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Solar disk radius measured by Solar occultation by the Moon using bolometric and photometric instruments on board the PICARD satellite

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1. Scientific rational

The solar disk radius is a basic metrological quantity as the planet's radius of the solar system. Despite the importance of having an accurate value of the solar disk radius, the existing measurements show differences likely due to large uncertainties due to the use of different measurement techniques, instrument calibration (if any), wavelength domain of measurements, and atmospheric effects for instruments running from the ground. Furthermore, is the solar radius constant or changing with time in particular with solar activity? The solar radius value depends on the solar atmosphere opacity, which allows solar model validation by comparing model predictions with the observations.

2. PICARD solar radius measurements and results

PICARD is a spacecraft developed by the Centre National d'Etudes Spatiales (CNES). It was launched on 15 June 2010. PICARD mission is described by Thuillier *et al.* (2006). Several instruments are carried, among them, the Bolometric Oscillations Sensor (BOS, B), the PREcision MOnitoring Sensor (PREMOS, CH), and a solar sensor (SES, F). They are used to derive the solar disk radius using the light curves produced when the Sun is occulted by the Moon. 17 occultations occurred from 2010 to 2013. One of them was not usable due to lack of spacecraft stability. Our approach is the use of the lunar radius as the reference. The solar disk radius for each occultation was simultaneously obtained for five spectral domains in the visible and IR solar continuum (535, 607, 750, 782, 784 nm) and two in UV (210, 263 nm). The calculation of the solar disk radius uses a simulation of the light curve taking into account the center to limb variation provided by the Non-local thermodynamic Equilibrium Spectral SYnthesis (NESSY, Tagirov *et al.* 2017). The positions of the Sun and Moon are provided by IMCCE (Institut de mécanique céleste et de calcul des éphémérides), and the spacecraft position by CNES. For a set of solar to Moon ratios, the quadratic difference between the measured and simulated light curve is calculated for each ratio. Among these differences, a minimum is found from which the solar radius is derived from knowing the lunar radius. The solar radius determined as explained above is referred to the lunar radius given by the Kaguya mission (Kato *et al.* 2010). At one astronomical unit, the solar radius is 959.78 arcseconds at 782 nm; 959.79 arcseconds at 750 nm; 959.76 arcseconds at 535 nm. We found 960.07 arcseconds at 210nm, which is a larger value than the others given the photons at this wavelength originate from the upper photosphere and lower chromosphere. The minimum solar disk radius is found around 600 nm. This is shown in Figure 1. The decrease from UV to visible wavelengths and increase in the near IR was expected by the solar models (Thuillier *et al.* 2011). Figure 1 also displays results from different techniques from the ground, planetary transits, imaging telescopes, and the Solar Disk Sextant (#3) on board a stratospheric balloon, which is in close agreement with our results. For the period of observations within solar cycle 24, no relation with the solar activity was found. However, this cycle was weak and the F10.7 only varies from 90 to 130 units during the period of observations. The center to limb variation is manifested at the beginning and end of the occultation and at maximum occultation. It varies with wavelength from 35 milliarcseconds (mas) in the UV to 2 mas at 784 nm. Furthermore, Figure 1 shows the recent solar radius obtained by other techniques obtained at different wavelengths. No consistent organization is revealed by these measurements as a function of wavelength as models suggest. Likely, each technique has its own scale and no direct relationship between these scales exists up to now. We note that the solar radius measured by the Venus and Mercury transits are systematically greater by 100 to 300 mas than our results calibrated on the Moon radius as well as the measurements using the total solar eclipses and Sun transits from the ground. The best agreement between our results is found with the Solar Disk Sextant (Sofia *et al.* 2013), which operates on board a stratospheric balloon, and uses an angular reference incorporated in the instrument. The details of this work are given in Thuillier *et al.* (2017).

Haberreiter *et al.* (2008) uses the seismic radius obtained by helioseismology from Schou *et al.* (1997), who provided a solar radius equal to 959.2 arcseconds. Calculating the angular distance between the region where waves are reflected and the inflection point of the limb at 500 nm is estimated by the COSI model (Shapiro *et al.* 2010) to be 0.46 arcsecond. By adding this value to the seismic radius, the optical solar radius is obtained to be 959.66 arcseconds at 500 nm. The B3 IAU solar radius reference (Prša *et al.* 2016) recommends the solar radius provided by Haberreiter *et al.* (2008).

3. Uncertainties

The uncertainty affecting the measured solar radius is calculated by taking into account several sources:

— the noise of the measurement,

— the uncertainty of the Moon radius,

— the uncertainty of the three bodies' positions (Earth, Moon, spacecraft) with respect to the Sun,

— the uncertainty on the pre and post solar irradiance to determine the light curve.

These uncertainties have been quadratically combined, and their mean for the seven wavelengths is 26 mas.

4. Conclusions

Sixteen solar occultations by the Moon observed from orbit by the PICARD spacecraft from June 2011 to April 2014 have allowed us to simultaneously measure the solar radius in seven spectral domains from the UV to the near IR calibrated on the lunar radius. For each occultation, the light curve is modeled taking into account the position of the

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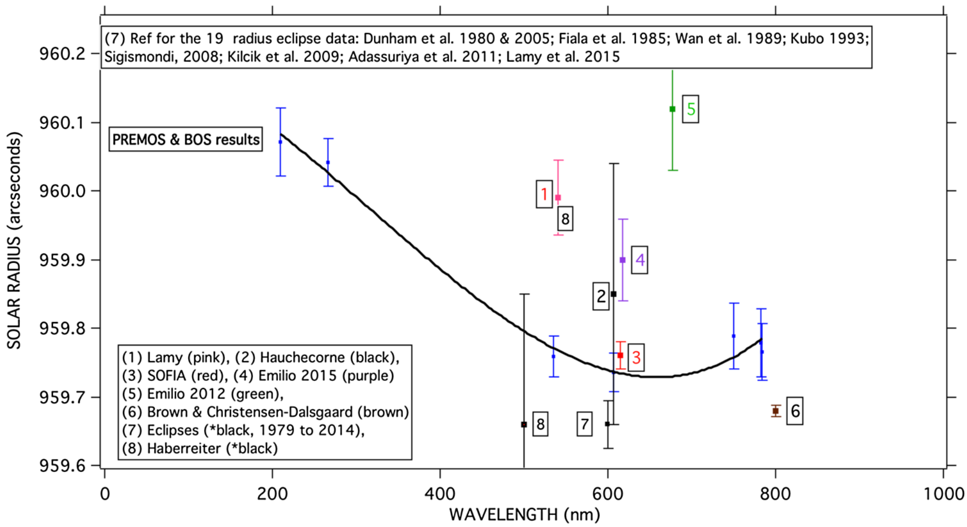

Figure 1. Display of all available solar disk values. 1 to 8 references are given in Thuillier *et al.* (2017).

Sun, Moon, and spacecraft, the center to limb darkening provided by the wavelength-dependent NESSY model, and a given set of solar radius to Moon ratios. For these ratios, the quadratic differences between the measured light curve and the modeled light curve are calculated. The minimum is found, the corresponding Sun to Moon ratio is determined from which the solar radius is extracted using the lunar radius measured by the Kaguya mission. Normalization to one AU is made afterward. The results are:

— the center to limb variation decreases with wavelength from the UV (35 mas at 210 nm) to the near IR (2 mas at 784 nm)

— With the 16 occultations, no significant radius variation related to solar activity was detected meaning that, if extant, it would be smaller than 26 mas. However, during that period, the F10.7 solar index varied only from 90 to 130 units.

— Based on the absence of variation with solar activity, the results were averaged for each spectral domain. The results show a variation with wavelength consisting of a decrease of 130 mas from 210 nm to 600 nm and followed by an increase of 50 mas at 784 nm. Such a variation was expected by the solar models. At one AU and 535 nm, the solar radius is 969.759 arcseconds.

— Solar models have, in general, the capability of producing the radius variation with wavelength using the inflection point position (IPP). In order to avoid a possible scale bias between two different techniques (IPP and lunar radius), the radii were referred to the radius at 535 nm. Comparing our results with NESSY calculations, it appears that NESSY has provided consistent results in the visible and near IR. In the UV, the agreement is at the three σ limit, which is interpreted as due to the present knowledge of the Fraunhofer lines structure.

— We point out that the Moon provides a stable reference for instruments in space, allowing long-term studies by using simple photometers and bolometers, which are robust instruments able to survive without significant aging in the harsh orbital environment.

— Our results referred to the Moon radius show the dependence of the solar radius with wavelength. This is why it is suggested that future solar radius measurements should be made in several wavelength domains in the solar continuum if possible, to ease the comparison between different data sets.

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