

THE BEHAVIOR OF THE 17 GHz SOLAR RADIUS AND LIMB BRIGHTENING IN THE SPOTLESS MINIMUM XXIII/XXIV

C. L. SELHORST¹, C. G. GIMÉNEZ DE CASTRO², A. VÁLIO², J. E. R. COSTA³, AND K. SHIBASAKI⁴

¹ IP&D-Universidade do Vale do Paraíba-UNIVAP, São José dos Campos, SP, Brazil; caius@univap.br

² CRAAM, Universidade Presbiteriana Mackenzie, São Paulo, SP, Brazil

³ CEA, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil

⁴ NoRH, Nobeyama Radioheliograph, Japan

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ABSTRACT

The current solar minimum has surprised the entire solar community because the spotless period is presently almost 2–3 years longer than the usual minima. To better understand this, we studied the variation of the solar radius and the polar limb brightening at 17 GHz, comparing the results from the minimum at the end of cycle XXIII with those of the previous one. Daily maps obtained by the Nobeyama Radioheliograph (NoRH) from 1992 through 2010 were analyzed. Whereas the variation of the solar radius at radio frequencies indicates the heating of the solar atmosphere due to solar activity, the limb brightening intensity depends on the organization of the polar magnetic field of the Sun, including the global dipole and the features formed around it. These features are more prominent during minima periods. As a common result, researchers have observed a decrease in both radius and limb brightness intensity at 17 GHz during the present minimum when compared with the previous one. The mean solar radius is $0'.9 \pm 0'.6$ smaller and the limb brightening reduced its intensity by around 20%. Both decrements are interpreted in terms of the weaker solar chromospheric activity of the present cycle. Measurement of the radius and limb brightening at 17 GHz can be used as an alternative solar activity index and should be included in the set of parameters used to predict future cycles.

Key words: Sun: activity – Sun: faculae, plages – Sun: general – Sun: radio radiation

1. INTRODUCTION

Since the 11-year solar cycle was proposed by Schwabe (1843), solar physicists have never observed such a long minimum period as that at the end of cycle XXIII and the beginning of cycle XXIV. Despite the great increase in our knowledge about solar physics in the last few decades, this unexpected event showed that it is very hard to predict the behavior of our star (Pesnell 2008).

The absence of sunspots during this long period clearly indicates the necessity of alternative indexes to characterize minimum activity times. Among the solar features observed in white light, polar faculae may be a good choice to describe the minimum, since they have a variation anti-correlated with the sunspot cycle (Sheeley 1964; Makarov & Makarova 1996) and their number reflects the mean magnetic flux in the polar region (Sheeley 1991; Erofeev 2001). Recently, the position of polar faculae was correlated to the intense magnetic field patches that can reach kG intensities (Okunev & Kneer 2004; Tsuneta et al. 2008). In Sheeley (2008), the author studied the variation of polar faculae for the past 100 years and pointed out that the number of faculae in 2006 was smaller than that observed in previous minima, indicating a less intense mean magnetic field at both poles, which was confirmed by Janardhan et al. (2010) and Wang et al. (2009).

The polar activity variation can also be observed at higher atmospheric layers. Chromospheric 17 GHz maps show a remarkable increase of the limb brightening in polar regions due to the presence of bright patches (Shibasaki 1998). Selhorst et al. (2003) found that the mean intensity of the polar limb brightening follows the faculae cycle and is anti-correlated with the solar cycle. This same behavior was observed in extreme-ultraviolet (EUV) 30.4 nm images, whose emission originates in the transition region (Selhorst et al. 2010). Although polar faculae do not have one-to-one correlation with the bright

patches that characterize the polar limb brightening at radio and EUV wavelengths, these measurements reflect the activity due to the interactions between the polar magnetic fields and the features emerging around them, for example, spicules and emerging magnetic regions (Selhorst et al. 2010).

Together with the limb brightening observations, the study of solar radius variation at radio frequencies can help measure the heating of the solar atmosphere during the solar cycle. A positive correlation between the mean solar radius and the solar cycle was found, for example, at 17 GHz and 48 GHz, respectively, by Selhorst et al. (2004) and Costa et al. (1999). At these chromospheric wavelengths the solar radius can be modulated by the emission from many small features, such as spicules, that exist in the solar atmosphere.

In this work, we extend the study of polar limb brightening and solar radius variation at 17 GHz (Selhorst et al. 2003, 2004), comparing the changes in their behavior during this long solar minimum period.

2. DATA ANALYSIS AND RESULTS

Daily solar maps at 17 GHz have been analyzed in the present work. These maps have been obtained since 1992 by the NoRH (Nakajima et al. 1994). The time period studied allows us to compare the current spotless minimum with the previous one. This analysis provides the chromospheric response to the absence of sunspots, since the 17 GHz emission is mainly produced in this layer of the atmosphere (Selhorst et al. 2005). The analysis of NoRH maps is separated into two parts: (1) solar radius and (2) polar limb brightening, both described below.

2.1. Solar Radius

Following the proposal by Costa et al. (1999), the solar radius was defined as the position where the brightness temperature of the quiet Sun drops to 50% of its value. Apart from steps 2 and

Table 1
Brightening Intensity Maxima During Cycles XXII and XXIII

Pole	Cycle XXII (% above Quiet Sun)	Cycle XXIII (% above Quiet Sun)	Difference (% above Quiet Sun)	Relative Variation (%)
North	16.3 ± 1.5	13.7 ± 1.8	2.6 ± 2.3	16 ± 15
South	17.5 ± 1.6	13.4 ± 1.3	4.1 ± 2.1	23 ± 11

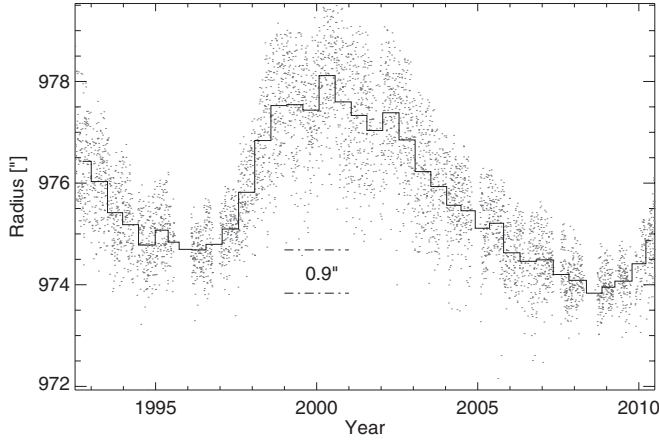


Figure 1. Daily variation of solar radius at 17 GHz (dots) and a 180 days average (thick line). The horizontal dot-dashed lines represent the two minima.

3 in the analysis sequence listed below, the procedure employed here is identical to that used in Selhorst et al. (2004), and can be resumed as follows:

1. The quiet-Sun temperature was defined as the most common temperature in the map (about 10^4 K).
2. The solar limb position was defined using the CONTOUR procedure of IDL as the position.
3. 1440 points were determined over the curve resulting from step 2.
4. A circumference fit was adjusted to the points.
5. The points with discrepancy greater than $\pm 30''$ were discarded.
6. A new circumference was fit to the remaining points (at least 1040 were used).
7. Steps 5 and 6 were applied recursively until the mean uncertainty between two subsequent fits differed by less than $0''.025$.

An increase in the solar radius at 17 GHz (chromospheric/transition region heights) represents a measurement of the solar atmosphere heating during the rise of the solar activity. The circumference fit considering points within $\pm 30''$ deviation prevents the influence of active regions close to the solar limb; however, as shown in Selhorst et al. (2004), the variation of the resulting mean radius has a very good correlation with the solar cycle.

Figure 1 shows the daily variation of the solar radius at 17 GHz (dots) and its 180 day average. We have removed the yearly oscillation (Selhorst et al. 2004) and have computed a running mean and its standard deviation over 365 days. All points above (below) the mean value plus (minus) 1σ were rejected. The remaining points were averaged over 180 days. The result not only reproduces the long time period of the present minimum, but also shows that the solar radius is smaller than that observed in the previous one. Indeed, we obtain $974''.7 \pm 0''.4$ and $973''.8 \pm 0''.4$ for the previous and present minima, respectively, or a difference of $\Delta R_{\min} = 0''.9 \pm 0''.6$.

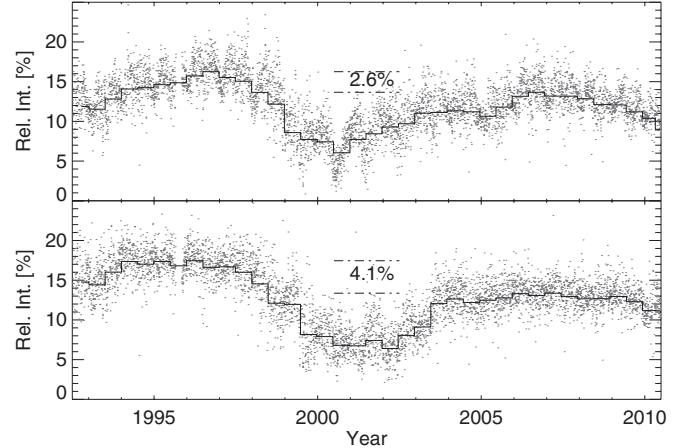


Figure 2. Dots represent the significant daily intensities of the limb brightening at the North (top) and South (bottom) poles. The thick lines are the average taken every 180 days. The horizontal dot-dashed lines represent the average limb brightening intensity during solar minima.

2.2. Polar Limb Brightening

As proposed by Shibasaki (1998), the limb brightening at 17 GHz in the poles has two distinct components: the chromospheric gradient of temperature (also present in the equatorial region) and polar features observed as bright patches in NoRH maps. In this work, we analyze the variation of the polar limb brightening intensity due to the presence of bright patches. The analysis follows the same steps of our previous works (Selhorst et al. 2003, 2010).

We applied the same statistical procedure as for the radius variation; only the significant points were used to compute the averages. Limb brightening is given in percent of the quiet-Sun brightness temperature ($\sim 10^4$ K). It varies in time anti-correlated with solar activity indexes (see Figure 2). It is apparent from the figure that cycle XXII had more prominent limb brightenings than cycle XXIII. Indeed, the averaged limb brightening intensities during the solar minima at the North Pole are $(16 \pm 1.5)\%$ and $(13.7 \pm 1.8)\%$ during cycles XXII and XXIII, respectively, yielding an intercycle variation of $(2.6 \pm 2.3)\%$ or a relative decrease between minima of $(16 \pm 15)\%$. The analysis of the South Pole yields more significant results. The maximum limb excesses over quiet-Sun brightness temperature were $(17.5 \pm 1.6)\%$ and $(13.4 \pm 1.3)\%$ for the cycles XXII and XXIII, respectively. The intercycle difference is hence $(4.1 \pm 2.1)\%$, or a $(23 \pm 11)\%$ relative decrease. The results are summarized in Table 1.

3. DISCUSSION AND CONCLUSIONS

The results above show a remarkable decrease of the solar radius and polar limb brightening at 17 GHz during this unusual solar minimum. Selhorst et al. (2004) reported the correlation between the sunspot number and the solar radius at 17 GHz; here

we note that the solar radius is also susceptible to this atypical period in the Sun. Spotless days were reported during the cycle XXII minimum, but only in a few days was the radius smaller than 974'' (see the dots below the dashed line in Figure 1).

Although the actual solar minimum is poor in spots, the results from Svalgaard (2010) may point to a regular sunspot number. Also, as suggested by Penn & Livingston (2010), sunspots present a reduction in the magnetic field intensity when compared with previous cycles and possibly have a minor appearance due to a low contrast. Aside from this fact, it is necessary to take into account that measurement of the radius at 17 GHz may represent the mean emission of many small chromospheric features (spicules, plages, prominences, faculae) joined with the emission originating from sunspots/active regions. From this perspective, our results can be interpreted as a reduction in the activity related to the 17 GHz atmospheric level during the actual long minimum.

The NOAA/NASA panel for the prediction of cycle XXIV realizes that the brightness temperature at 17 GHz of the polar bright patches is well correlated (index $R = 0.88$) with the magnetic field of the same polar regions determined from the Wilcox Solar Observatory magnetograms. Therefore, the panel included the use of the limb brightening as a proxy of the polar magnetic field (Svalgaard & Cliver 2006; Svalgaard et al. 2006). Selhorst et al. (2010) proposed, independently, that the 17 GHz limb brightening is determined by the presence of the polar magnetic field itself and the structures emerging around it. Since the present analysis shows a clear reduction in the polar limb brightening intensities during the current minimum, the observed decreases in faculae number (Sheeley 2008) and polar magnetic field intensities (Wang et al. 2009; Janardhan et al. 2010) support the theory that the magnetic features are the origin of the limb brightening. Indeed, Janardhan et al. (2010) reported that the South polar magnetic field is weaker than the North polar magnetic field during the minimum at the end of cycle XXIII, which should produce a weaker South limb brightening as we have observed.

As a final consideration, we note that both the radius and the polar limb brightening at 17 GHz are good solar cycle indexes

that can be more sensitive during long minimum periods like this one, when the sunspot number and 10.7 cm radio flux are almost constant in their lower measurement limits.

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