The Submillimeter Active Region Excess Brightness Temperature during Solar Cycles 23 and 24

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Abstract

We report the temporal evolution of the excess brightness temperature $\Delta T_b$ above solar active regions (ARs) observed with the Solar Submillimeter Telescope (SST) at 212 ($\lambda = 1.4$ mm) and 405 GHz ($\lambda = 0.7$ mm) during Cycles 23 and 24. Comparison with the sunspot number (SSN) yields a Pearson’s correlation coefficient $R = 0.88$ and 0.74 for 212 and 405 GHz, respectively. Moreover, when only Cycle 24 is taken into account the correlation coefficients go to 0.93 and 0.81 for each frequency. We derive the spectral index $\alpha$ between SST frequencies and find a slight anticorrelation with the SSN ($R = -0.25$); however, since the amplitude of the variation is lower than the standard deviation we cannot draw a definite conclusion. Indeed, $\alpha$ remains almost constant within the uncertainties with a median value of $\approx 0$ characteristic of an optically thick thermal source. Since the origin of the AR submillimeter radiation is thermal continuum produced at chromospheric heights, the strong correlation between $\Delta T_b$ and the magnetic cycle evolution could be related to the available free magnetic energy to be released in reconnection events.

Unified Astronomy Thesaurus concepts: Active solar chromosphere (1980)

1. Introduction

Solar active regions (ARs) are “The totality of all observable phenomena preceding, accompanying and following the birth of sunspots including radio-, X-, EUV- and particle emission” (extracted from van Driel-Gesztelyi & Green 2015). In particular, at radio frequencies they are areas of enhanced brightness on the solar disk observed near sunspots. At microwaves Selhorst et al. (2014) have shown the correlation between the monthly average of the maximum and mean excess brightness temperatures at 17 GHz of ARs and the solar cycle; this work is based on images obtained by the Nobeyama Radioheliograph (NoRH; Nakajima et al. 1994) with synthesized beam sizes of the order of 10$.^{1}$ Kundu (1970) conducted the first millimeter observations using the 11 m (36 foot) single-dish antenna installed at Kitt Peak (USA). Around 40 solar maps were obtained at 33.3, 85.6, and 249.8 GHz (although only three at the last frequency) with spatial resolutions between 3/5 and 1/2 from which he derived typical brightness temperatures of 1000, 700, and 150 K for the three frequencies, respectively. Using the Caltech Submillimeter Observatory Bastian et al. (1993) were able to analyze brightness observed at 352 GHz, associated with Hα filaments and determined temperatures close to or below that of the quiet Sun. Moreover, they observed a prominence at 352 and 240 GHz; in both cases they arrived at the conclusion that the millimeter/submillimeter emission of filaments and prominences is optically thin. At higher frequencies Lindsey & Kopp (1995) used the James Clerk Maxwell Telescope to make maps of the Sun at 250, 350, and 855 GHz with beam sizes between 16$^{\prime\prime}$ and 5$^{\prime\prime}$. They showed for the first time that sunspots, when observed at submillimeter wavelengths, have an umbra cooler than the quiet Sun, while their penumbras could have temperatures similar to that of the quiet Sun; furthermore, in some ARs, sunspots could be as hot as the surrounding plages. Indeed, Iwai & Shimojo (2015) used the 45 m Nobeyama telescope to determine the temperature of the umbra and penumbra at 85 and 115 GHz and also reported finding an umbra cooler than the quiet Sun. These findings were recently confirmed by Loukitcheva et al. (2017) and Iwai et al. (2017), using the images obtained with the Atacama Large Millimeter/submillimeter Array (ALMA) with a synthesized beam of 0.5$^{\prime\prime}$ at frequencies of 100 ($\lambda = 3.0$ mm) and 239 GHz ($\lambda = 1.2$ mm). With lower spatial resolution, Silva et al. (2005) analyzed ARs during 23 days at 212 ($\lambda = 1.4$ mm) and 405 GHz ($\lambda = 0.7$ mm) with the Solar Submillimeter Telescope (SST), adding complementary data from NoRH at 17 and 34 GHz ($\lambda = 8.8$ mm). They concluded that an overall AR behaves as an optically thick thermal source, because of the average flux density spectral index $\alpha \approx 2$. This result was confirmed by Valle Silva et al. (2020), who, besides SST and NoRH, included single-dish ALMA maps at 107 ($\lambda = 2.8$ mm) and 239 GHz ($\lambda = 1.2$ mm). Moreover, they showed that an AR without associated sunspots has a harder flux density spectral index.

However, a study comprising a whole solar cycle at submillimeter wavelengths, analyzing possible changes in the AR characteristics, was never before attempted. Garcia Pereira et al. (2020) used SST and NoRH observations obtained between 2001 and 2017, and an artificial intelligence (AI) algorithm, based on neural networks and computer vision, to identify, extract, classify, and obtain physical properties of ARs observed in more than 16,000 maps. They showed that the number of ARs per year follows the solar cycle, and confirmed, at a solar cycle timescale, Silva et al. (2005) and Valle Silva et al. (2020) conclusions. In the present work, we use the statistical results from Garcia Pereira et al. (2020) and focus in...
the temporal evolution of the physical properties of ARs at submillimeter wavelengths.

2. Data Reduction and Analysis

The SST (Kaufmann et al. 2008) is a multibeam radio telescope, installed at the Complejo Astronómico El Leoncito (CASLEO, Argentina), composed of six independent radiometers arranged in the focus of a Cassegrain 1.5 m antenna that observe simultaneously. Daily and continuous observations started on 2001 March and, with few stops for maintenance work, SST already gathered almost 20 yr of data. The SST main objective is to spectrally and spatially characterize the temporal evolution of the physical properties of ARs at submillimeter wavelengths. More important than the noise temperature is the atmospheric attenuation at 212 GHz but can severely reduce the emission at 405 GHz (Melo et al. 2005; Cassiano et al. 2018).

SST provides several solar maps per day as a calibration procedure. These maps are the basic data of our work. SST solar maps are typically made out of azimuth raster scans (on-the-fly maps) of 60′ length. The elevation changes at every scan to make a square that covers the entire solar disk. A typical map has a separation between scans equal to 2′. The scan speed is between 0.1 and 0.2 deg s⁻¹. Since we use 40 ms integrated data, these speeds produce a separation between successive points in azimuth between 0′24 and 0′48. Therefore, observations are oversampled in azimuth creating a rectangular pixel of (0.24–0.48) × 2 arcmin²; maps have either 375 × 31 pixels or 187 × 31 pixels. We interpolate the raw data to create a square map with a field of view of 31′ and 288 × 288 pixels. Then, the map is rotated with north up, and the collected intensity units are converted to temperature, using the Sun brightness temperature as a reference (see Silva et al. 2005). We note that there is no need to equalize the beam sizes by convolving 405 GHz observations with the 212 GHz beam and vice versa, since, from the results presented above, both beams have similar spatial response.

The AI procedure implemented to detect ARs in SST maps is based on an artificial convolutional neural network (ConvNet; Cireşan et al. 2011; O’Shea & Nash 2015) composed of four convolutional layers and two fully connected layers. Every convolutional layer has one max pooling and one flattening layer. Including the input layer, the neural network has a total of 13 layers used to classify every map in 11 different categories. There is only one category representing a map with one or more ARs. To train the ConvNet we use data augmentation techniques (Bishop 2006; Goodfellow et al. 2016; Aloysius & Geetha 2017) to increase the size of the test data. We achieve ≈97% and ≈98% accuracy for testing and validation, respectively. The method reliability is increased by comparing SST maps with 17 GHz images from the NoRH, which should confirm the presence of the AR. Maps with detected ARs are binarized: a black (1) or white (0) pixel means it does or does not belong to an AR. The AR is extracted from the map using the Canny algorithm (Canny 1986), and its physical properties: position, size and maximum excess brightness temperature are automatically included in a database for later analysis. More than 16,000 maps between 2001 March and 2017 December are analyzed. Observing times are restricted to the Sun meridian transit (14:00–16:00 UTC) to reduce the atmospheric interference. Details of the methodology can be found in García Pereira et al. (2020), along with preliminary statistical analysis.

In this work we concentrate in the AR excess brightness temperature ΔTb with respect to the quiet Sun, i.e., the maximum temperature of the AR with respect to the quiet Sun. Since SST has beams with sizes of the order of a typical AR size, we do not have spatial resolution to discriminate different zones of the AR, and ΔTb represents the average over the whole region weighted by the telescope beams. Table 1 summarizes the observations. For every year and month, a mark × and/or ○ indicates that ARs are detected at 212 or 405 GHz; at the end of each line we show the total number of detected ARs during the year and the yearly median of ΔTb. The superscript and subscript are the differences to the third and first quartiles of the sample, respectively. The absence of marks means either there are no observations or that no AR is
detected. During some years (2003, 2004, and 2008) technical problems temporarily stopped or reduced observations. On the other hand, it can be seen that there are more ARs detected at 212 GHz than at 405 GHz, an expected result since the opacity is much higher at 405 GHz. Another remark from the table is that from mid-May to mid-October (winter time) when the atmospheric humidity is lower we detect more ARs.

3. Results

3.1. Excess Brightness Temperature Time Evolution

Figure 2 shows the evolution of the AR excess brightness temperature $\Delta T_b$ for the two SST observing frequencies in the form of boxplots. Every box represents one year of observations, the central, horizontal black line is the median; the lower (upper) limit of the box is the first (third) quartile, and the vertical line extends from the minimum to the maximum; the open circles represent the outliers of the distribution. Golden boxes represent results for 212 GHz, while green boxes are for 405 GHz. The purple dots are the monthly mean values of the sunspot number (SSN) obtained from the sunspot Index and Long-term Solar Observations which is an activity of the Solar Influences Data Analysis Center (SDIC) of the Royal Observatory of Belgium. The error bars correspond to $1\sigma$ for the month. We can see that $\Delta T_b$ at the two frequencies follow the solar cycle represented by the SSN. The overall cross-correlation coefficients between the annual median $\Delta T_b$ and the annual mean SSN are $R = 0.88$ for 212 GHz and $R = 0.74$ for 405 GHz; but if we restrict to the years 2009 and 2017, $R = 0.93$ and 0.81 for 212 and 405 GHz, respectively. One reason why $R$ increases after 2009 is that the antenna was in commission during almost the first decade after installation in 1999. During 2008, in particular, we detected ARs during three months only, resulting in a small sample that produces a significant increase in the uncertainty (see the boxplot for 405 GHz in Figure 2). On the contrary, after 2009, we observe that boxplots are smaller, an indication of a narrow data dispersion.

3.2. Spectral Index

From $\Delta T_b$ we can derive the spectral index $\alpha$ defined as

$$\alpha = \frac{\log(\Delta T_{b,405}) - \log(\Delta T_{b,212})}{\log(405) - \log(212)},$$

where $\Delta T_{b,405}$ and $\Delta T_{b,212}$ are the excess brightness temperatures at 405 and 212 GHz, respectively. The temporal evolution of $\alpha$ is shown in Figure 3; green dots are the monthly mean, while the uncertainty bars correspond to $1\sigma$; purple dots are the SSN as in Figure 2. In Figure 4 we see the frequency distribution of $\alpha$, and a boxplot of the sample; both ways graphically show the rather symmetric distribution with a mean value $\langle \alpha \rangle = 0.16$ and median $\alpha_{\text{med}} = 0.05$, implying that the sample dispersion is related to random noise. On the other hand, the overall cross-
correlation coefficient $R = -0.25$ is consistent with an apparent slight anticorrelation observed in Figure 3.

## 4. Discussion

Previous works with better spatial resolution have shown that at submillimeter wavelengths the sunspot umbra is cooler than the quiet Sun, while the penumbra has a similar temperature and the surrounding plage is much hotter (Lindsey & Kopp 1995; Iwai et al. 2017; Loukitcheva et al. 2017). However, SST beam sizes, which are of the same order of the AR, cannot resolve these spatial variations and $\Delta T_b$ is an average over the whole region, with the penumbra and surrounding plages dominating the emission, i.e., what we are determining is the variation of the umbra + penumbra + plage temperature averaged by the beam size along the solar

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Total 212 | Total 405 | $\Delta T_b$ (K) |
|------|---|---|---|---|---|---|---|---|---|----|----|----|----------|----------|-------------|
| 2001 | xo | xo | xo | xo | xo | xo | xo | xo | xo |     |    |    | 164 | 98   | 611$^{183}_{216}$ | 412$^{197}_{216}$ |
| 2002 | xo | x  | xo | xo | xo | o  | xo | xo | xo |     |    |    | 151 | 78   | 362$^{85}_{84}$  | 383$^{72}_{99}$  |
| 2003 | xo | xo |     |    |    |    |    |    |    |     |    |    | 35  | 25   | 304$^{43}_{54}$  | 304$^{43}_{54}$  |
| 2004 | xo |     | xo | x  |     |    |    |    |    |     |    |    | 12  | 10   | 298$^{144}_{94}$ | 20477     |
| 2005 | xo | xo | xo | x  |     |    |    |    |    |     |    |    | 92  | 86   | 273$^{74}_{59}$  | 312$^{95}_{83}$  |
| 2006 | xo | xo | xo | xo |     |    |    |    |    |     |    |    | 47  | 27   | 246$^{75}_{52}$  | 257$^{77}_{61}$  |
| 2007 | xo | xo | xo | xo | xo |     |    |    |    |     |    |    | 85  | 51   | 208$^{163}_{69}$ | 176$^{133}_{42}$ |
| 2008 | xo | x  |     |    |    |    |    |    |    |     |    |    | 10  | 7    | 175$^{187}_{98}$ | 325$^{92}_{175}$ |
| 2009 | xo | xo | xo | xo | xo | xo | xo | xo | xo |     |    |    | 99  | 74   | 133$^{211}_{65}$ | 168$^{132}_{86}$ |
| 2010 | x  | xo | xo | xo | xo | xo | xo | xo | xo |     |    |    | 121 | 96   | 229$^{135}_{62}$ | 202$^{90}_{53}$  |
| 2011 | x  | xo | xo | xo | xo | xo | xo | xo | xo |     |    |    | 129 | 78   | 317$^{95}_{76}$  | 266$^{71}_{51}$  |
| 2012 | x  | xo | xo | xo | xo | xo | xo | xo | xo |     |    |    | 116 | 68   | 309$^{96}_{86}$  | 310$^{103}_{63}$ |
| 2013 | x  | xo | xo | x  | x  | x  | x  | x  | x  |     |    |    | 126 | 5    | 310$^{87}_{65}$  | 386$^{70}_{105}$ |
| 2014 | xo | x  | xo | xo | xo | xo | xo | xo | xo |     |    |    | 62  | 33   | 364$^{72}_{63}$  | 323$^{79}_{68}$  |
| 2015 | x  | xo | xo | xo | xo | xo | xo | xo | xo |     |    |    | 136 | 56   | 320$^{109}_{82}$ | 241$^{107}_{51}$ |
| 2016 | xo | xo | xo | xo | xo | xo | xo | xo | x  |     |    |    | 34  | 7    | 256$^{75}_{52}$  | 299$^{21}_{05}$  |
| 2017 | xo | xo | xo | xo | xo | xo | x  | xo | x  |     |    |    | 28  | 15   | 237$^{88}_{73}$  | 229$^{248}_{41}$ |

**Note.** The symbol $x$ (o) represents one or more ARs detected at 212 (405) GHz during the month. No symbol means either no detection or no observation. The columns labeled “Total” show the total number of ARs detected during the year, and the last two columns give median $\Delta T_b$ for the year with the ± uncertainties defined as the difference to the third quartile (superscript) and first quartile (subscript) of the sample.
Valle Silva et al. (2020) have shown that there are many ARs observed at submillimeter wavelengths without a spot, as it was previously seen by Selhorst et al. (2014) at centimeter wavelengths. We also note that, since we use the quiet Sun as a calibrator, and we assume that the quiet Sun brightness temperature does not change with the cycle, the absolute $\Delta T_b$ may be different at different phases of the cycle if this hypothesis is not correct. However, even if the quiet Sun temperature changes during the cycle, $\Delta T_b$ variations are real.

Cycles 23 and 24 were double peaked with an evident gap in between them (see Gnevyshev 1967); Figure 2 shows this behavior for the SSN. SST started observations in 2001, during the recovery from the Gnevyshev gap that was relatively fast and took less than a year for the SSN. Therefore, it is not possible to identify the gap in the $\Delta T_b$ time-series. In Cycle 24, the gap between peaks occurred between 2012 and 2013, which is not apparent in the $\Delta T_b$ time-series. We cannot, however, draw any firm conclusion about this point, since SST data are limited by the atmospheric attenuation and beam sizes that reduce the detected AR peak temperature, which may create false negatives. For this reason we present only one year average values. We are working now in an enhanced AI method to increase the AR detectability in the SST data.

As was already pointed out, Selhorst et al. (2014) have shown the correlation between the AR brightness temperature and the solar cycle at 17 GHz. This is an expected result at this frequency due to the emergence of ARs with strong magnetic fields ($|B| \geq 2200$ G at the photosphere; Vourlidas et al. 2006).
These ARs may present a gyroresonance contribution that is able to increase their brightness temperatures from \((2 \sim 3) \times 10^4\) K to values as high as \(T_b > 10^5\) K, if the 17 GHz gyroresonance third harmonic (2000 G) occurs above the transition region (Shibasaki et al. 1994; Vourlidas et al. 2006). However, within solar conditions, the same mechanism does not apply at submillimeter wavelengths. The millimeter-to-submillimeter emission is mostly a thermal continuum produced at chromospheric height in local thermodynamic equilibrium (LTE; e.g., Loukitcheva et al. 2017). Instead of the flux density, as it was used in previous works and that depends on the brightness temperature and the source solid angle, here we only use the brightness temperature to characterize the spectrum, reducing the uncertainty of the spectral index. Indeed, after the propagation of temperature uncertainties in Equation (1), the \(\alpha\) uncertainty is

\[
\Delta^2 \alpha = \left( \frac{\partial \alpha}{\partial T_{\text{b,405}}} \right)^2 \Delta^2 (\Delta T_{\text{b,405}}) + \left( \frac{\partial \alpha}{\partial T_{\text{b,212}}} \right)^2 \Delta^2 (\Delta T_{\text{b,212}}) = \frac{Q \left( \Delta (\Delta T_{\text{b,405}}) \right)^2}{\Delta T_{\text{b,405}}} + \frac{\left( \Delta (\Delta T_{\text{b,212}}) \right)^2}{\Delta T_{\text{b,212}}} = Q \left( \epsilon_{\text{405}}^2 + \epsilon_{\text{212}}^2 \right),
\]

where \(\Delta (\Delta T_{\text{b,405}})\) and \(\Delta (\Delta T_{\text{b,212}})\) are the total uncertainties in excess brightness temperatures for 405 and 212 GHz, respectively, while \(\epsilon_{\text{405}}\) and \(\epsilon_{\text{212}}\) are their relative uncertainties and \(Q = 1/\log(405/212)\). Substituting \(\epsilon_{\text{405}} = 0.02 \approx 0.1\) in Equation (2) we get \(\Delta \alpha \approx 0.22\), a value which agrees with Figure 4 and reinforces our conclusion that the dispersion is produced by random noise. Therefore, we are very cautious to draw any conclusions about the anticorrelation between \(\alpha\) and the SSN given by the coefficient \(R = -0.25\). The spectral index \(\alpha\) obtained here represents the average source properties, encompassing plages, penumbra, and umbra from one or more sunspots; however, we note that the spectrum of an AR can be well represented by a unique spectral index from 34 GHz to 405 GHz when the spatial resolution is of order \(1^\prime\) (Silva et al. 2005; Valle Silva et al. 2020) lending support to the optically thick emission of a thermal source.

The temporal variation of \(\Delta T_b\) has to be also interpreted in terms of an average value. The evolution of an AR is modulated by the magnetic field whose dissipated energy should heat the plasma. As a solar cycle progresses the dissipated magnetic energy should increase or decrease following it, and therefore the AR average temperature should follow the cycle. However, to confirm this hypothesis, a statistical study relating the photospheric magnetic field and \(\Delta T_b\) should be completed.

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