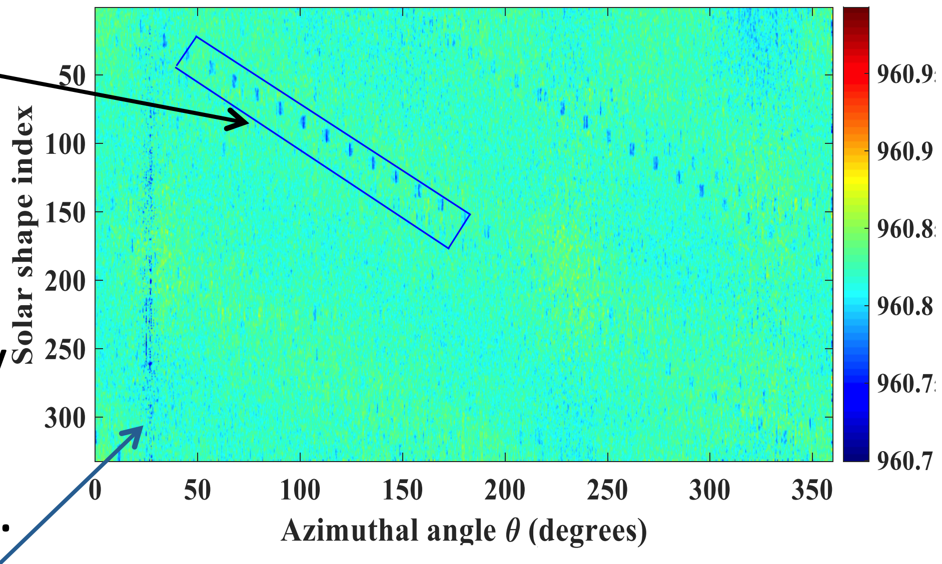


$R(\theta)$ is fitted with **low order Legendre polynomials** $P_k(\cos(\theta))$:

$$R(\theta) = R_{mean}\left(1 + \sum_{k=2,4} c_k P_k(\cos(\theta))\right)$$

Illustration of the processing method: the July 22, 2015 roll sequence

(a)

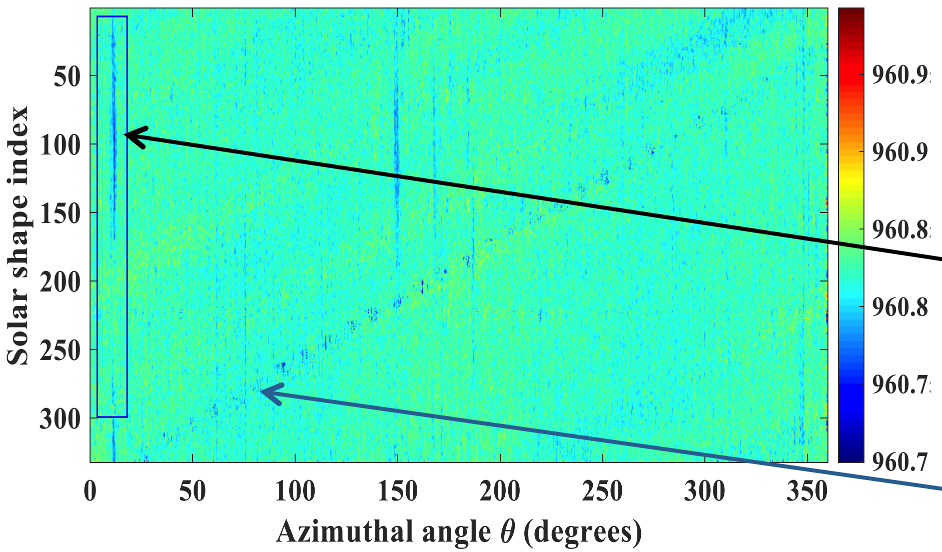


Some **active regions** on the Sun (sunspots, faculae, etc.) existed that day and will **affect the solar shape**.

(**a**) Azimuthal variations of solar radius obtained from the roll images.
Each frame line corresponds to a solar shape calculated from an image.
They are 332 images in this sequence and the number of angular samples is 1800.

CCD defaults

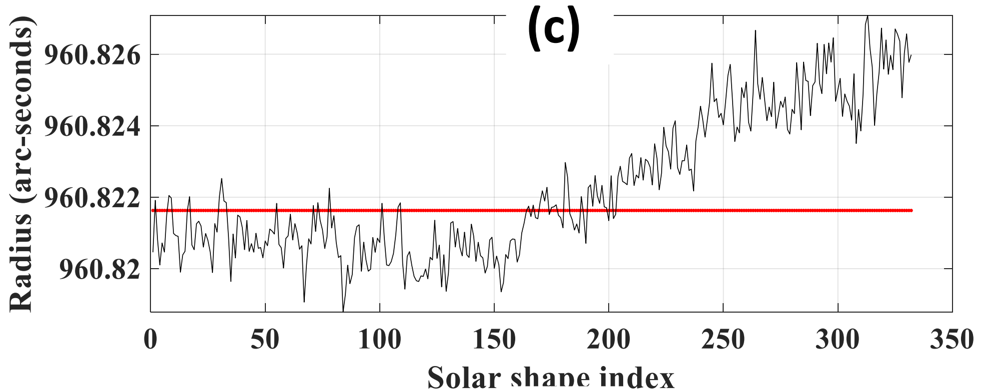
(b)



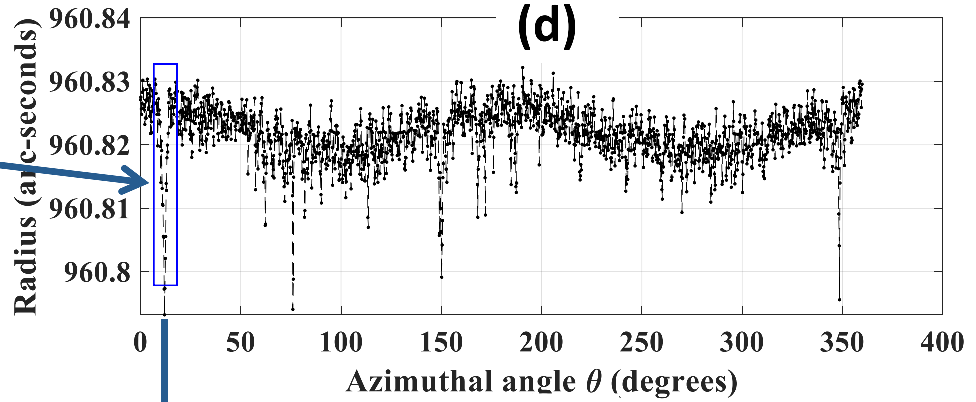
(**b**) Solar shapes are shifted to all have the western equator of the Sun at the zero azimuthal angle.
Signatures of active regions affecting the shape are then spread out along frame columns while **CCD defaults are on oblique directions**.

Illustration of the processing method: the July 22, 2015 roll sequence

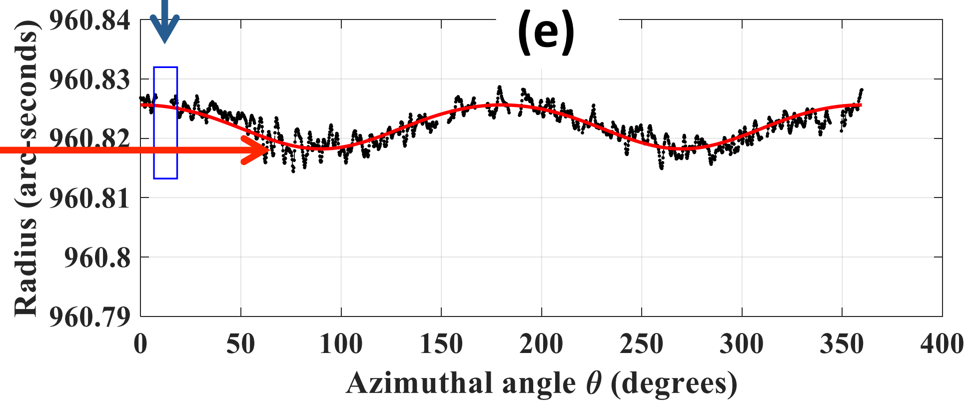
(c) **A slight time drift of solar radius calculated from each shape** (the black line) **is observed during the roll**. It is **corrected** using an iterative process (the red line).



(**d**) All shapes of the roll sequence are averaged to compute the mean, where **active regions effects are clearly seen**.



(e) **Active region effects on the mean solar shape are removed** and then it is filtered to reduce the noise. The **mean solar shape** is fitted with **low order Legendre polynomials** (red curve) to estimate **c_2** and **c_4 distortion coefficients** and then the **oblateness ΔR**:



$$\Delta R = -\frac{3}{2}c_2 - \frac{5}{8}c_4 \quad (mas) \text{ or } \frac{\Delta R}{R_{mean}} = -\frac{3}{2}C_2 - \frac{5}{8}C_4$$ (*in case of dimensionless variables*)

Presentation outline

- Measurements and variations of solar oblateness, a brief history
- Solar oblateness measurements with HMI/SDO
- **Main results**
- Conclusion

Main results

- **16 roll sequences** between **October 2010** and **July 2018**
- **Mean solar oblateness** obtained over **2010–2018** is **8.8 ± 0.8 mas** (**6.4 ± 0.6 km**), **in good agreement with measurements made over the past two decades**.
  They are also **consistent** with **values predicted by helioseismology-based models**
- Variations in time of the solar shape are of particular importance in view of the scientific controversies surrounding historical measurements: **solar oblateness exhibits variations during Cycle 24** in **anti-phase with activity of the Sun** (sunspot number taken as proxy)

Main results -2-

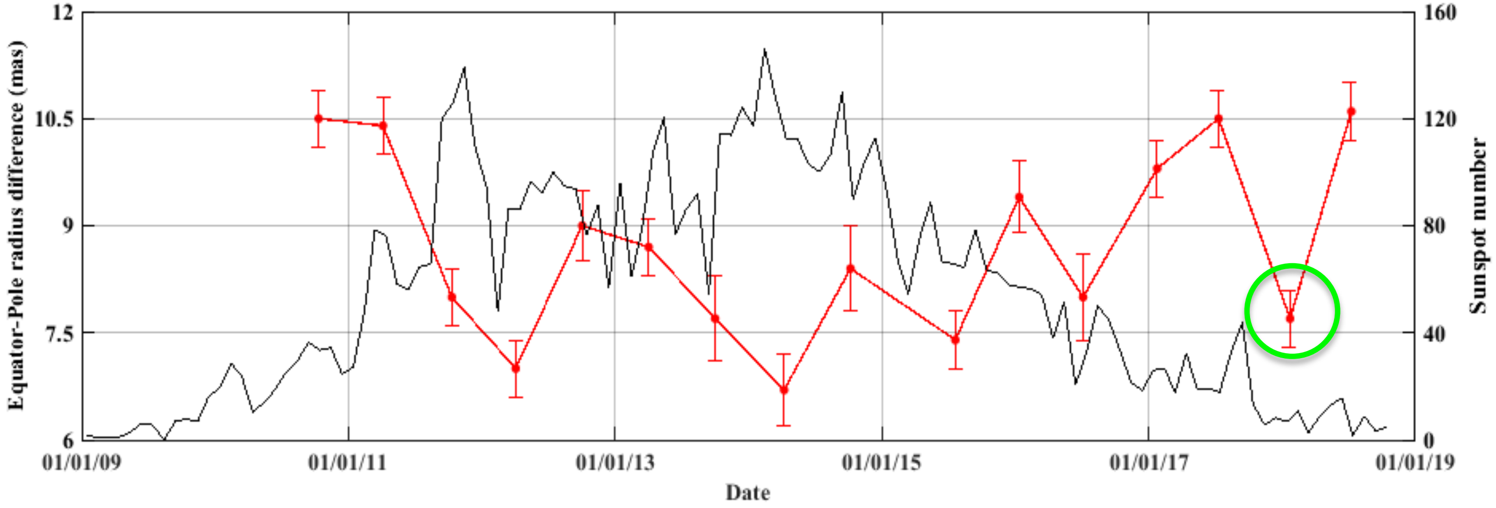
Fit model parameters of Equator-Pole radius difference from HMI roll during Cycle 24.

(a) Time variations of **solar oblateness** (red curve) are **clearly in anti-phase** with the **sunspot number** (black line). The **value surrounded in green** is thought to be **underestimated** due to **poor determination and/or sudden solar events**.

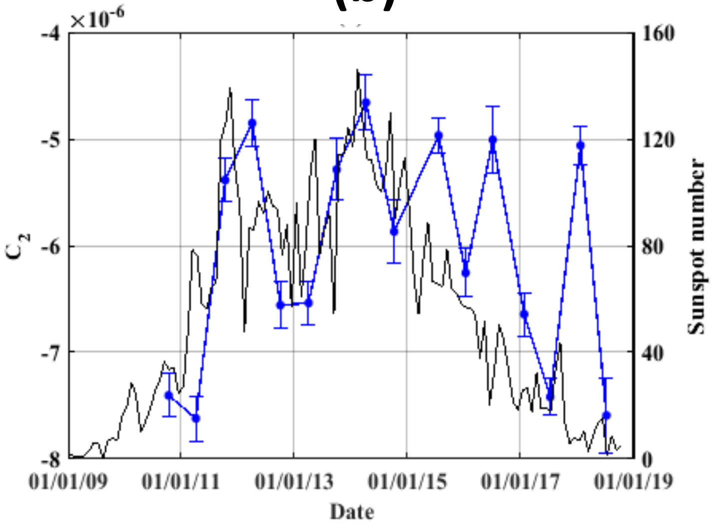
(b) The **quadrupole variations C_2** (blue curve) appear **in phase with solar activity**, whereas

(c) The **hexadecapole C_4** (black dots) has **anti-symmetric variations** relative to **the time of solar activity maximum**, where they are very small.

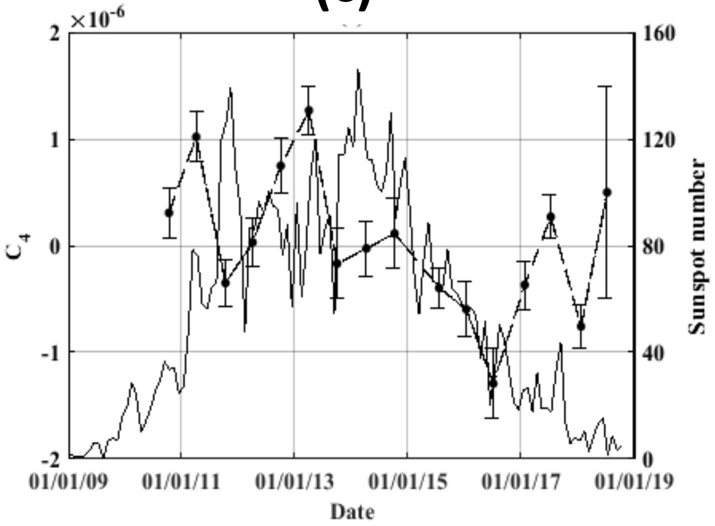
(a)



(b)

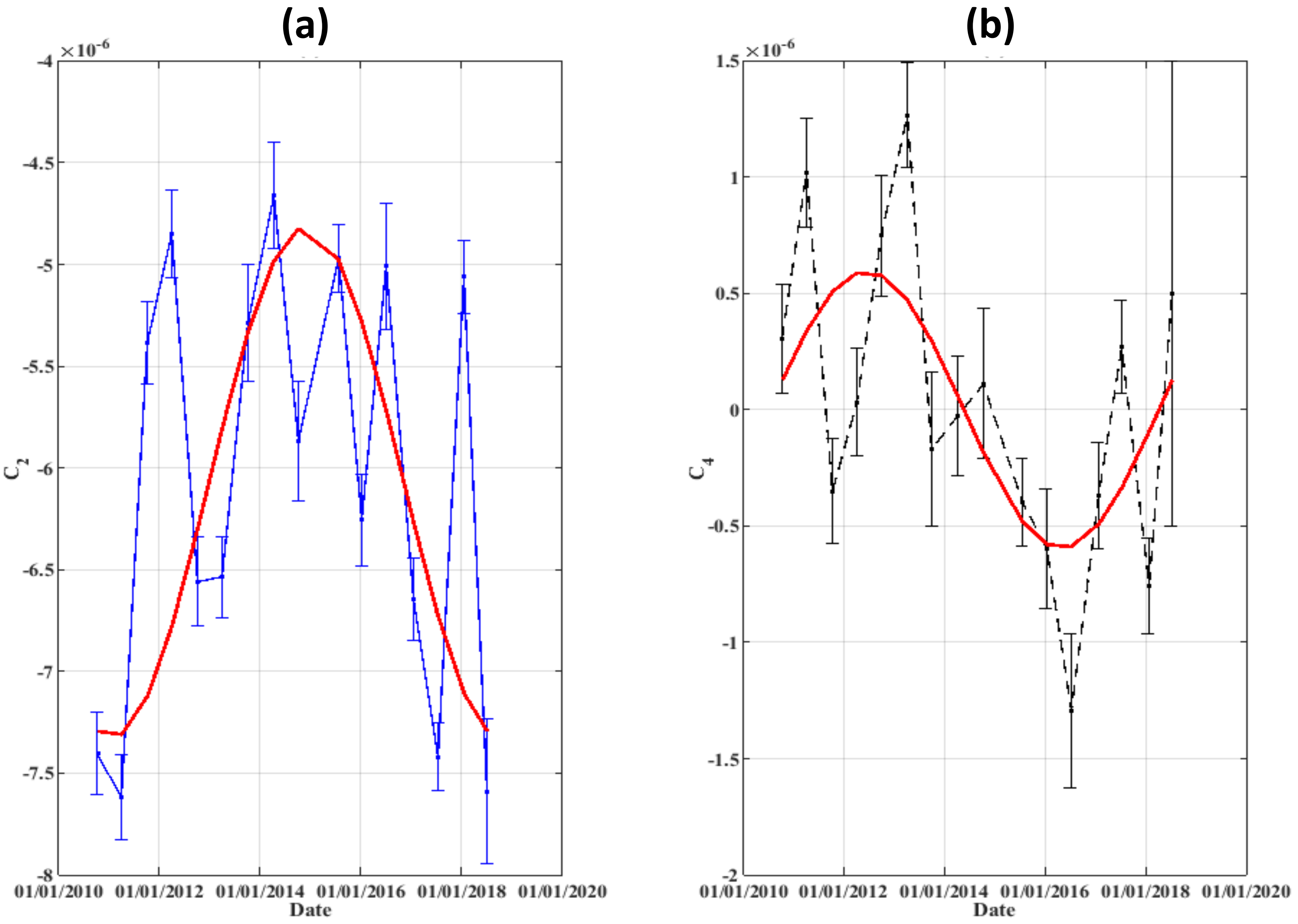


(c)



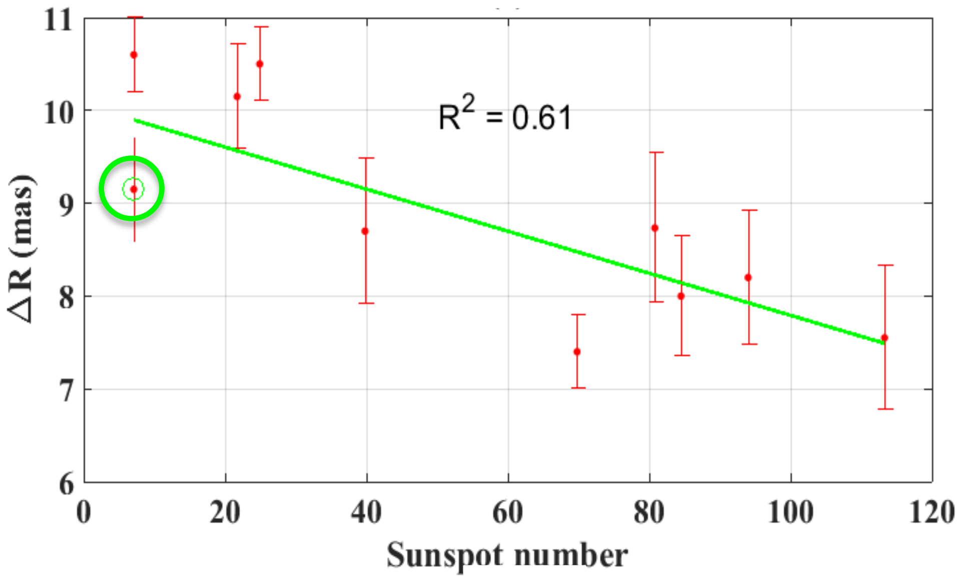
Main results -3-

(a) C_2 and (b) C_4 **temporal trends** fitted with sine functions (solid red lines) showing how they evolve **during solar activity**.

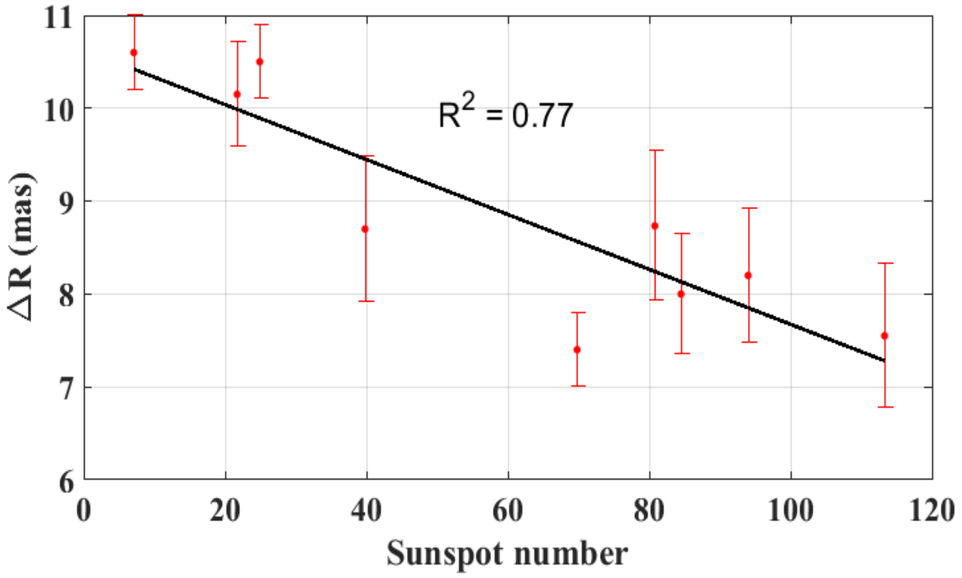


Main results -4-

(a)



(b)



(a) All measurements of Equator-Pole radius difference made **during Cycle 24** with different space mission are plotted vs. sunspot number. The **linear regression** performed on these two solar parameters is **good** giving **R^2 = 61%** (green line).
The **negative slope** shows that **oblateness variations is in anti-phase with activity**.

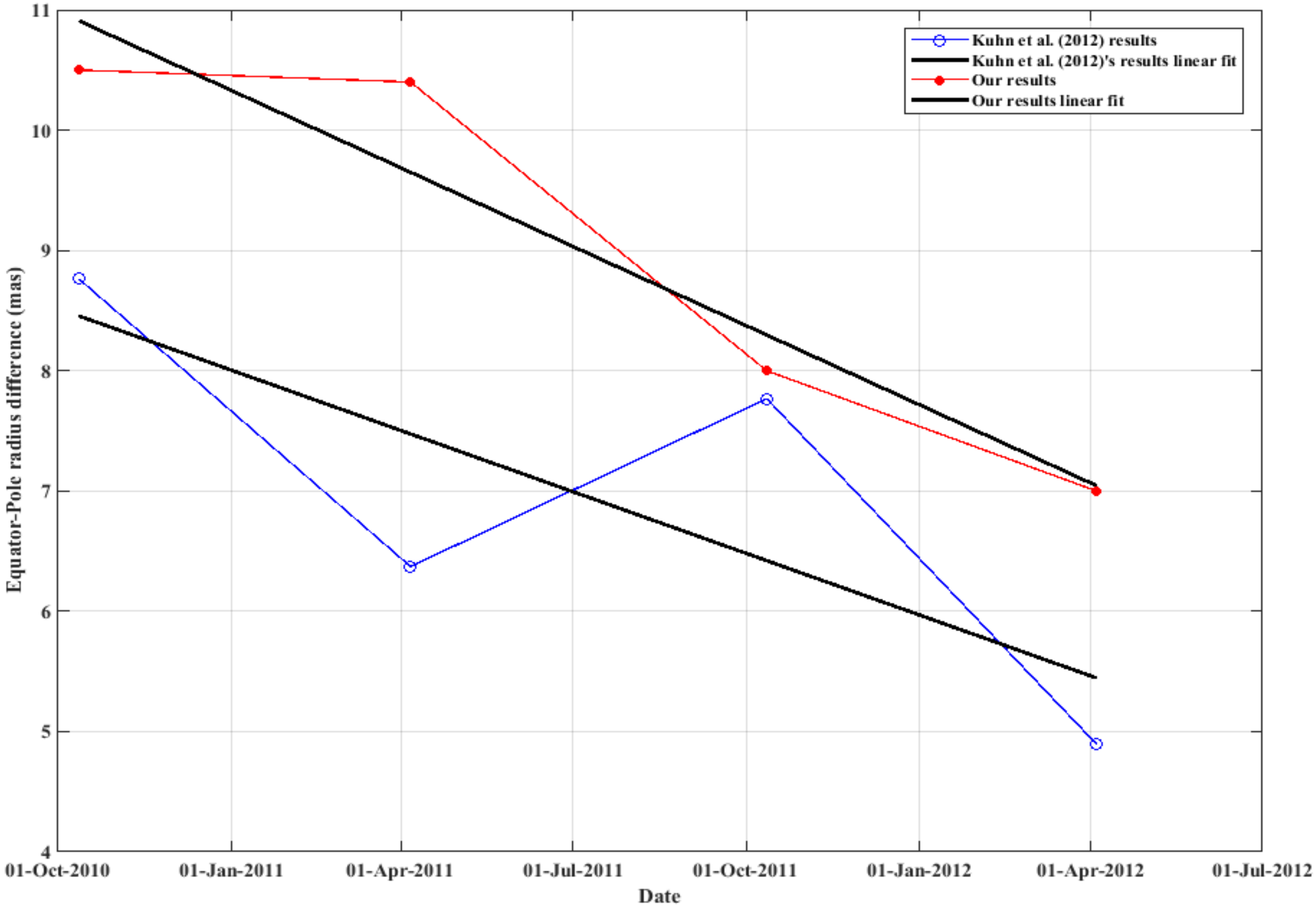
(b) The linear regression is better with **R^2 = 77%** (black line) when the perturbed HMI measurement **surrounded in green** is not taken into account.

Main results -5-

Kuhn et al. (Science, 2012) reported no variations of solar oblateness over the period 2010-2012

A **similar temporal trend** of solar oblateness is **found** in **Kuhn *et al*. (2012)'s results** when using $\mathbf{c_2}$ **and** $\mathbf{c_4}$ **parameters** extracted **from their paper**.

They analyzed a **period** corresponding to the **beginning of activity of Cycle 24**.

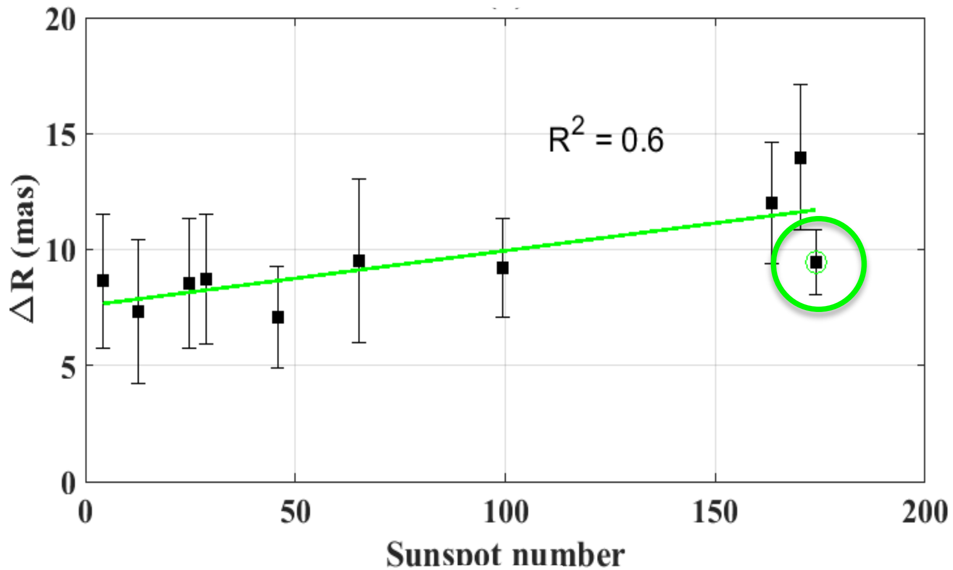


Main results -6-

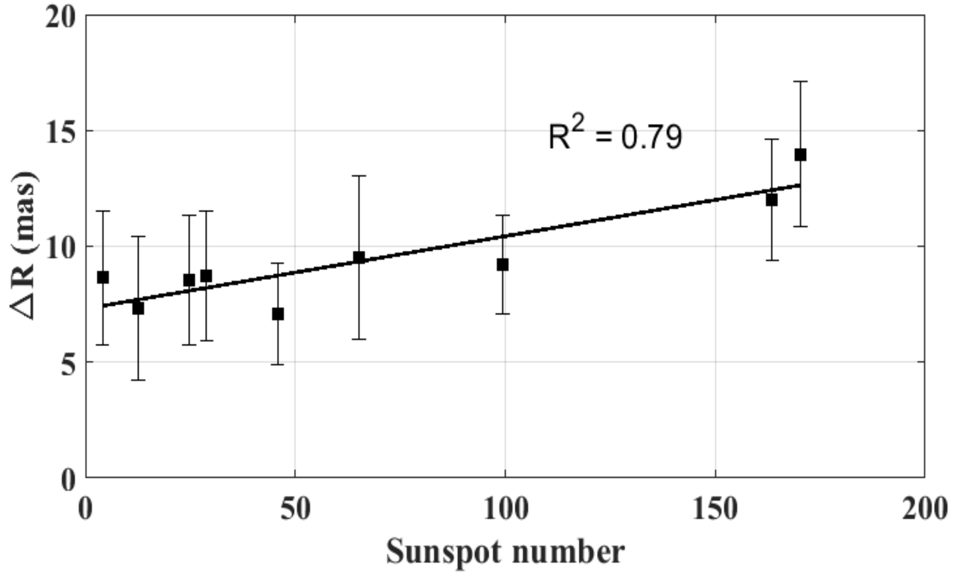
(a) All measurements of Equator-Pole radius difference made **during** **Cycle 23** with **the Heliometer** instrument (ground-based experiment at *pic-du-midi*, France) and **RHESSI** and **MDI** on board spacecrafts are plotted vs. sunspot number.
The **linear regression** shows a positive slope with **R^2 = 60%** expressing that **oblateness variations are in phase with solar activity during Cycle 23**.

(b) A better linear regression is obtained with **R^2 = 79%** (black line) when **the value recorded in 2000** with the Heliometer is **not taken into account** (**resumption of measurements after a 2 yr interruption**).

(a)



(b)



Main results - Conclusion

- **Few measurements** exist during Cycle 22: **oblateness measurements** performed on balloons with the Solar Disk Sextant (SDS) **in the descent of Cycle 22** show **anti-phase variations with the activity** (**like during Cycle 24**).

- The **conclusion** is that the **Sun initiates a physical process** that results in a **pulsation with a period of twice the 11 yr solar cycle**.

- The **Sun** has **maximum swelling during odd cycles** and **vice versa for even ones** i.e. the **solar shape oscillates like the magnetic field having extreme values during its polarity inversion**.

Conclusions

- This **conclusion** is **supported** by **Poor's analysis** (1905) of **earlier oblateness measurements made during Cycles 11 and 13**, as well as that of **Ambronn and Schur (1905)** made during **Cycles 11 and 12. Despite the limited precision** of these historical measurements:
  - **variations**, although very large, **are clearly in phase** with **solar activity** of **Cycles 11 and 13**.
  - During **Cycle 12**, they are very **similar to HMI variations** observed around the maximum of solar activity; that is to say, **in anti-phase**.

- It is the **time of the measurements**, **with respect to the temporal oscillation of solar oblateness**, that largely **explains** the **controversy surrounding past measurements reported in the literature**.

See for more details

THE ASTROPHYSICAL JOURNAL LETTERS

Variations of Solar Oblateness with the 22 yr Magnetic Cycle Explain Apparently Inconsistent Measurements

Abdanour Irbah *et al.* 2019 *ApJL* **875** L26

THANK YOU !!!