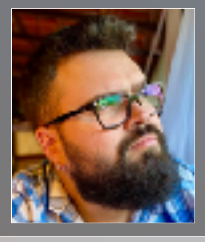

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THE SUBTERAHERTZ SOLAR CYCLE

POLAR AND EQUATORIAL RADII DERIVED FROM SST AND ALMA

COOL STARS 20.5

... virtually cool

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INTRODUCTION

- Measurements show the altitude where the emission at determined observation frequency is generated, and as the observation frequency changes the altitude changes as well.
- Gap of subterahertz frequencies in the measurements of the solar radius and other parameters of the atmosphere.
- Important parameter to improve solar atmosphere models.
- Correlated to solar activity and its variations over time indicate changes in the solar atmosphere

GOALS

- Average **equatorial** and **polar** radius at 100, 212, 230 and 405 GHz.
- Correlation of the solar equatorial and polar radii in relation to the solar activity cycle.

INSTRUMENTS

- **Submillimeter Solar Telescope (SST)**, CASLEO, Argentina (2550 m)
  - Data from 2007 to 2019
  - **212 GHz** (25.880 maps), **405 GHz** (9.580 maps)
- **Atacama Large mm/submm Array (ALMA)**, Atacama, Chile (5059 m)
  - 4 campaigns from 2015 to 2018
  - **100 GHz** (125 maps), **230 GHz** (71 maps)

SST

ALMA

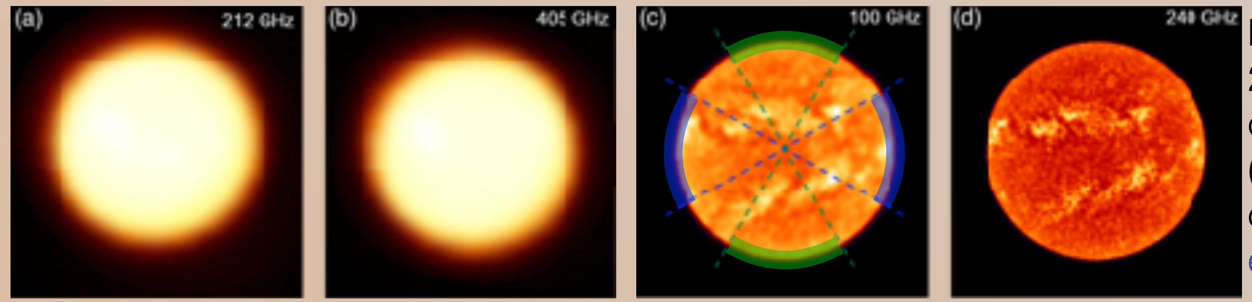

Fig.: SST maps (upper panels) obtained on 2008-02-09 and ALMA maps (lower panels) obtained on 2015-12-17. (a) **212 GHz**; (b) **405 GHz**; (c) **100 GHz** (green lines and crosses are the constraints of the polar region and in blue, the equatorial ones); (d) **230 GHz**.

RADIUS DETERMINATION

- Solar **limb points** coordinates
  - From each scan over the solar disk maximum and minimum points of the numerical differentiation (**red** curve)
- **Average radius** of each map
  - Limb coordinates are fit by a circle; the radius is calculated as the average of the center-to-limb distances.
- **Equatorial** radius: points between 30ºN and 30ºS; **Polar** radius: points above 60ºN and below 60ºS.

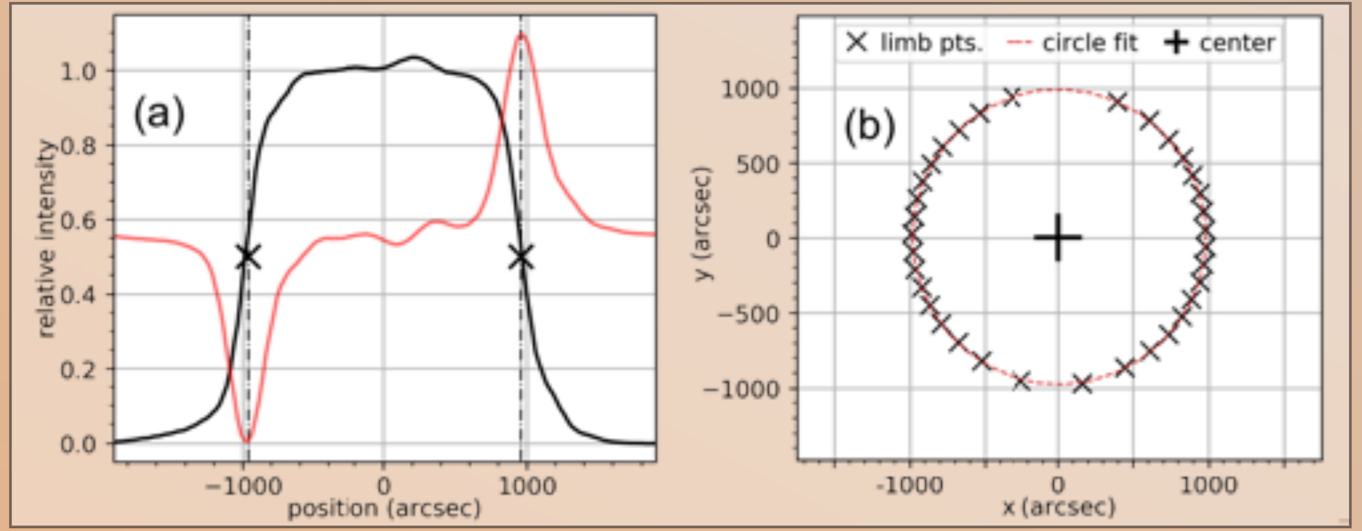

Fig.: Solar radius determination.
(a): Indication of the points corresponding to the solar limb of one scan.
(b): Limb coordinates with circle fit.

SSC MODEL

- 2-D solar atmospheric model developed by Selhorst et al. (2005) to generate T_B profiles of at 100, 212, 230, and 405 GHz.
- Radii derived from this model are compared with our results

RESULTS

Average Radii

Freq. (GHz)	Latitude	Radius (arcsec)	Altitude (10^3 km)	SSC R_θ (arcsec)
100 (ALMA)	Equatorial	968±3	6.1±2.2	964.2
	Polar	968.4±2.3	6.4±1.7	
212 (SST)	Equatorial	963±4	3±3	963.8
	Polar	963±4	2±3	
230 (ALMA)	Equatorial	963.7±1.8	3.0±1.3	963.2
	Polar	963.7±1.6	3.0±1.2	
405 (SST)	Equatorial	963±5	3±4	962.8
	Polar	963±6	2±4	

Correlation Coefficients

Freq.	Latitude	$\rho_{F10.7}$	$\rho_{\|B\|}$
212 GHz	Equatorial	0.05	0.16
	Polar	-0.36	-0.23
405 GHz	Equatorial	0.64	0.50
	Polar	-0.39	-0.23

Fig.: Time series for equatorial R_θ at 100 (green), 212 (dark blue) and 230 GHz (orange), and for polar R_θ at 100 (light green), 212 (light blue) and 230 GHz (yellow), from Jan/2014 to Dec/2019. Every box represents data for a 6-month period. The red line represents $F_{10.7}$ and the gray line represents $|B|$.

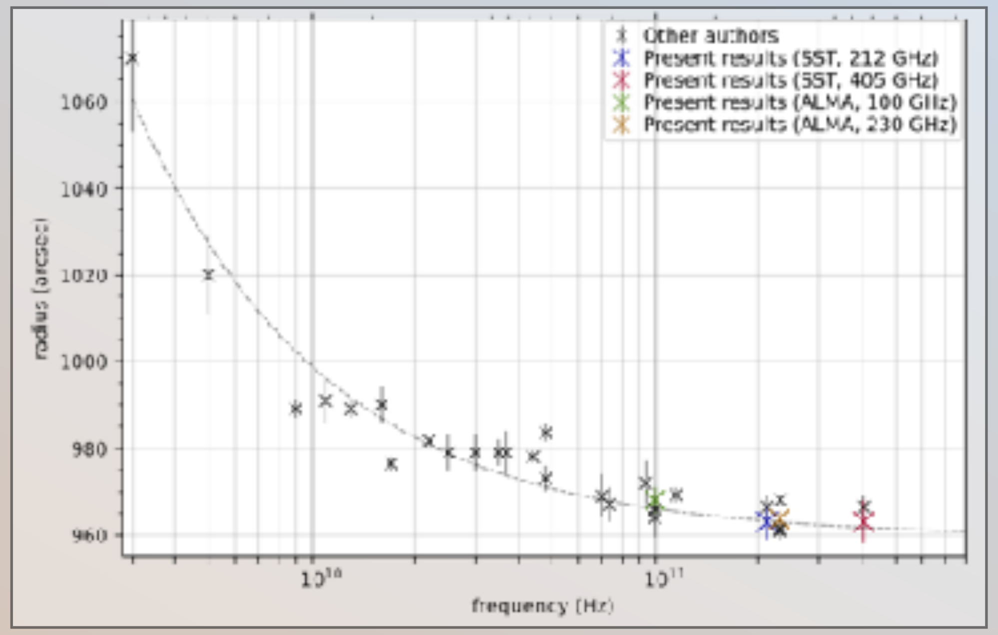

Fig.: Solar radius as a function of frequency. The dashed line represents the exponential trend of the radius. The black crosses are measurements from other authors, the blue (212 GHz), red (405 GHz), green (100 GHz) and yellow (230 GHz) crosses are the present radii results

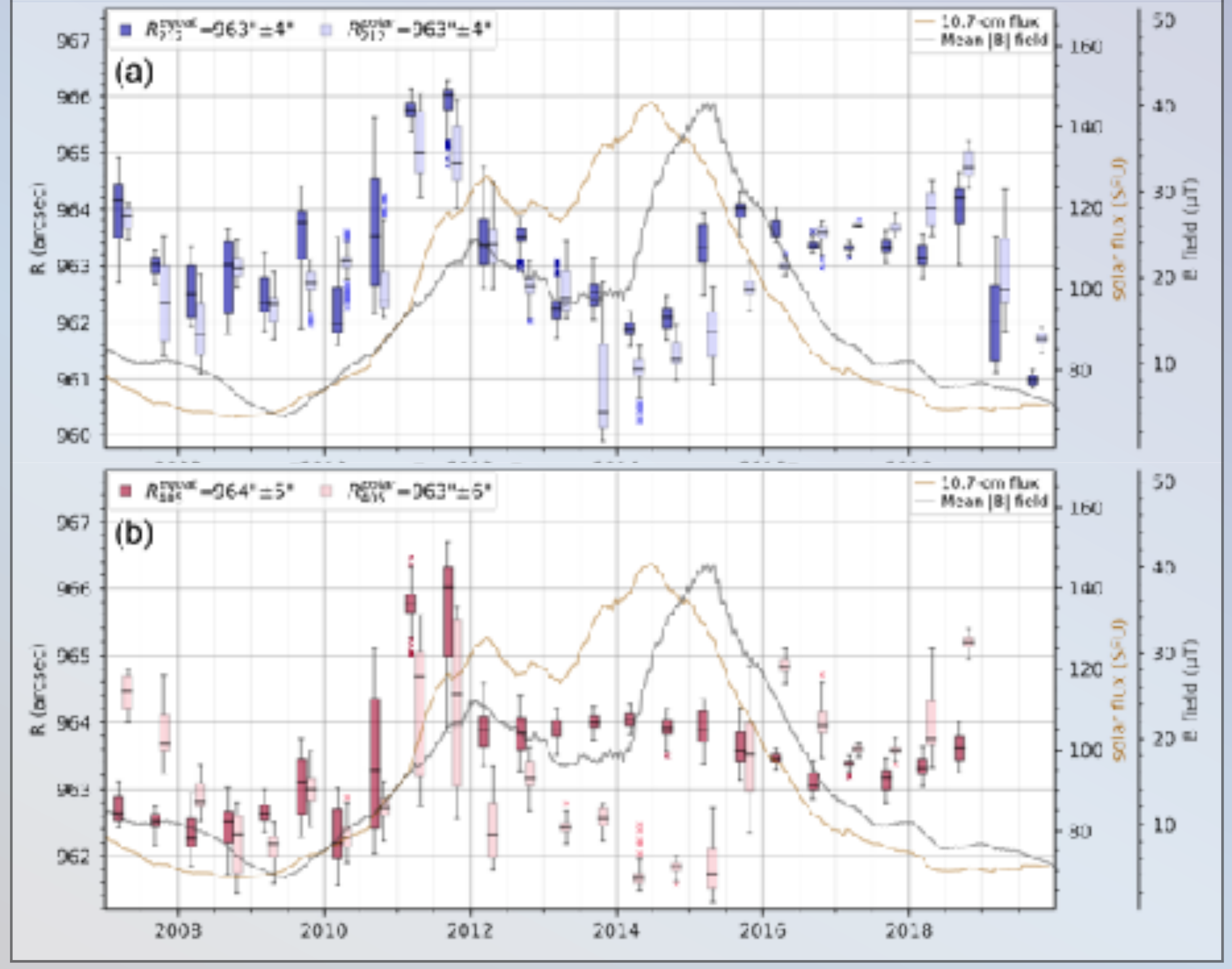

Fig.: Solar radius time series from Jan/2007 to Dec/2019. **(a)**: Equatorial (dark blue) and polar (light blue) radii at 212 GHz. **(b)**: Equatorial (red) and polar (pink) radii at 405 GHz. The orange and gray lines represent $F_{10.7}$ and $|B|$, respectively. Every box represents data for a 6-month period.

FINAL REMARKS

- Average subterahertz radii
  - The average polar and equatorial subterahertz radii of the Sun at 100, 212, 230, and 405 GHz are in agreement with the radius-vs-frequency trend
  - The average subterahertz radii agrees with SSC radii (except at 100 GHz).
- Correlation to solar activity proxies (the radio 10.7-cm solar flux, $F_{10.7}$, and the mean photospheric magnetic field intensity, $|B|$).
  - R_{212}^{Equat} is very weakly correlated.
  - R_{405}^{Equat} is moderately correlated.
  - R_{212}^{Polar} and R_{405}^{Polar} are weakly anticorrelated.
  - Radii at 100 and 230 GHz have analogous behavior from this of SST's time series:
    - Equatorial radii decrease from 2015 to 2017 and increase from 2017 to 2018.
    - The polar radii time series increases from 2015 to 2018.
  - The subterahertz emission altitudes are much closer to the photosphere, which probably reflects the behavior from both the photosphere and the lower chromosphere.
  - Equatorial radii time series are expected to be positively correlated to the solar cycle, since the equatorial regions are more affected by the increase of active regions during solar maxima, making the solar atmosphere warmer in these regions.
  - The anticorrelation between polar radius time series and the solar activity proxies could be explained by a possible increase of polar limb brightening during solar minima (Selhorst et al. 2003).

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