Association of Radio Polar Cap Brightening with Bright Patches and Coronal Holes

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Abstract

Radio-bright regions near the solar poles are frequently observed in Nobeyama Radioheliograph (NoRH) maps at 17 GHz, and often in association with coronal holes. However, the origin of these polar brightenings has not been established yet. We propose that small magnetic loops are the source of these bright patches, and present modeling results that reproduce the main observational characteristics of the polar brightening within coronal holes at 17 GHz. The simulations were carried out by calculating the radio emission of the small loops, with several temperature and density profiles, within a 2D coronal hole atmospheric model. If located at high latitudes, the size of the simulated bright patches is much smaller than that of the beam size and they present the instrument beam size when observed. The larger bright patches can be generated by a great number of small magnetic loops unresolved by the NoRH beam. Loop models that reproduce bright patches contain denser and hotter plasma near the upper chromosphere and lower corona. On the other hand, loops with increased plasma density and temperature only in the corona do not contribute to the emission at 17 GHz. This could explain the absence of a one-to-one association between the 17 GHz bright patches and those observed in extreme ultraviolet. Moreover, the emission arising from small magnetic loops located close to the limb may merge with the usual limb brightening profile, increasing its brightness temperature and width.

Key words: Sun: chromosphere – Sun: general – Sun: radio radiation

1. Introduction

Bright areas in the polar regions of the Sun have been frequently reported at radio to infrared frequencies, ranging from ~15 to 860 GHz (see Selhorst et al. 2003, and references therein). Most of those observations were obtained by single-dish telescopes with low spatial resolution, posing challenges to draw firm conclusions about the physical origin of the increase in emission.

Efano et al. (1980) observed the presence of bright regions near the poles at 22 and 37 GHz during the period of minimum solar activity, and reported that such bright regions were not seen during the maximum of solar activity.

Similar findings were also reported through other single-dish observations (Riehokainen et al. 1998, 2001), also suggesting that the polar brightening could be associated with regions in which the white-light polar faculae are observed and follows their cycle, i.e., anti-correlated with the solar cycle.

Great advances in the study of the polar brightening were obtained due to interferometric solar observations at 17 GHz by the Nobeyama Radioheliograph (NoRH; Nakajima et al. 1994), in operation since 1992. Shibasaki (1998) concluded that these polar cap bright regions observed at 17 GHz were the sum of two components: a limb brightening effect superposed on bright features intrinsic to the poles, which can increase the brightening up to 40% above the quiet-Sun temperature.

The polar cap brightening at 17 GHz is characterized by the presence of small bright structures (bright patches) that appear in the regions close to the limb, with their sizes ranging from the NoRH beam size (about 15") up to 50"–55" (Nindos et al. 1999). Through synoptic limb charts, Oliveira e Silva et al. (2016) showed a good association between the presence of coronal holes and the 17 GHz polar brightening in the period of 2010–2015. Moreover, the authors attributed the enhancement of radio brightness in coronal holes to the presence of bright patches closely associated with the presence of intense unipolar magnetic fields.

In Figure 1, we present an example of 17 GHz bright patches (top panel), with good correspondence with small bright structures observed in extreme ultraviolet (EUV) emission, from images of the Atmospheric Imaging Assembly (AIA) instrument (Lemen et al. 2012), on board of the Solar Dynamics Observatory (SDO). Moreover, the EUV lines formed above the transition region (171, 193, and 211 Å) show that these bright structures are embedded in a coronal hole. Nevertheless, not all bright structures observed in EUV have 17 GHz association, as reported before (Nindos et al. 1999; Riehokainen et al. 2001; Nitta et al. 2014).

Apart from being more frequently observed at the poles, the association between coronal holes and the presence of bright patches was also observed at lower latitudes (Gopalswamy et al. 1999; Maksimov et al. 2006).

While the radio limb brightening is now relatively well understood (Selhorst et al. 2005a), the origin of the intrinsic bright patches near the solar poles has not been identified yet. In this work, we propose a model to explain the observed radio-bright patches within coronal holes near the solar poles. Using small magnetic loop models to represent the source of the bright patches, we were able to reproduce the typical brightness temperature and size of the small (around 10") polar bright
The inclusion of spicules reduced the initial limb brightening to limb brightening of 36% above the quiet-Sun values, which is the number of small loops, unresolved by NoRH.

Selhorst et al. (2005b) explain the high polar brightening values by the presence of holes in the spicule forest caused by intense magnetic features (i.e., faculae), hereafter referred to as bare regions. For a large bare region located between 80°2 and 90°0 heliographic angle, the simulation results showed a sharp and intense brightening, up to 40% above the quiet Sun. However, the intensity decreased to 21.4% for a low latitude bare region located between 76°2 and 81°4. Thus, the authors concluded that a simple hole in the spicule forest is only able to reproduce the brightness temperature increase caused by large bright patches very close to the limb ($\geq 80°$).

However, since the high intensity bright patches at 17 GHz were also observed at lower heliographic angles, another physical source is necessary to explain their brightness temperature values. As first suggested in Selhorst et al. (2010), the simulations presented here include small magnetic loops in the regions without spicules, within coronal holes.

Figure 1. Comparison between the 17 GHz polar bright patches and the EUV images obtained by SDO/AIA. The 17 GHZ contour curves correspond to 15% above the quiet-Sun temperature.

patches. We suggest that larger regions ($\sim 50°$) are formed by a number of small loops, unresolved by NoRH.

2. Modeling Coronal Holes and Polar Bright Patches

In this section, we describe our proposed atmospheric model for coronal holes and the small magnetic structures to represent the origin of the polar bright patches.

2.1. The Atmospheric Model

Selhorst et al. (2005a) proposed an atmospheric model (hereafter referred to as the SSC model) with the distributions of temperature and density (electron and ions) as a function of height, from the photosphere up to 40,000 km in the corona. To calculate the 17 GHz limb brightening and verify the influence of spicules, the radiative transfer was performed through a 2D space, in order to account for the curvature of the Sun, from the disk center to the limb, and the SSC solar atmosphere. In this work, we follow the same procedure, with the appropriate atmospheric model for coronal holes (Section 2.2) and inclusion of magnetic loops to represent the sources of radio-bright patches (Section 2.3).

Assuming that the NoRH maps have an spatial resolution of $10''$, the SSC model without the inclusion of spicules showed a limb brightening of 36% above the quiet-Sun values, which is compatible with the maximum values observed at the poles. The inclusion of spicules reduced the initial limb brightening to $\sim 10\%$, which is close to the values observed at equatorial regions.

Selhorst et al. (2005b) explain the high polar brightening values by the presence of holes in the spicule forest caused by intense magnetic features (i.e., faculae), hereafter referred to as bare regions. For a large bare region located between 80°2 and 90°0 heliographic angle, the simulation results showed a sharp and intense brightening, up to 40% above the quiet Sun. However, the intensity decreased to 21.4% for a low latitude bare region located between 76°2 and 81°4. Thus, the authors concluded that a simple hole in the spicule forest is only able to reproduce the brightness temperature increase caused by large bright patches very close to the limb ($\geq 80°$).

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2.2. Coronal Holes

Using the SSC models as a starting point, the presence of coronal holes was simulated by reducing the coronal temperature and density (electron and ions) distributions, above 3650 km, in which the original values were multiplied by constant values, $N_T$, and $N_{Ne}$. Figure 3 shows (a) temperature and (b) electron density profiles for the quiet Sun (black curves), coronal holes (red curves), and bright patches (blue curves; see Section 2.3).

The temperature reduction in the coronal hole was set as $N_T = 0.5$, whereas the densities were reduced by a factor of $N_{Ne} = 0.5$. These settings resulted in temperatures and densities of $0.49 \times 10^6$ K and $1.93 \times 10^6$ cm$^{-3}$ at 10 Mm above the surface, while, at 40 Mm the values were $0.71 \times 10^6$ K and $0.79 \times 10^6$ cm$^{-3}$. The upper atmosphere temperature and density are compatible with plume regions reported by Wilhelm (2006). The simulation of a coronal hole located at $65°$ of latitude with the characteristics above present a reduction in the 17 GHz limb brightening (21%) when compared with the standard SSC simulation without spicules (36%), this comparison is shown in Figure 4(a). If the inter-plume temperature and density, observed by Wilhelm (2006), were adopted ($N_T = 0.8$ and $N_{Ne} = 0.1$), the limb brightening was reduced to 16%. All simulations in this work were convolved with a 10'' Gaussian beam, which represents the NoRH best spatial resolution.

Similar to the procedure used in previous works (Selhorst et al. 2005a, 2005b) to estimate the contribution of spicules in coronal holes, they were randomly distributed in the temperature and density matrices covering about 10% of the solar surface. Except for the width, which was fixed at 500 km, all spicules’ physical parameters were randomly chosen, with temperatures ranging from 7000 to 13,000 K, densities in the interval of $2 - 6 \times 10^{10}$, heights from 5000 to 7000 km and inclination angles from $30°$ to $150°$. These parameters are consistent with the values inferred from observations of optical lines, mainly Hα and Ca II (Sterling 2000; Tsiropoula et al. 2012).

The brightness temperature was calculated every 100 km, instead of the 700 km used in previous works. To obtain a final mean profile, $N$ simulations were performed until a convergence criterion was satisfied, that is, the rms of the 400 points of the mean profile closest to disk center should be less than...
0.0003 in comparison with the rms calculated in the previous simulation. Usually, it sufficed to perform 20–40 simulations.

As can be seen in Figure 4(b) (black curve), the presence of spicules prevents the reduction of the brightness temperature caused by the coronal hole at low latitude angles ($\leq$930° in Figure 4(b)). Moreover, the limb brightening is completely absorbed by the presence of spicules, in agreement with Selhorst et al. (2005a, 2005b). As a result, although the inclusion of spicules in a plume region produces emission at the limb 7% more intense than the quiet Sun, this brightening cannot be identified from the emission originating in their surroundings.

As has been proposed by Selhorst et al. (2005b), the intense limb brightening can be caused by the magnetized regions that inhibit the presence of spicules causing a hole in the spicule forest. Nevertheless, a polar bare region within a coronal hole cannot reproduce the high 17 GHz bright patch temperatures. The blue curve in Figure 4(b) differs from the black one by the inclusion of a polar bare region above 70° of latitude.

The simulated spicules are optically thick at 17 GHz, and their adopted density range lies around the lowest density values reported (Tsiropoula et al. 2012). This absorption is caused by the optical thickness of the spicules at 17 GHz, which, in the SSC model, is formed ($\tau$ $\sim$ 1) around a region 2900 km above the solar surface, where the local density and temperature are $9.3 \times 10^9$ cm$^{-3}$ and 10, 390 K, respectively. Since, this density is approximately half of the minimum density value adopted for the spicules, all the spicules reaching heights above 2900 km are optically thick at 17 GHz.

Moreover, observationally, spicules are not easily identified in the chromosphere, being predominantly seen when reaching above chromospheric heights (Pereira et al. 2014). Recent simulations suggest that spicules do not maintain their structure in the chromosphere, but only may become spicules once the chromospheric material flows upwards along the magnetic field strands (Martinez-Sykora et al. 2017). For these reasons, we designed our spicules model to focus on the main aspects affecting the formation/propagation of the radio emission.

2.3. Polar Bright Patches

Since the spicule-less regions below 80° of latitude are not able to reproduce the intense bright patches observed in the NoRH maps (Selhorst et al. 2005b) and the presence of coronal holes reduce the expected limb brightening at 17 GHz (Figure 4), other solar features should be acting inside the coronal holes to increase their brightness temperature at 17 GHz (Gopalswamy et al. 1999; Oliveira e Silva et al. 2016). To simulate the observed 17 GHz bright patches, we introduced small magnetic loops inside coronal hole regions (Figure 2). In these simulations, the coronal hole was set to have temperature and density distributions consistent with plume regions (red curves in Figure 3).

The simulated magnetic loops were set as half circumference, perpendicular to the solar surface, with two possible external radii of 5.0 Mm (6°9) and 7.5 Mm (10°3) and a fixed cross-section width of 2.5 Mm. Inside the magnetic loop, the temperatures and densities varied as an active region flux tube (Selhorst et al. 2008), i.e., hotter and denser than the atmosphere surrounding it. The blue curves in Figure 3 show the example of the assumed atmospheric variation in the magnetic loops, in which the chromospheric gradients of temperature and density were $\nabla T = 7.08 \text{ K km}^{-1}$ and $\nabla n_e = -4.08 \times 10^7 \text{ cm}^{-3} \text{ km}^{-1}$, respectively, the transition region was considered to be at 3000 km. Moreover, the coronal temperature and densities were considered to be twice the quiet atmospheric values.

Table 1 lists 30 bright patch simulations, with distinct plasma compositions and locations. The reference simulation numbers are placed in the first column, with different distribution of temperature ($\nabla T$ and $N_T$) and density ($\nabla n_e$ and $N_{n_e}$) in the flux tubes organized in the next four columns, followed by the magnetic loop’s size and position. The simulations outcomes are listed in the last four columns, where the first two are the maximum brightness temperature, $T_{\text{max},B}$, and the width obtained at the point in which $T_B = 0.5 T_{\text{max},B}$ obtained from the bright patch simulation without the convolution with the NoRH beam, whereas the last two represent the same values after the beam convolution. All small magnetic field loops were simulated inside the coronal hole limits. The widths were measured at half power of the maximum brightness temperature of the bright patches, after the subtraction of the coronal hole brightness temperature profile (blue curve in Figure 4(a)).

3. Results

Since most of the 17 GHz emission is generated in the chromosphere, the size of the magnetic loop determines the
position where the emission is produced. While in the smaller loops (5.0 Mm) the emission is formed at the loop top, the emission in the larger loops (7.5 Mm) comes from their footpoints, whereas their tops are optically thin. In the first six simulations presented in Table 1, the loops are placed at the center of the solar disk. These results show the brightness temperature increase due to the larger gradients of the chromospheric temperatures and densities. In these simulations, when the plasma composition inside the loop is the same, the obtained $T_{\text{max}}$ is independent of the magnetic loop size before the beam convolution, as expected. Nevertheless, smaller loops produced a bright patch (11″/3) larger than the larger loops (7″/9). This is easily explained by the different sizes of their emitting areas: while for the smaller loops the loop top is bright, for the larger loops only the footpoints are brighter than the surroundings. This can be visualized in Figure 5, which shows the results of simulations using (a) 5.0 Mm and (b) 7.5 Mm loops. The dotted lines are the unconvolved results with 100 km spatial resolution and the continuous lines are the result of the convolution with the NoRH beam (∼10″). Because the emitting area of the footpoint is smaller than the NoRH resolution, after the beam convolution, $T_{\text{max}}$ reduces more significantly in the brighter loop (Figure 5(b)). Moreover, the convolved brightness temperature profile still presents a double peak with ∼21″ width, i.e., more than 10″ increase in width. On the other hand, the small loop (Figure 5(a)) shows a smaller reduction in $T_{\text{max}}$, a single peaked profile and less than 2″ increase in its width.

Due to projection effects and the curvature of the Sun, the size of the emitting magnetic loops is strongly reduced when they are simulated at high latitudes. The unconvolved width of the hotter small loops was reduced from ∼11″ at disk center to ∼1″ when they were placed at 81°4 (Sim. 3 and 25 in Table 1). After the convolution, the resulting bright patches mimic the beam size (∼10″). With respect to their brightness temperatures, $T_{\text{max}}$ is seen to increase with the angular position in the unconvolved values; however, due to the reduction in the emitting source size, the convolved values follows in the opposite way, reducing the $T_{\text{max}}$ values.

The profile of simulations 7–30 from Table 1 are plotted in Figures 6(a)–(d). The continuous lines refer to the small magnetic loops and the dotted ones represent the larger loops, for the same plasma configuration (temperature and electron density) the same color is used. The emission from loops located at 71°1 and 74°1 can be identified apart from the limb brightening (Figures 6(a) and (b)). However, those located at 77°4 and 81°4 cannot be distinguished from the usual limb brightening (Figures 6(c) and (d)).

| $\nabla T$ (K km$^{-1}$) | $N_T$ | $\nabla n_e$ (cm$^{-3}$ km$^{-1}$) | $n_e$ (cm$^{-3}$) | Loop Radius (Mm) | Loop Position (°) | Bright Patch Results |
|-------------------------|-------|------------------------------|-----------------|------------------|-------------------|---------------------|
|                         |       | $T_{\text{max}}$ ($\times 10^3$ K) | Width (°) | $T_{\text{max}}$ ($\times 10^3$ K) | Width (°) |
| 1 3.04 1.2 $-5.14 \times 10^2$ 1.2 0 12.2 (T) 11.3 11.8 (T) 13.1 |
| 2 4.56 1.5 $-5.01 \times 10^2$ 1.5 0 15.1 (T) 11.3 14.2 (T) 13.0 |
| 3 7.08 2.0 $-4.80 \times 10^2$ 2.0 0 20.0 (T) 11.3 18.3 (T) 13.0 |
| 4 3.04 1.2 $-5.14 \times 10^2$ 1.2 12.2 (F) 7.9 11.0 (T) 20.7 |
| 5 4.56 1.5 $-5.01 \times 10^2$ 1.5 15.1 (F) 7.9 12.1 (T) 20.7 |
| 6 7.08 2.0 $-4.80 \times 10^2$ 2.0 20.0 (F) 7.7 13.9 (T) 21.2 |
| 7 3.04 1.2 $-5.14 \times 10^2$ 1.2 13.3 (T) 3.2 11.9 (T) 9.9 |
| 8 4.56 1.5 $-5.01 \times 10^2$ 1.5 16.6 (T) 3.2 12.9 (T) 9.9 |
| 9 7.08 2.0 $-4.80 \times 10^2$ 2.0 22.5 (T) 3.2 14.6 (T) 9.9 |
| 10 3.04 1.2 $-5.14 \times 10^2$ 1.2 7.5 13.3 (F) 1.9 11.6 (T) 11.7 |
| 11 4.56 1.5 $-5.01 \times 10^2$ 1.5 7.5 16.6 (F) 1.8 12.2 (T) 11.7 |
| 12 7.08 2.0 $-4.80 \times 10^2$ 2.0 7.5 22.5 (F) 1.9 13.2 (T) 11.6 |
| 13 3.04 1.2 $-5.14 \times 10^2$ 1.2 7.5 13.8 (T) 2.5 12.6 (T) 9.8 |
| 14 4.56 1.5 $-5.01 \times 10^2$ 1.5 7.5 16.9 (T) 2.6 12.8 (T) 9.8 |
| 15 7.08 2.0 $-4.80 \times 10^2$ 2.0 5.0 22.8 (T) 2.6 14.3 (T) 9.8 |
| 16 3.04 1.2 $-5.14 \times 10^2$ 1.2 7.5 13.4 (F) 1.4 12.6 (F) 11.0 |
| 17 4.56 1.5 $-5.01 \times 10^2$ 1.5 7.5 16.9 (F) 1.4 12.6 (F) 11.0 |
| 18 7.08 2.0 $-4.80 \times 10^2$ 2.0 7.5 22.2 (F) 1.4 13.1 (T) 11.0 |
| 19 3.04 1.2 $-5.14 \times 10^2$ 1.2 5.0 14.1 (T) 1.8 12.6 (T) 9.8 |
| 20 4.56 1.5 $-5.01 \times 10^2$ 1.5 5.0 17.7 (T) 1.8 12.9 (T) 9.7 |
| 21 7.08 2.0 $-4.80 \times 10^2$ 2.0 5.0 23.8 (T) 1.8 14.1 (T) 9.8 |
| 22 3.04 1.2 $-5.14 \times 10^2$ 1.2 7.5 14.2 (F) 0.8 12.6 (F) 10.5 |
| 23 4.56 1.5 $-5.01 \times 10^2$ 1.5 7.5 17.8 (F) 0.7 12.6 (F) 10.5 |
| 24 7.08 2.0 $-4.80 \times 10^2$ 2.0 7.5 23.9 (F) 0.7 13.1 (T) 10.6 |
| 25 3.04 1.2 $-5.14 \times 10^2$ 1.2 5.0 21.5 (T) 1.0 12.9 (T) 9.8 |
| 26 4.56 1.5 $-5.01 \times 10^2$ 1.5 5.0 21.5 (T) 1.1 13.2 (T) 9.8 |
| 27 7.08 2.0 $-4.80 \times 10^2$ 2.0 5.0 25.3 (T) 1.1 14.0 (T) 9.7 |
| 28 3.04 1.2 $-5.14 \times 10^2$ 1.2 7.5 21.5 (F) 0.4 12.6 (F) 9.9 |
| 29 4.56 1.5 $-5.01 \times 10^2$ 1.5 7.5 21.5 (F) 0.3 12.8 (F) 10.5 |
| 30 7.08 2.0 $-4.80 \times 10^2$ 2.0 7.5 23.4 (F) 1.3 13.2 (T) 10.3 |
shown in the figure, for the unconvolved results with 100 km resolution, the $T_B$ increase caused by each loop can be easily resolved. Here, $T_{B_{\text{max}}}$ in both simulations is the same as that of simulation 27; however, the width increased to $\sim 19''$ and $21''$ in the profiles plotted in Figures 6(e) and (f), respectively.

4. Discussion and Conclusions

The purpose of this work is to model the emission of the 17 GHz polar bright patches, which are frequently observed in the NoRH maps in association with coronal holes (Gopalswamy et al. 1999; Selhorst et al. 2003; Oliveira e Silva et al. 2016). The simulations were based on the temperature and density distributions proposed in the SSC atmospheric model (Selhorst et al. 2005a), with modifications to include a coronal hole atmospheric model and magnetic loops as the sources of the radio-bright patches.

We have calculated the radio emission at 17 GHz from coronal holes, in comparison with typical quiet-Sun regions. As expected, in a static atmosphere, the lower temperature and density (red profiles in Figure 3) inside a coronal hole resulted in lower brightness temperature values (Figure 4(a)). Our results show, however, that the presence of (spatially unresolved) spicules can produce brighter regions than what would be expected from coronal holes (Figure 4(b)).

To simulate the bright patches, we have introduced small magnetic loops, with hotter and denser plasma than its surroundings. We find that the radio emission from smaller loops (5.0 Mm of radius) comes from the top of the loop, while...
the emission from larger loops (7.5 Mm of radius) originates from the footpoints. As a consequence, the size of the simulated bright patches originating from small loops was larger than from larger loops, \( \sim 1'' \) and \( \sim 8'' \), respectively. However, after convolving the results with NoRH beam, a large loop produced broader and colder bright patches in comparison with the results obtained for the small loops.

The inclusion of magnetic loops in the model only affects the radio brightness at 17 GHz if their temperature and density properties are substantially different from the surrounding plasma at heights where \( \tau \approx 1 \), which happens near the upper chromosphere and lower corona. These results are in agreement with the findings of Brajša et al. (2007). Moreover, loop models with increased density and temperature only at coronal heights do not contribute significantly to the radio emission at 17 GHz. Such loops could be brighter at EUV wavelengths, and thus this could explain the absence of a one-to-one correlation between the 17 GHz bright patches and those observed in EUV (Nindos et al. 1999; Riehokainen et al. 2001; Nitta et al. 2014).

The maximum brightness temperature \( T_{\text{max}} \) in the simulations increased up to 30\% by placing the loops at higher latitudes; however, the sizes of these bright regions were reduced to 1'' much smaller than the NoRH beam. As a consequence, after the beam convolution, the size of the bright patch corresponds to the beam size (as expected), in agreement with the minimum size of the bright patches observed in the NoRH maps (Nindos et al. 1999).

On the other hand, a single small loop located near the pole is not able to reproduce the larger bright patch sizes observed (50''–55''), Nindos et al. (1999), which could be caused by the presence of a great number of small magnetic loops unresolved by the NoRH beam. As showed in Figures 6(e) and (f), even loops separated by an angular distance of 3'' (\( \sim 37 \) Mm) will not be resolved in the NoRH maps. Moreover, the presence of small magnetic loops close to the limb can result in a merged brightness limb profile, increasing the observed limb brightening temperature and width.

To improve our knowledge about these small bright structures inside the coronal holes, high resolution observations at different wavelengths are necessary. Today, only solar observations with ALMA can achieve these spatial resolutions (Wedemeyer et al. 2016).

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