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How are the EUV and radio polar limb-brightenings correlated?

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ABSTRACT

Aims. We correlate the polar limb brightening time evolution observed with pass-band filters centered at the EUV 17.1 nm (Fe IX,X) and 30.4 nm (He II) lines with radio continuum images obtained at 17 GHz (~1.76 cm) during solar cycle 23.
Methods. We determine the limb brightening in units of the quiet Sun from daily maps at 17.1 and 30.4 nm obtained by the Extreme Ultraviolet Imager (EIT) aboard the SOHO satellite between 1997 and 2007. The limb brightness at 17 GHz is obtained from daily maps taken by the Nobeyama Radioheliograph (NoRH) since 1992.
Results. The variation in the limb brightening observed at coronal heights (17.1 nm) is correlated positively with the 11 year cycle. However, the observation at chromospheric/transition region heights (17 GHz / 30.4 nm) shows a clear negative correlation with the solar cycle.
Conclusions. The limb brightening measurements at 17.1 nm reproduce the emission measure clearly in the solar corona during a solar cycle in which coronal holes are constantly present at the poles during the minimum. On the other hand, the negative correlation of the polar brightening at 17 GHz and 30.4 nm with the solar cycle are shown to depend upon polar features in the lower atmosphere (chromosphere/transition region). Moreover, the polar brightening variation at these frequencies is similar to that of the photospheric faculae observed at the poles.

Key words. Sun: general – Sun: chromosphere – Sun: corona

1. Introduction

Multi-wavelength solar observations provide an excellent tool for understanding the solar atmosphere complexity, since each frequency originates in different atmospheric heights with distinct temperature and particle densities. Taking the solar poles as an example, we observe faculae in white light, radio bright points at 17 GHz and plumes, bright points, and coronal holes at EUV wavelengths.

The relationship between these solar features is still not clearly understood. Shibasaki (1998) studied the variation in the limb brightening observed at 17 GHz microwave continuum based on north-south scans and concludes that the brightness has a gradual increase above 50° of latitude in both hemispheres. The author attributes this temperature increase to polar structures, observed as bright patches at the poles (see Fig. 1). No correlation was observed between the polar cap brightening and the coronal holes observed in soft X-ray images.

Polar faculae and spicules have often been invoked as favoring or inhibiting the limb brightening. We summarize some of these works below:

– Gelfreikh et al. (2002) and Riehokainen et al. (2001) find that bright patches observed at 17, 37, and 87 GHz mimic the region of polar faculae occurrence.
– The time evolution of limb brightening is anti-correlated with respect to the sunspot number (Efanov et al. 1980; Selhorst et al. 2003); however, it agrees with the facular cycle (Sheeley 1964; Makarov & Makarova 1996).

– This decrease in the limb brightening has been widely ascribed to spicules at radio wavelengths (Fürst et al. 1974; Kanno & Tanaka 1975; Simon & Zirin 1969; Wannier et al. 1983), as well as at EUV lines (Nishikawa & Kanno 1979; Withbroe & Mariska 1976).
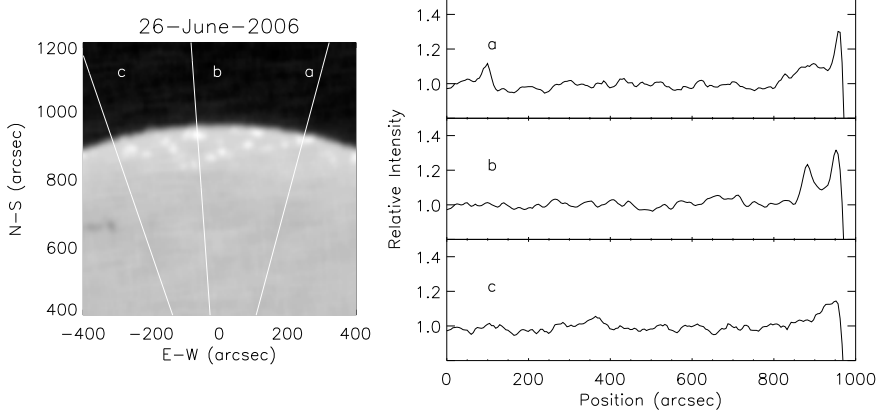
Selhorst et al. (2005a) show that spicules may reduce the intensity of the limb brightening at 17 GHz by absorbing part of the emission. Since faculae may inhibit the presence of spicules in polar regions, the limb brightening in a delimited region may be observed as a bright patch in the radio maps (Selhorst et al. 2005b).

Similar features to the 17 GHz bright patches are observed at EUV lines, but, no one to one correlation has been found (Nindos et al. 1999; Riehokainen et al. 2001). In this work, we try a different approach to study the correlation between these features and analyze the temporal variation in the mean polar limb brightening at 17 GHz and EUV lines (30.4 and 17.1 nm). These wavelengths are formed at distinct heights of the solar atmosphere, and their time evolution comparison gives us clues about the atmospheric structure.

2. Observations and results

In operation since 1992, the Nobeyama Radioheliograph (NoRH, Nakajima et al. 1994) is a dedicated solar interferometer, which obtains synthesized maps of the Sun at the microwave continuum frequencies of 17 GHz (1.76 cm) and, after 1996, 34 GHz (0.88 cm). Both frequencies have an optical depth of
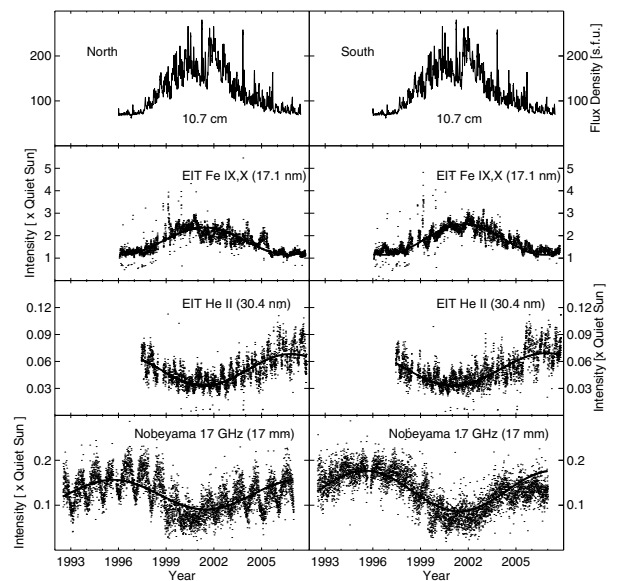
Fig. 1. *Left*: north Pole observed at 17 GHz during the solar minimum showing bright patches. The white lines represent scans in the map. Three scans were selected to show the importance of the bright patches in the limb brightening. *Right* **a)** a radial scan with one limb bright patch yields a maximum profile of around 30% above the quiet Sun; **b)** a radial profile along two polar bright patches results in a double peaked profile, and **c)** a radial scan with no bright patch has a profile with a maximum limb brightening of around 15%.
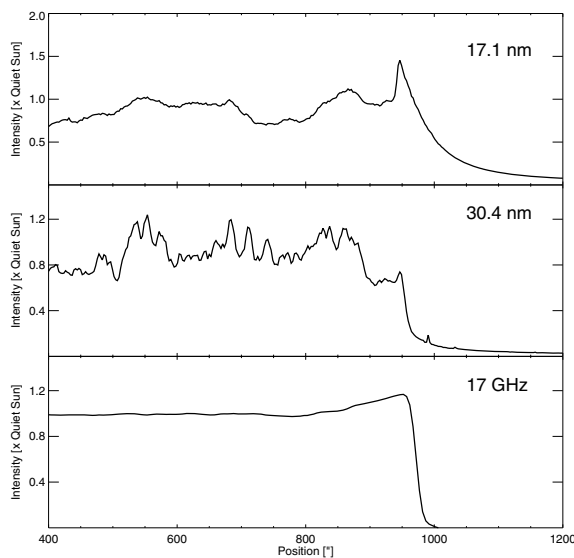
Fig. 2. Comparison between the mean profiles at the three wavelengths studied in this work.

Fig. 3. *From top to bottom*, the time evolution of the solar cycle, represented by the flux at 10.7 cm, the polar limb brightening intensity at the EUV 17.1 nm and 30.4 nm spectral lines and the 17 GHz microwave continuum. The points represent individual measurements and the thick lines represent the 11 years period found for each time series. North pole measurements are shown in the left column, while the South pole is in the right.

$\tau = 1$ in the chromosphere, although the limb is better delimited at 17 GHz. Despite its presence around the solar disk, the limb brightening is more intense at the poles, a phenomenon attributed to the bright structures near the poles (Shibasaki 1998). Here, we extend the study of the polar limb brightening time variation at 17 GHz presented in Selhorst et al. (2003) to cover a complete solar cycle. The polar limb intensity is measured by averaging 60 scans within ±30° around the solar poles (for details see Selhorst et al. 2003). Figure 1 shows the bright patches at the north pole and 3 distinct intensity profiles crossing regions with bright points (a and b) and without their presence (c). While the profiles crossing bright patches presented maxima limb brightening above 30%, the maximum intensity in the profile c was lower than 15%.

The SOlar and Heliospheric Observatory (SOHO) was launched in 1996 and is composed of 12 instruments, which allows study of the Sun structure from its interior toward the upper corona. The EIT obtains EUV images of the Sun with passband filters centered on four wavelengths (Moses et al. 1997). We chose two different frequencies for our analysis: the He II Ly α (30.4 nm) is an emission line formed in the upper chromosphere/TR with a formation temperature ranging from 6 to 8×10^4 K. The coronal lithium–like Fe IX,X (17.1 nm) is formed

in a region with temperatures $T \sim 10^6$ K. Both, 17.1 and 30.4 nm images show a limb brightening due to the positive gradient of temperature in the transition region/corona. To determine the limb brightening, radial profiles are extracted every half a degree in the same polar region as analyzed in 17 GHz, i.e. ±30° of the solar poles. The limb brightening intensity of each profile is fitted to a cusp function at 17.1 nm and an arctangent function for the 30.4 nm profiles. For a detailed description, see Giménez de Castro et al. (2007). Figure 2 shows a comparison between the mean profiles observed at 17 GHz, 30.4 nm, and 17.1 nm.

The top of Fig. 3 presents the time evolution of the solar cycle represented by daily means of the total flux at the 2.8 GHz (10.7 cm) microwave continuum. It presents the 17.1 nm coronal, 30.4 nm chromospheric/TR, and 17 GHz chromospheric polar daily limb intensities. Observed short time variations are the subject of a separate paper, but here we concentrate on the 11 year period. Positive correlation between the solar cycle and the coronal limb brightening, and negative correlation between solar

Table 1. Summary of the cross-correlations.

Frequency	Pole	Cross-correlation
17 GHz	North	−0.75
17 GHz	South	−0.90
30.4 nm	North	−0.77
30.4 nm	South	−0.77
17.1 nm	North	0.83
17.1 nm	South	0.91

cycle and the chromospheric/TR limb brightenings are clearly seen here. We removed the shortest scale variations by taking running means of 180 days and calculating the cross-correlation between the different limb intensities. Table 1 shows the cross-correlation between the solar activity represented by the continuum daily mean density flux at 2.8 GHz, and the intensity of the limb brightening at the frequencies analyzed in this work to quantify the observed trends in Fig. 3. As another approach, we used a Bayesian spectrum analysis (Loredo 1990, and references therein) to obtain the main components of the limb brightening time series. The Bayesian analysis clearly shows the 11 year cycle in the EUV lines, as well as in the 17 GHz maps.

3. Discussion and conclusions

Besides not having sunspots or active regions, the solar poles are far from being a quiet area. We studied the variation in the polar limb brightening intensities during the solar cycle at three distinct wavelengths, which are formed at different heights in the solar atmosphere. Our results may be summarized as:

– We confirm the negative correlation between the 17 GHz continuum limb brightening and the solar cycle already proposed by Selhorst et al. (2003) using a time series shorter than 11 years.
– The 30.4 nm emission, formed in a range of temperatures compatible with the transition region, also presents a polar limb brightening negatively correlated with the solar cycle.
– The coronal emission (17.1 nm) shows a positive correlation between limb brightening intensity and the solar cycle.

The positive correlation we find between polar limb brightening in a coronal line (Fe IX,X) and the solar activity cycle is understandable because the emission measure of optically thin coronal lines is decreased in the polar coronal holes known to be present around activity minima.

On other hand, the 17 GHz and 30.4 nm emissions are formed below the corona and are affected by dynamic chromosphere features, which increase the difficulty of interpreting the anti-correlation between them and the solar cycle found here. Increased limb brightness in these radiations around activity minima might arise directly from the 30.4 nm and 17 GHz polar bright points reported to mimic the region in which the white-light polar faculae are observed (Gelfreikh et al. 2002; Nindos et al. 1999; Riehokainen et al. 2001). However, this interpretation is not unique because the radiation from spicules might mask the contribution of the bright points in both wavelengths (Horne et al. 1981; Fürst et al. 1974; Selhorst et al. 2005b).

Figure 4 presents some of the features acting in the polar region, which may change the intensity of the limb brightening. Recent observations show that the position polar faculae coincide with intense magnetic patches that can reach kG intensities
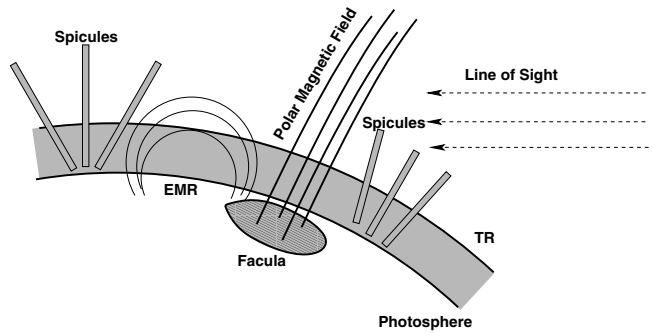
Fig. 4. Some features present in polar regions, related to the emission at microwave continuum and EUV.

(Okunev & Kneer 2004; Tsuneta et al. 2008) and that may be associated to small scale magnetic regions called ephemeral magnetic regions (Liu 2008) emerging around them. Both features prevent the presence of spicules and could be responsible for the bright patches observed at 17 GHz and 30.4 nm. However, a clear distinction between these contributions require high-resolution maps in all frequencies, which is not possible at the present time.

As a final remark, the polar limb brightening variation at the three wavelengths analyzed here can be considered as manifestations, in different ways, of polar features related to the magnetic field variation along the solar cycle. While the 17.1 nm emission is dominated by the coronal holes, the 17 GHz and 30.4 nm limb brightening time variation reflects the changes caused by polar structures in the lower atmosphere.

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