The Subterahertz Solar Cycle: Polar and Equatorial Radii Derived from SST and ALMA

Fabian Menezes1,2, Caius L. Selhorst2, Carlos Guillermo Giménez de Castro1,3, and Adriana Valio1

1 Centro de Rádio Astronomia e Astrofísica Mackenzie (CRAAM), Universidade Presbiteriana Mackenzie, São Paulo, Brazil; menezes.astroph@gmail.com
2 Núcleo de Astrofísica, Universidade Cruzeiro do Sul/Universidade Cidade de São Paulo, São Paulo, SP, Brazil
3 Instituto de Astronomia y Física del Espacio, UBA/CONICET, Buenos Aires, Argentina

Received 2020 October 26; revised 2021 January 19; accepted 2021 February 2; published 2021 March 29

Abstract

At subterahertz frequencies—i.e., millimeter and submillimeter wavelengths—there is a gap in measurements of the solar radius, as well as other parameters of the solar atmosphere. As the observational wavelength changes, the radius varies because the altitude of the dominant electromagnetic radiation is produced at different heights in the solar atmosphere. Moreover, radius variations throughout long time series are indicative of changes in the solar atmosphere that may be related to the solar cycle. Therefore, the solar radius is an important parameter for the calibration of solar atmospheric models enabling a better understanding of the atmospheric structure. In this work, we use data from the Solar Submillimeter-wave Telescope (SST) and the Atacama Large Millimeter/submillimeter Array (ALMA) at frequencies of 100, 212, 230, and 405 GHz to measure the equatorial and polar radii of the Sun. The radii measured with extensive data from the SST agree with the radius-versus-frequency trend present in the literature. The radii derived from ALMA maps at 230 GHz also agree with the radius-versus-frequency trend, whereas the 100 GHz radii are slightly above the values reported by other authors. In addition, we analyze the equatorial and polar radius behavior over the years by determining the correlation coefficient between solar activity and subterahertz radius time series at 212 and 405 GHz (SST). The variations of the SST-derived radii over 13 yr are correlated to the solar activity when considering equatorial regions of the solar atmosphere and anticorrelated when considering polar regions. The ALMA-derived radius time series for 100 and 230 GHz show very similar behaviors with those of SST.

Unified Astronomy Thesaurus concepts: Solar atmosphere (1477); Solar radio emission (1522); Center to limb observations (1972); Time series analysis (1916)

1. Introduction

Due to technological limitations, until some decades ago, only optical observations of the Sun were available. Observations at radio wavelengths began to take place after 1950 (Coates 1958), and many authors had been using measurements of the solar disk size—i.e., the center-to-limb distance—as ways to determine the solar disk radius (hereafter solar radius) at different radio wavelengths (Coates 1958; Wrixon 1970; Swanson 1973; Kislyakov et al. 1975; Labrum et al. 1978; Furst et al. 1979; Horne et al. 1981; Bachurin 1983; Pelyushenko & Chernyshev 1983; Wannier et al. 1983; Costa et al. 1986, 1999; Selhorst et al. 2004; Alissandrakis et al. 2017; Menezes & Valio 2017; Selhorst et al. 2019a, 2019b). There are different techniques to measure the solar radius at radio frequencies, such as the determination from total solar eclipse observations (Kubo 1993; Kilicik et al. 2009) and from direct observations using the inflection point method (Alissandrakis et al. 2017) and half-power method (Costa et al. 1999; Selhorst et al. 2011; Menezes & Valio 2017).

The study of the radio solar radius provides important information about the solar atmosphere and activity cycle (Swanson 1973; Costa et al. 1999; Menezes & Valio 2017; Selhorst et al. 2019b). Using radio measurements of the solar radius derived from eclipse and direct observations, one can probe the solar atmosphere, since these measurements show the height above the photosphere at which most of the emission at a determined observation frequency is generated (Swanson 1973; Menezes & Valio 2017; Selhorst et al. 2019b). However, as the observation frequency changes, the height changes as well (Selhorst et al. 2004, 2019b; Menezes & Valio 2017). To determine the height above the photosphere of the radio emission, we consider the optical solar radius. At optical wavelengths, the canonical value of the mean apparent solar radius is \( R_o = 959.6 \text{ km} \), corresponding to \( R_o = 6.9599 \times 10^8 \text{ m} \). This value has been widely used in the literature; hence, we adopt it as the reference value. In this work, we focus on the solar disk radius at subterahertz radio frequencies, i.e., millimeter and submillimeter wavelengths.

Therefore, with observations at several frequencies, different layers of the solar atmosphere can be observed and studied. Furthermore, these parameters can be used to improve and calibrate solar atmosphere models as an input parameter and boundary condition. In other words, the solar radius at radio frequencies reflects the changes in the local distribution of temperature and density of the solar atmosphere. In Table 1 and Figure 3, we compile the data of the solar radius at several radio frequencies from different authors. We note, however, that the different works use different definitions and methods for determining the solar radius.

Another aspect to be considered is that the Sun’s radius measured at the same radio frequency over time shows slight variations. Temporal series of observations obtained over many years show that the radius can be modulated with the 11 yr activity cycle (mid-term variations), as well as longer periods (long-term variations), as suggested by Rozelot et al. (2018) and references therein. Costa et al. (1999) measured the radii from solar maps at 48 GHz taken with a 13.7 m dish at the Pierre Kaufmann Radio Observatory (formerly the Itapetinga Radio Observatory) and reported an average radius of 983.6 ± 1.9. In a period of 3 yr (from 1990 to 1993),
temporal variations were observed following the linear relation

\[ R_{18\text{GHz}} = [1.029 - 0.0015(\text{year} - 1990)] R_{\odot}. \]  

(1)

which yields a total decrease of 8° if extrapolated for a period of 5.5 yr (half a cycle). Considering this short period, the data suggest that the radius decreases in phase with the monthly mean sunspot number and the soft X-ray flux from the Geostationary Operational Environmental Satellite. At 37 GHz using data from Metsähovi Radio Observatory from 1989 to 2015, Selhorst et al. (2019a) measured a radius of 979° ± 5° and obtained a positive correlation coefficient of 0.44 between the monthly averages of the solar radius and the solar flux at 10.7 cm. In Selhorst et al. (2004), the average solar radius from the Nobeyama Radioheliograph daily solar maps at 17 GHz is found to be 976°6 ± 1°5. Over 11 yr (one solar cycle), from 1992 to 2003, the variation in the solar radius is correlated with the sunspot cycle with a coefficient \( \rho = 0.88 \). However, the polar radius—measurements above 60° N and below 60° S of the solar disk—is anticorrelated with the sunspot cycle. The anticorrelation between polar radius and sunspot number yields a coefficient \( \rho = -0.64 \).

At subterahertz frequencies, there is a gap of measurements of the radius and other parameters of the solar atmosphere (Table 1 and Figure 3). In this work, we determine the mean equatorial and polar radii of the Sun at 100, 212, 230, and 405 GHz using single-dish observations from the Solar Submillimeter-wave Telescope (SST) and the Atacama Large Millimeter/submillimeter Array (ALMA).

Moreover, we present an investigation about the relation between subterahertz radius time series and solar activity cycle proxies—solar flux at 10.7 cm, \( F_{10.7} \), and mean magnetic field, \( B \), of the Sun. We analyze the equatorial and polar radius behavior over time, with qualitative analysis for 100 and 230 GHz (ALMA) from 2015 to 2018. Also, we determine the correlation coefficient between the solar activity proxies and equatorial and polar radius time series at 212 and 405 GHz (SST) from 2007 to 2019. The methodology used for this is an improved version of the methodology presented in Menezes & Valio (2017) with a new approach and different analysis. In this work, we focused on the behavior of the polar and equatorial solar radii over time.

### 2. Observations and Data

The data used for the determination of the solar radii were provided by daily solar observations of the SST (Kaufmann et al. 2008) at 212 and 405 GHz and ALMA (Wootten & Thompson 2009) at 100 and 230 GHz. The SST radio telescope was conceived to continuously monitor the submillimeter spectrum of the solar emission in quiescent and explosive conditions. In operation since 1999, the instrument is located at CASLEO observatory (lat.: 31°47'54.7'' S; lon.: 69°17'44.4'' W) at 2552 m elevation in the Argentine Andes. From its six receivers, we used data from one radiometer at 405 GHz and three at 212 GHz that have nominal half-power beamwidths (HPBW) of 2' and 4', respectively (Kaufmann et al. 2008).

The SST radiometers were upgraded in 2006 to improve bandwidth, noise, and performance, and in 2007, the SST reflector was repaired to provide better antenna efficiency, according to Kaufmann et al. (2008). Therefore, we used data from 2007 onward. From 2007 to 2019, there were 3093 days of solar observation, with an average of approximately 17 solar
maps per day considering all receivers, resulting in an extensive data set of 36,034 maps (27,109 at 212 GHz and 8925 at 405 GHz). Most of the maps are obtained from azimuth and elevation scans from a 60° × 60′ area with a 2° separation between scans and tracking speed in the range of 0°1 and 0°2 s⁻¹ (Giménez de Castro et al. 2020). For an integration of 0.04 s, for example, it results in rectangular pixels of 0′4 × 2′, which are then interpolated to obtain a square matrix (600 × 600), as shown in the top panels of Figure 1. ALMA is an international radio interferometer located in the Atacama Desert of northern Chile (lat.: 23°1′44″40 S; lon.: 67°45′18″00 W) at 5000 m elevation. From four solar single-dish observation campaigns between 2015 and 2018, we use 196 fast-scan maps (125 at 100 and 71 at 230 GHz). These maps are derived from full-disk solar observations, which consist of a circular field of view of diameter 2400″ using a “double-circle” scanning pattern (White et al. 2017). The nominal HPBW are 58″ and 25″ at 100 (Band 3) and 230 GHz (Band 6), respectively. Figure 1 (lower panels) shows examples of the ALMA maps obtained at 100 (left panel) and 230 GHz (right panel), where the color represents the brightness temperature.

2.1. Radius Determination

Two widely used methods for measuring the radio solar radius are the inflection point method (Alissandrakis et al. 2017) and the the half-power method (Costa et al. 1999; Selhorst et al. 2011; Menezes & Valio 2017). In F. Menezes et al. (in preparation), both methods are compared, and it is shown how the combination of limb brightening of the solar disk with the radio telescope beamwidth and shape can affect the radius determination depending on the method. F. Menezes et al. (in preparation) showed that the inflection point method is less susceptible to the irregularities of the telescope beams and the variations of the brightness temperature profiles of the Sun (e.g., limb-brightening level and active regions). Thus, the inflection point method brings a low bias to the calculation of the solar radius; therefore, we use this method to determine the solar radius.

The first step is to extract the solar limb coordinates from each map, which are defined as the maximum and minimum points of the numerical differentiation red curve in Figure 2(a) of each scan that the telescope makes on the solar disk. All solar maps are rotated so that the position of solar north points upward, and the coordinates are corrected according to the eccentricity of the Earth’s orbit; the apparent radius of the Sun varies between 975°3 (perihelion) and 943°2 (aphelion) during the year. During the limb point extraction, some criteria are adopted to avoid extracting limb points associated with active regions, instrumental errors, or high atmospheric opacity, which may increase the calculated local radius in that region and hence the average radius. With this radius determination filter, only points with a center-to-limb distance between 815″ (0.85R⊙) and 1100″ (1.15R⊙) are considered.

The second step is to calculate the average radius of each map. The solar limb coordinates are fit by a circle, and the radius is calculated as the average of the center-to-limb distances. Successive circle fits are made until certain conditions are met. For each fit, the points with center-to-limb distance (obtained from the fitting) outside the interval (R − 10″, R + 10″) are discarded, and then a new circle fit is performed with the remaining points. This process is repeated until no other points are discarded. If there are less than 6 points remaining, the entire map is discarded, otherwise, the radius is calculated. If there are fewer points remaining, the entire map is discarded; otherwise, the radius is calculated. If the radius value is between 800″ and 1300″ and the standard deviation is below 20″, then the calculated radius is stored, and the next map is submitted to this process. The same method is applied to both telescopes, so that a comparison between the 212 GHz radius of SST and the 230 GHz radius of ALMA could be made.

As mentioned in Section 1, both the equatorial and polar radii are calculated. First, the radius of each map is determined using only the equatorial latitudes of the solar disk—points between 30° N and 30° S. Then, the polar radius is determined considering only points above 60° N and below 60° S. These latitude boundaries are depicted in Figure 1(c) with dashed blue (equatorial) and green (polar) lines. Finally, the visible solar radius is subtracted from the mean subterahertz radii to determine the altitudes in the atmosphere at which the 100, 212, 230, and 405 GHz emissions are predominantly produced.

Even with the strict criteria adopted in the mean radius determination, there is still a large scattering in the distribution of SST radius values. Thus, we applied a sigma clipping on the distribution, subtracting from the distribution a running mean of 300 points and then discarding values that are outside the ±2.5σ range. From the remaining values, we obtain the average radii.

Giménez de Castro et al. (2020) showed the influence of the SST irregular beams in the study of quiescent solar structures. To assess the quality of the radius determinations, here we carry out a series of simulations convolving 2D antenna beam matrix representations with a solar disk with uniform temperature. The results show that azimuth-elevation maps increase the uncertainty of radius determination in the direction perpendicular to scans. Since SST has an altazimuthal mount.
and maps are obtained at different times of the day, the uncertainty is uniformly distributed in the data set.

2.2. Observational Time Series

To analyze the radius variation over the solar activity cycle, we use the average taken every 6 months from the solar radii and proxies. We use radius daily averages smoothed over a 100 day period to build time series at radio frequencies. As solar activity proxies, we used the 10.7 cm solar flux, \( F_{10.7} \), and the intensity of the mean photospheric magnetic field, \( |B| \), both smoothed by a 396 day running mean (13 months) to avoid the influence of annual modulations. Daily flux values of the 10.7 cm solar radio emission (Dominion Radio Astrophysical Observatory, DRAO), given in solar flux units (1 SFU = \( 10^{-22} \) W m\(^{-2}\) Hz\(^{-1}\)), is a very good proxy for the solar activity cycle, as it is always measured by the same instruments and has a smaller intrinsic scatter than the sunspot number. Another proxy used was the mean solar magnetic field, given in \( \mu \)T, provided by the Wilcox Solar Observatory (Scherrer et al. 1977).

3. Results

We used 29,088 SST maps (from a total of 36,034 maps) to calculate the radii at 212 GHz (24,186 maps) and 405 GHz (4902 maps) and 196 ALMA maps to calculate the radii at 100 GHz (125 maps) and 230 GHz (71) maps with the method described in Section 2.
function of the observing frequency or wavelength, indicating that the radius decreases exponentially at radio frequencies. Note that the trend curve is just a least-squares exponential fit, not a physical model. Our results are shown with green (100 GHz), blue (212 GHz), yellow (230 GHz), and red (405 GHz) crosses. The SST and ALMA radii seem to agree within the uncertainties with the trend of Figure 3 and the solar atmospheric model predictions.

Next, we used a 2D solar atmospheric model developed by Selhorst et al. (2005; hereafter referred to as the SSC model) to generate profiles of temperature brightness, $T_B$, at 100, 212, 230, and 405 GHz, which yield radii of 964°2, 963°78, 963°2, and 962°8, respectively (also listed in the last column of Table 2). Our results at 212, 230, and 405 GHz are very close to the radii derived from the model, whereas the 100 GHz radii are about 4″ bigger, not agreeing with the model.

3.2. Correlation with Solar Activity

We investigated the temporal variation of the solar radius and its relationship with the 11 yr solar cycle. The subterahertz radius time series was analyzed from 2007 to 2016 using radii derived from the whole solar disk only (Menezes & Valio 2017). Here we analyze a 13 yr period—from 2007 January to 2019 December—using radii derived from equatorial and polar latitude regions. As solar activity proxies, we used the 10.7 cm solar flux, $F_{10.7}$, and the mean solar magnetic field intensity, $|B|$. The results are plotted in Figure 4.

We compared the equatorial and polar radius time series at 212 GHz (SST) with the time series of the equatorial and polar radii at 230 GHz (ALMA) with 6 month averages. The radii derived from SST’s maps are found to have both average values and behavior over time that are very close to ALMA’s, which can be seen in Figure 5. Moreover, besides the lower-frequency and higher-radius values, the equatorial and polar radii at 100 GHz seem to have similar behavior to those of the 212 and 230 GHz time series.

The comparison of the solar radii in time with the solar proxies is summarized in Table 3, where the calculated correlation coefficients, $\rho$, are organized by frequency, solar latitude region, and solar proxy. The correlation coefficients between equatorial radius, $R_{212}^{\text{equat.}}$, and solar proxy are very low (0.05 and 0.16, respectively). However, for $R_{212}^{\text{polar}}$, the coefficients indicate a weak anticorrelation ($-0.36$ for $F_{10.7}$ and $-0.23$ for $|B|$). Here $R_{405}^{\text{equat.}}$ is moderately correlated with $F_{10.7}$ (0.64) and $|B|$ (0.50), while $R_{405}^{\text{polar}}$ is weakly anticorrelated with $F_{10.7}$ ($-0.39$) and $|B|$ ($-0.23$). In summary, the radii $R_{212}^{\text{equat.}}$, $R_{212}^{\text{polar}}$, $R_{405}^{\text{equat.}}$, and $R_{405}^{\text{polar}}$ have a stronger correlation with $|B|$ than with $F_{10.7}$.

4. Discussion and Conclusions

From the extensive SST and the ALMA data set, we determined the polar and equatorial radii of the Sun at 100, 212, 230, and 405 GHz. The average radii are in agreement with the radius-versus-frequency trend (Figure 3); however, the values obtained for the ALMA maps are higher than those obtained by Alissandrakis et al. (2017) and Selhorst et al. (2019b). The 100 GHz average radius is about 2″ larger than those measured by Labrum et al. (1978) and Selhorst et al. (2019b), and about 4″ larger than that measured by Alissandrakis et al. (2017). Nevertheless, the 100 GHz radius was measured by Labrum et al. (1978)
using observations of the total eclipse of 1976 October 23, and by Alissandrakis et al. (2017) and Selhorst et al. (2019b) using maps observed only in December 2015. Also, there is a difference of roughly 4° between our 100 GHz measurements and the radius derived from the SSC model. F. Menezes et al. (in preparation) showed that the radius increases as a function of the limb-brightening intensity. By convolving the ALMA beam with the SSC model (limb-brightening level = 33.6% above the quiet Sun level), they estimated an increase of 2°.5 on the radius at 100 GHz. The limb-brightening levels could be increasing over time as the solar activity decreases, therefore affecting the solar radius.

Moreover, we have analyzed the subterahertz solar radius time series for more than a solar cycle, over 13 yr (2007–2019), at 212 and 405 GHz. The radius time series are not strongly correlated with the solar proxies; however, one can observe particular behaviors of these time series, with the polar radius being anticorrelated and the equatorial radius being correlated with $|\beta|$. This is a similar behavior to that of the radio radius presented in the literature for lower frequencies (Costa et al. 1999; Selhorst et al. 2004, 2019a). The subterahertz radii measured in this work correspond to emission altitudes much closer to the photosphere. Therefore, our results correspond to a frequency range (212–405 GHz) that probably reflects the behavior from both the photosphere and the lower chromosphere. In part, this would explain the weak (212 GHz) and moderate (405 GHz) correlation of the radii with the solar proxies.

Moreover, we could also observe analogous behavior between the SST and ALMA time series, even with the shorter period of the ALMA solar observations. Besides lower-frequency and higher-radius values, equatorial and polar radii at 100 GHz seem to have similar variations with those of 212 and 230 GHz time series. At both ALMA frequencies, the equatorial radii decrease from 2015 to 2017 and increase from 2017 to 2018, roughly close to $|\beta|$. The polar radius time series just increases from 2015 to 2018, which is the opposite of $|\beta|$. As the subterahertz radiation is influenced by bremsstrahlung emission, the observed variations are expected, since the solar atmosphere’s density, temperature, and magnetic field change with time. Longer periods of future observations at these frequencies will reveal the polar and equatorial trends of the solar atmosphere.

Measuring the solar radius at subterahertz frequencies is not an easy task, since there are high uncertainties in the measurements. Also, it is difficult to compare values from different studies, since they use different instruments and methods. Our results are important for testing atmospheric models and better understanding the solar cycle, since they directly probe different layers of the solar atmosphere over time. More studies of this kind at other frequencies and for longer periods of time are needed to achieve this goal.

The authors thank J. Valle, P. J. A. Simões, and D. Cornejo for fruitful discussions. F. M. thanks MackPesquisa and CAPES for the scholarship.

We acknowledge financial support for the operation of the Solar Submillimeter-wave Telescope (SST) from São Paulo Research Foundation (FAPESP) proc. No. 2013/24155-3 and AFOSR grant No. FA9550-16-1-0072. A.V. acknowledges partial financial support from the FAPESP, grant No. 2013/10559-5. C.L.S. acknowledges financial support from the

![Box-plot time series for equatorial $R_0$ at 100 (dark green), 212 (dark blue), and 230 GHz (brown) and polar $R_0$ at 100 (light green), 212 (light blue), and 230 GHz (beige) from 2014 January to 2019 December. Every box represents data for a 6 month period; the horizontal line inside the box is the period median. The crosses represent the outliers of the distribution. The red line represents $F_{10.7}$, and the gray line represents $|\beta|$.](image)

**Figure 5.** Box-plot time series for equatorial $R_0$ at 100 (dark green), 212 (dark blue), and 230 GHz (brown) and polar $R_0$ at 100 (light green), 212 (light blue), and 230 GHz (beige) from 2014 January to 2019 December. Every box represents data for a 6 month period; the horizontal line inside the box is the period median. The crosses represent the outliers of the distribution. The red line represents $F_{10.7}$, and the gray line represents $|\beta|$.

| Frequency | Latitude | $\rho_{F_{10.7}}$ | $\rho_{|\beta|}$ |
|-----------|----------|------------------|------------------|
| 212 GHz   | Equatorial | 0.05            | 0.16             |
| 212 GHz   | Polar     | −0.36            | −0.23            |
| 405 GHz   | Equatorial | 0.64             | 0.50             |
| 405 GHz   | Polar     | −0.39            | −0.23            |

**Table 3**

Linear Correlation Coefficients, $\rho$, between Solar Radii and Solar Proxies

The 212 and 405 GHz radius time series do not seem to be as well defined as at lower frequencies, such as 17, 37, and 48 GHz (Costa et al. 1999; Selhorst et al. 2004, 2019a). The subterahertz radii measured in this work correspond to emission altitudes much closer to the photosphere. Therefore, our results correspond to a frequency range (212–405 GHz) that probably reflects the behavior from both the photosphere and the lower chromosphere. In part, this would explain the weak (212 GHz) and moderate (405 GHz) correlation of the radii with the solar proxies.
This work is based on data acquired at Complejo Astronómico El Leoncito, operated under agreement between the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina and the National Universities of La Plata, Córdoba, and San Juan.

This paper makes use of the following ALMA data: ADS/JAO. ALMA #2011.0.00020.SV #2016.1.00050.S, #2016.1.00070.S, #2016.1.00156.S, #2016.1.00166.S, #2016.1.00182.S, #2016.1.00201.S, #2016.1.00202.S, #2016.1.00423.S, #2016.1.00572.S, #2016.1.00788.S, #2016.1.00789.S, #2016.1.00870.S, #2016.1.00971.S, #2016.1.01129.S, #2016.1.01408.S, #2016.1.01532.S, #2017.1.00009.S, #2017.1.00870.S, #2017.1.01138.S. ALMA is a partnership of the ESO (representing its member states), NSF (USA), and NINS (Japan), together with the NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ.

This work makes use of data provided by the Wilcox Solar Observatory, which was obtained via the website http://wso.stanford.edu.

Also, we acknowledge Dr. Ken Tapping, Research Council Officer, DRAO, and the Solar Radio Monitoring Program, operated jointly by the National Research Council Canada and Natural Resources Canada, for the radio flux data.

ORCID iDs

Fabian Menezes https://orcid.org/0000-0002-4703-4027
Caius L. Selhorst https://orcid.org/0000-0002-5897-5236
Carlos Guillermo Giménez de Castro https://orcid.org/0000-0002-8979-3582
Adriana Valio https://orcid.org/0000-0002-1671-8370

References

Alissandrakis, C. E., Patsourakos, S., Nindos, A., & Bastian, T. S. 2017, A&A, 605, A78
Bachurin, A. F. 1983, IzKry, 68, 68
Coates, R. J. 1958, ApJ, 128, 83
Costa, J. E. R., Homor, J. L., & Kaufmann, P. 1986, in Solar Flares and Coronal Physics Using P/OF as a Research, ed. E. Tandberg, R. M. Wilson, & R. M. Hudson (Washington, DC: NASA)
Costa, J. E. R., Silva, A. V. R., Makhmutov, V. S., et al. 1999, ApJL, 520, L63
Fürst, E., Hirth, W., & Lantos, P. 1979, SoPh, 63, 257
Giménez de Castro, C. G., Pereira, A. L. G., Valle Silva, J. F., et al. 2020, ApJ, 902, 136
Horne, K., Hurford, G. J., Zirin, H., & de Graauw, T. 1981, ApJ, 244, 340
Kaufmann, P., Levato, H., Cassiano, M. M., et al. 2008, Proc. SPIE, 7012, 70120B
Kilcik, A., Sigismondi, C., Rozelot, J., & Guel, K. 2009, SoPh, 257, 237
Kislyakov, A. G., Kulikov, I. I., Fedoseev, L. I., & Chernyshev, V. I. 1975, SvAL, 1, 79
Kubo, Y. 1993, PASJ, 45, 819
Labrum, N. R., Archer, J. W., & Smith, C. J. 1978, SoPh, 59, 331
Menezes, F., & Valio, A. 2017, SoPh, 292, 195
Pelyushenko, S. A., & Chernyshev, V. I. 1983, SvA, 27, 340
Rozelot, J. P., Kosovichev, A. G., & Kilcik, A. 2018, SanGe, 13, 63
Scherrer, P. H., Wilcox, J. M., Svalgaard, L., et al. 1977, SoPh, 54, 353
Selhorst, C. L., Giménez de Castro, C. G., Válio, A., Costa, J. E. R., & Shibasaki, K. 2011, ApJL, 734, 64
Selhorst, C. L., Kallunki, J., Giménez de Castro, C. G., Valio, A., & Costa, J. E. R. 2019a, SoPh, 294, 175
Selhorst, C. L., Silva, A. V. R., & Costa, J. E. R. 2003, A&A, 401, 1143
Selhorst, C. L., Silva, A. V. R., & Costa, J. E. R. 2004, A&A, 420, 1117
Selhorst, C. L., Silva, A. V. R., & Costa, J. E. R. 2005, A&A, 433, 365
Selhorst, C. L., Silva, A. V. R., Costa, J. E. R., & Shibasaki, K. 2003, A&A, 401, 1143
Selhorst, C. L., Simões, P. J. A., Brajša, R., et al. 2019b, ApJ, 871, 45
Swanson, P. N. 1973, SoPh, 28, 77
Wanner, P. G., Hurford, G. J., & Seielstad, G. A. 1983, ApJ, 264, 660
White, S. M., Iwai, K., Phillips, N. M., et al. 2017, SoPh, 292, 88
Wootten, A., & Thompson, A. R. 2009, IEEEP, 97, 1463
Wrixon, G. T. 1970, Natur, 227, 1231