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Limb Prominences Seen in UV, EUV and SXR

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Abstract. We use SOHO/SUMER, EIT and Yohkoh/SXT prominence observations to study the absorption and/or volume blocking of UV, EUV and SXR coronal radiation by cool prominence plasma. An example of such a complex behaviour is the limb prominence observed on 5 September 1996. The SUMER spectrograph has detected two coronal lines, MgX at 625 Å which is absorbed by the hydrogen Lyman continuum and blocked within a volume occupied by cool prominence plasma, and FeXII at 1242 Å where the prominence appears dark due to blocking (no absorption at this wavelength). A similar behaviour show also the EUV images taken by EIT. We find that a darkening similar to that detected in the FeXII line is quite well visible also in the SXR images obtained by Yohkoh/SXT. To explain this feature, we exclude the absorption by the HeI and HeII resonance continua (hydrogen absorption is quite negligible) and suggest that it is entirely due to the volume blocking. Based on a quantitative analysis of these data, we discuss the physical conditions in cool prominences and their coronal environment. Finally, we propose new high-resolution EUV and SXR observations of prominences by Solar-B, using the EUV imaging spectrometer (EIS) and the X-ray telescope (XRT), respectively.

1. Introduction

Solar prominences are usually observed on the limb in the hydrogen Hα line or in some other optical emission lines. This emission arises mainly from the scattering of the incident solar radiation by the central cooler parts of prominences. The region between these cool parts and the surrounding corona is called the prominence-corona transition region, in which other emission lines formed at higher temperatures arise. These lines are typically detected in UV or EUV parts of the spectrum. However, the limb prominences can be also observed in hot lines emitted in the corona by highly ionised elements like MgX or FeXII. We frequently observe (SOHO, TRACE) dark features in some UV or EUV coronal lines at positions where prominences appear in emission in optical or transition-region lines. This was recently studied by Kucera et al. (1998) who demonstrated that the coronal lines having a wavelength below the hydrogen Lyman-continuum head at 912 Å are weaker at the prominence location compared to the surrounding corona (see also Schmieder et al. 1999 and Engvold et al. 2001). In this paper we analyse such darkenings for a prominence observed by SOHO and Yohkoh on 5 September 1996.

2. Mechanisms of Lowering the Coronal Brightness in UV and EUV Lines

The brightness lowering of coronal lines at the location of a limb prominence is due to the Lyman-continuum absorption of the coronal line radiation by prominence cool structures in which this resonance continuum has sufficient opacity. This opacity is proportional to the photoionisation cross-section for Lyman continuum multiplied by the hydrogen ground-state density. This absorption decreases with the decreasing wavelength as λ^3. For shorter wavelengths, below 504 Å and 228 Å, additional absorption takes place due to the resonance continua of neutral (HeI) and ionised (HeII) helium, respectively. Then the total optical thickness of the prominence will be

$$\tau = \sigma_H N_{HI} + \sigma_{HeI} N_{HeI} + \sigma_{HeII} N_{HeII} \,, \qquad (1)$$

where N_{HI} is the column density of neutral hydrogen, and N_{HeI} and N_{HeII} are those of neutral and singly ionised helium, respectively. While the wavelength-dependent photoionisation cross-sections are well known (given analytically or tabulated), the column densities depend on the ionisation degree of hydrogen and helium. This in turn is a rather complicated function of the prominence thermodynamic conditions and the irradiation by the solar atmosphere. A detailed discussion can be found in Anzer and Heinzel (2005).

The second mechanism which can lead to a brightness depression at the prominence position on the limb is called here *volume blocking* (see Anzer and Heinzel 2005), although this term can be somewhat misleading. The volume occupied by the cool prominence plasma or a cavity around the prominence does not emit in coronal lines which are formed at much higher temperatures and this leads to the lowering of the coronal brightness at the prominence location, relative to surrounding quiet corona. We had in mind that such cool plasmas 'block' a certain volume in the corona which could otherwise emit radiation in hot coronal lines. This volume blocking is also discussed in detail by Anzer and Heinzel (2005), who give the formula for a depression due to the combined effects of absorption (photoionisation) and volume blocking, i.e.

$$r = \frac{1}{2}(1 + e^{-\tau}) r_b \,, \qquad (2)$$

where r is the contrast (i.e. the intensity at the prominence location relative to the background corona) and r_b is that due to volume blocking. For example, in the case of negligible blocking (the prominence extension along the line of sight is small) and large τ the contrast approaches 1/2. This means that only half of the line-of-sight coronal radiation, in front of the prominence, is detected, the other half behind the prominence is fully absorbed. On the other hand, in the

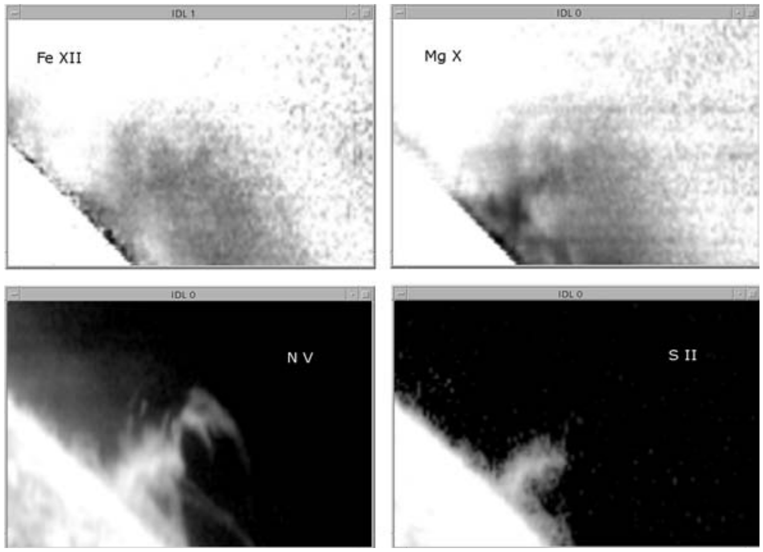

Figure 1. SOHO/SUMER images of the 5 September 1996 prominence. The rasters in four lines are shown. In the FeXII and MgX lines we clearly see a lowering of the coronal brightness at the location of the prominnece.

case of weak absorption when τ goes to zero the contrast is only due to volume blocking.

3. SOHO/SUMER Observations of Prominences in Transition-Region and Coronal Lines

The limb prominence observed on September 5, 1996 is shown in Figure 1 in four SUMER rasters which correspond to four lines. SII (1250 Å) and NV (1238 Å) are lower-temperature transition-region lines and the prominence appears bright on dark coronal background. On the other hand, in the two coronal lines MgX (624 Å) and FeXII (1242 Å) the prominence is dark relative to the bright corona. Similar examples can be found in the SUMER Atlas published by ESA as its special volume SP-1274 (see Feldman et al. 2003).

The mechanisms described in the previous section are well demonstrated in Figure 2. The MgX line shows a very dark feature similar in shape to the cool structure visible in the SII line. This is due to hydrogen Lyman- continuum absorption. The much more extended and less dark structure is similar in both MgX and FeXII lines. However, in FeXII we can not expect any significant absorption because this line lies above the Lyman- coninuum head. So this coronal line seems to show the importance of the volume blocking. Using Eq. (2) for these two lines, one can discriminate between the absorption and blocking quantitatively (Heinzel et al. 2006).

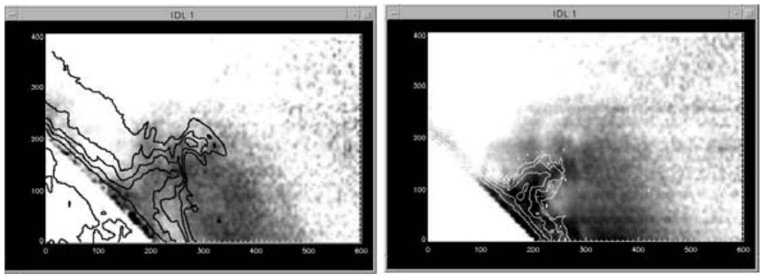

Figure 2. An overlay of the NV image (contours) over the FeXII image (left) and an overlay of the SII image (contours) over the MgX image (right).

4. SOHO/EIT Images

In Figure 3 we show the prominence under study observed by SOHO/EIT in four EIT lines: Fe IX/X 171 Å, FeXII 195 Å, FeXV 284 Å and HeII 304 Å. In the latter line the prominence appears bright. Although this HeII line is supposed to be formed at temperatures around 80 000 K (Delaboudiniére et al. 1994), its actual brightness is dominated by the resonance scattering of the chromospheric radiation in much cooler parts of the prominence (see Labrosse and Gouttebroze 2001, 2004). In other EIT lines the structure corresponding to HeII 304 emission is not visible, only a rather extensive brightness depression is well seen. We will show below that this corresponds to a low opacity at these wavelengths and the brightness depression is mainly due to the volume-blocking as in the case of the FeXII line at 1242 Å detected by SUMER.

5. Dark Structures in Soft X-Rays

In soft X-rays (SXR), a brightness depression in the corona was noticed by Batchelor and Schmahl (1994), who show several examples of coronal SXR darkenings detected by the soft X-ray telescope (SXT) onboard Yohkoh. Although these examples are not very convincing (the SXR corona is very inhomogeneous anyway), the dark features were interpreted as due to the continuum absorption in the X-ray region. Below we will check this possibility.

The region around our 5 September 1996 prominence was also observed by Yohkoh/SXT and thus we are able to compare the SXR features with the abovementioned UV and EUV structures seen by SOHO. In Figure 4 we show again the SOHO/EIT image in the HeII 304 Å line (left), which can be compared with an SXT image (right) taken in the Al.1 filter more than one hour later. We see clearly an extended dark feature, but it resembles more the brightness depression seen previously in hot EIT coronal lines, rather than narrower 'cool' structure. To demonstrate this better, we show in Figure 5 the SXT image overlaid by contours which correspond to EIT 304 line (left) and EIT 195 line (right).

The question now arises whether the dark SXR structure indeed results from an absorption of the background coronal radiation. Our answer is NO and we support it by quantitative estimates based on our multi- wavelength observations.

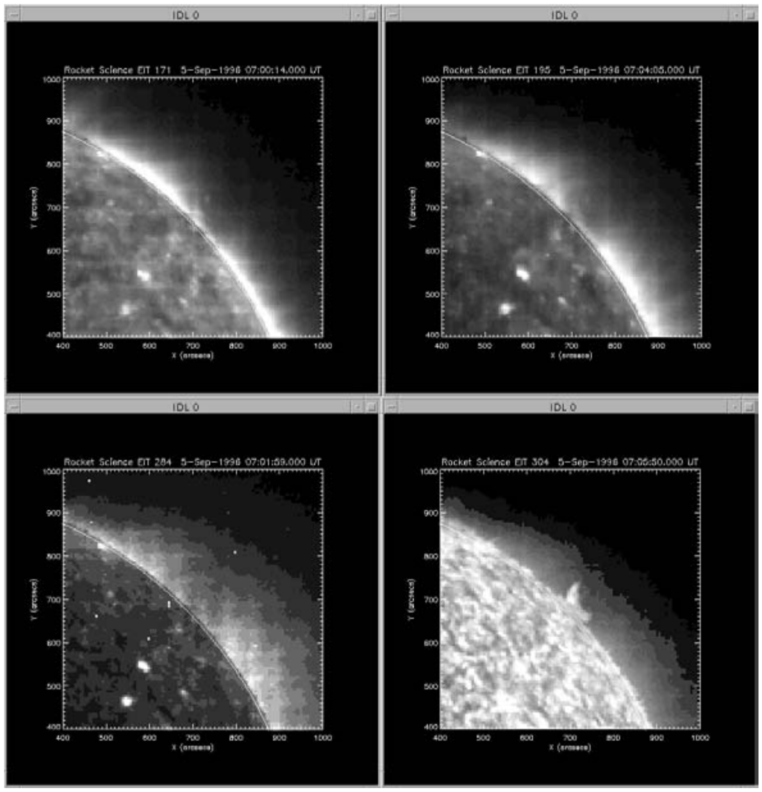

Figure 3. The prominence under study observed by SOHO/EIT in 171 Å (upper left), 195 Å (upper right), 284 Å (lower left) and 304 Å (lower right).

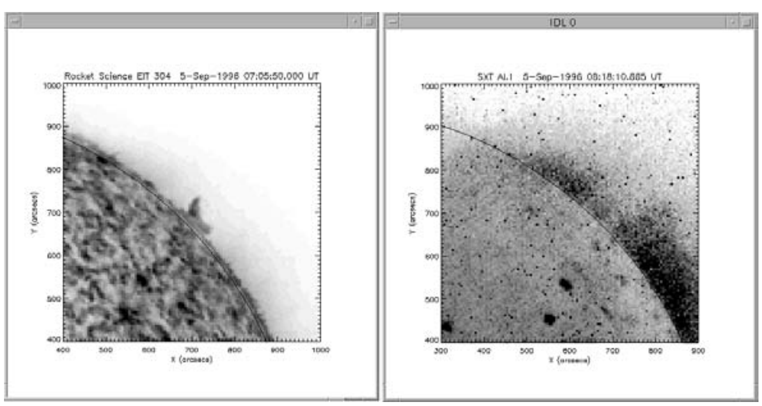

Figure 4. SOHO/EIT image of the prominence in 304 Å (left) and the Yohkoh/SXT image of the same region (both images here are negatives).

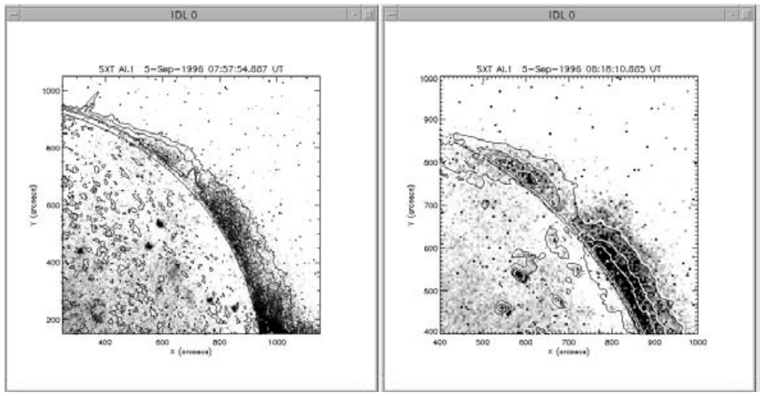

Figure 5. SOHO/EIT image in 304 Å (left) and 195 Å (right) overlaid as contours over the Yohkoh/SXT image. The structure in the middle seen in 304 Å fits well into the SXR emission gap.

6. Absorption in EUV and SXR Wavebands

Using Eq. (1) and assuming the hydrogen ionisation degree to be 0.5, we have estimated the ratio $x = \tau/\tau_{912}$ at the wavelength positions of SUMER and EIT lines and at three SXR wavelengths. The results are summarised in Table 1. To derive the actual optical thickness at a central location of the dark prominence as seen in the MgX image, we measured the contrasts r and r_b from the MgX and FeXII images, respectively. We get $r = r(\mathrm{MgX}){=}0.39$ and $r_b = r(\mathrm{FeXII}){=}0.73$. Assuming no absorption in the FeXII line and rewriting Eq. (2) to $\tau = -\ln(2r/r_b - 1)$, we obtained for the optical thickness of the hydrogen Lyman continuum at the position of the MgX line (625 Å) the value 2.7 . The values corresponding to other wavelengths of interest are given in Table 1.

From results of these calculations we see that the absorption by the hydrogen Lyman continuum is considerable and thus reduces the MgX line contrast as compared to that which results from pure volume blocking (FeXII line). However, at shorter wavelengths the opacity is much lower, even when we consider the cobtribution from HeI and HeII resonance continua. At 171 Å τ=0.27 which leads to a contrast $r = 0.64$, almost equal to r_b. This explains the fact that the central part of the prominence is barely visible in EIT coronal lines. In X-rays around 50 Å, where SXT observed our prominence, τ is quite negligible and we thus see only an extended dark structure similar to that visible in FeXII. This SXR darkening can thus be explained only by the volume blocking.

7. Conclusions

In this paper we have studied the absorption and volume blocking of coronal line emissions by relatively cool prominence structures and their environments seen on the limb. Using the SOHO/SUMER images, we have demonstrated the importance of the hydrogen Lyman-continuum absorption for the MgX line, while the FeXII line emissivity is lowered entirely due to the volume blocking

Table 1. Theoretical ratio $x = \tau/\tau_{912}$ and the optical thickness τ derived for a central dark part of the 5 Sept 1996 prominence

λ [Å]	912	625	284	171	100	50	10
x	1.0	0.4	0.1	$4\ 10^{-2}$	$7\ 10^{-3}$	$9\ 10^{-4}$	$7\ 10^{-6}$
τ	6.8	2.7		0.27		$6\ 10^{-3}$	

- this line has the wavelength above the Lyman-continuum head. Furthermore, we have shown that a lack of clear visibility of central prominence parts in SOHO/EIT coronal lines is due to low opacity of the hydrogen continuum and even of the helium resonance continua. In these lines, the dominant mechanism of the prominence darkening is the volume blocking due to a large prominence structure surrounding the central parts. Finally, using the Yohkoh/SXT images taken around 50 Å, we have demostrated that the observed darkening, spatially aligned with that seen in UV and EUV lines by SOHO, is entirely due to the volume blocking and that the absorption by hydrogen and helium is quite negligible at these X-ray wavelengths. The SXR absorption could be more efficient for higher column masses (like in the chromosphere, see Berlicki and Heinzel 2004), but in the case of prominences the density seems to be too low.

Combinations of UV lines (above 912 Å) and EUV lines plus SXR continua (below 912 Å) observed by SOHO (SUMER, CDS, EIT), TRACE and Yohkok/SXT provide us with a diagnostics tool for disentangling the absorption and volume-blocking mechanisms and the determination of the column densities of HI, HeI and HeII. This then leads to our better understanding of the behaviour of cool plasmas embedded in the hot coronal environment. A similar diagnostics will also be possible with Solar-B, namely with its EUV-imager (EIS) in combination with the X-ray telescope (XRT). Especially XRT will have better spatial resolution compared to SXT on Yohkoh and thus will allow us to study in greater detail the prominence-related darkenings on the limb.

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