PROMINENCE VISIBILITY IN HINODE/XRT IMAGES

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ABSTRACT

In this paper we study the soft X-ray ( SXR) signatures of one particular prominence. The X-ray observations used here were made by the Hinode/X-Ray Telescope instrument using two different filters. Both of them have a pronounced peak of the response function around 10 Å. One of them has a secondary smaller peak around 170 Å, which leads to a contamination of SXR images. The observed darkening in both of these filters has a very large vertical extension. The position and shape of the darkening correspond nicely with the prominence structure seen in SDO/AIA images. First, we have investigated the possibility that the darkening is caused by X-ray absorption. However, detailed calculations of the optical thickness in this spectral range show clearly that this effect is completely negligible. Therefore, the alternative is the presence of an extended region with a large emissivity deficit, which can be caused by the presence of cool prominence plasmas within an otherwise hot corona. To reproduce the observed darkening, one needs a very large extension along the line of sight of the region amounting to around \(10^9\) km. We interpret this region as the prominence spine, which is also consistent with SDO/AIA observations in EUV.

Key words: methods: observational – Sun: corona – Sun: filaments, prominences – Sun: X-rays, gamma rays – techniques: imaging spectroscopy

1. INTRODUCTION

Solar prominences observed above the limb are typically seen in emission against the dark coronal background. This is the case of monochromatic imaging in spectral lines formed at low temperatures, e.g., the hydrogen H\(\alpha\) line or transition-region spectral lines formed at temperatures of the prominence-corona transition region (PCTR). In the latter case we see bright UV or EUV prominences still against the dark corona, which is not emitting in such lines. However, at coronal temperatures, highly ionized atoms emit radiation in various lines of different species, and we thus see the bright corona extending to large altitudes. In lines that have wavelengths below the Lyman limit of the neutral hydrogen (912 Å), we can often see prominences as dark structures against such a bright coronal background. This “reversed” visibility of prominences in EUV coronal lines is mainly caused by the absorption of the background coronal radiation by cool hydrogen and helium plasma, where the neutral hydrogen (H\(_1\)), neutral helium (He\(_1\)), and singly ionized helium (He\(_\text{ii}\)) are photoionized at wavelengths below 912, 504, and 228 Å, respectively, depending on the wavelength of the coronal line under consideration. For the limb prominences, this was quantitatively studied by Kucera et al. (1998) and later by several other authors. The photoionization process is detailed in Anzer & Heinzel (2005), who also described an additional mechanism of EUV prominence darkening. The latter was initially called emissivity blocking, but in Schwartz et al. (2015) the more appropriate term emissivity deficit is introduced since the blocking may evoke the situation in which the background coronal radiation is somehow obscured by the prominence, which is actually the case of the photoionization absorption described above. Therefore, we will continue in using of the term “emissivity depression” also in this work.

Many nice examples of dark EUV prominence structures, both quiescent and eruptive, have been detected by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) EUV imager on board the Solar Dynamics Observatory (SDO) satellite, or the EUV Imager (EUVI; Wuelscher et al. 2004) instrument of the SECCHI instrument suite on board the Solar Terrestrial Relations Observatory (STEREO; Dresman et al. 2008) satellites. Similar observations were made in earlier times also by the EUV Imaging Telescope (EIT; Delaboudinière et al. 1995) on board the Solar and Heliospheric Observatory (SOHO) satellite or the Transition Region and Corona Explorer (TRACE; see http://trace.lmsal.com).

Prominences are also seen in rasters of the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on board the Hinode satellite (Kosugi et al. 2007). A natural question then arises: how far in EUV wavelengths can we detect such absorption and/or emissivity depression? This was studied by Anzer et al. (2007), who used the SOHO/EIT images of a quiescent prominence, together with soft X-ray (SXR) images obtained by the Soft X-ray Telescope (SXT; Tsuneta et al. 1991) on board the Yohkoh satellite. While in the 171 and 193 Å EIT channels the prominence was clearly visible as a dark absorbing structure, the co-aligned SXT image shows no signature of such darkening, perhaps except a weak visibility of the coronal cavity surrounding the prominence. Therefore, these authors have concluded that there is a negligible absorption at wavelengths around 50 Å, where the SXT image was taken. This was confirmed by numerical estimates performed according to Anzer & Heinzel (2005), under typical prominence conditions. Nevertheless, the emissivity depression cannot be excluded, and in fact it was used by Heinzel et al. (2008) and by Schwartz et al. (2015) for analysis of dark features on the limb where both the prominence and cavity were observed.
Going to shorter X-ray wavelengths around 10 Å, the Hinode X-Ray Telescope (XRT) has surprisingly revealed dark prominence features quite similar to those visible in EUV. It is therefore the aim of the present study to understand the nature of those SXR structures. We first consider the absorption of coronal SXR radiation by cool prominence plasmas, although this was shown to be negligible around 50 Å, where only hydrogen and helium was considered (Anzer et al. 2007). However, at the XRT X-ray wavelength range where the transmittance peaks around 10 Å, the absorption is much more complex. This was considered by various authors who demonstrated the importance of SXR absorption for heating of the solar chromosphere and chromospheric flare ribbons (Henoux & Nakagawa 1977; Hawley & Fisher 1992; Berlicki & Heinzel 2004). The absorption below 50 Å is enhanced, or even dominated, by various metals—for stellar applications see, e.g., London et al. (1981). The presence of such a kind of absorption in prominences, if any, could thus play a role in their energetics. We thus carefully compute the absorption by hydrogen, helium, and important metals under typical prominence conditions in this study. We also provide a first observational evidence of the emissivity deficit effect. The paper is organized as follows: the SXR and EUV observations of a quiescent prominence are described in the next section, and in Section 3 its visibility in SXR images taken by XRT is shown. In Section 4 and its subsections, three different mechanisms possibly leading to visibility of the prominence in XRT images are studied, and results are compared with observations. Section 5 gives the discussion and our conclusions.

2. OBSERVATIONS

A quiescent prominence at the northwest solar limb (position around 330°) was observed on 2010 June 22 by the Solar Optical Telescope (SOT; Suematsu et al. 2008) and in SXR by XRT (Golub et al. 2007), both on board the Hinode satellite, and by the SDI/AIA EUV imager. Observations of the prominence in the AIA 304, 171, and 193 Å channels are shown in Figure 1. Blue rectangles in the images mark the area that was used in calculations of the optical thickness $\tau_{93}$ of hydrogen and helium plasma by Gunár et al. (2014), which we use in this study. This optical thickness should be better denoted as $\tau_{H+He}(193\, \text{Å})$, but we will use the shorter and more simple name $\tau_{93}$ hereafter in this paper. The whole extended prominence is seen in the AIA 304 Å image, while only a narrow vertical dark feature is visible in the 193 Å channel. This thin dark structure is seen as well in the AIA 171 Å, but also extended parts of the prominence are visible in emission in this channel, which is the manifestation of a PCTR (see Parenti et al. 2012). The thin dark structure visible in EUV images from AIA can be identified with the filament spine seen edge-on on the limb using observations in the 304 Å channel made by the EUVI imager on board the STEREO-A satellite shown in Figure 2. STEREO-A was positioned at such an angle (approximately 75° from Hinode when viewed from the Sun) that the prominence was seen as a filament. The EUVI observations were made close in time to the AIA observations. On the other hand, filament barbs seen in Figure 2 are most probably extended parts of the prominence.

XRT observed the corona at the prominence location and its vicinity in SXR using two of its focal-plane analysis filters Al-mesh and Ti-poly. XRT observations were made between 13:18:13 and 17:39:31 UT with exposure times from 4.1 up to 16.4 s. The field of view of the observed images is 788 arcsec × 788 arcsec, and dimensions of one pixel are 2.06 arcsec × 2.06 arcsec. The data were processed using standard data reduction routines in SolarSoft (Freeland & Handy 1998) provided by the XRT team (Kobelski et al. 2014). Observations in the two filters made at 15:37:45 and 15:37:58 UT, respectively, are shown in Figure 3. There is a time-dependent contamination layer on the CCD (see Narukage et al. 2011, 2014) and contamination spots that appear as small dark areas in XRT observation images. Especially, the original Al-mesh image was studded with many such spots. In both images in Figure 3, spots were retouched by an interpolation to see better the darkening occurring at the prominence spine. In the Al-mesh image in the left panel of the figure, the dark radial structure (seen in the AIA 193 and 171 Å images) at the spine is clearly visible, while in Ti-poly it is much weaker. Because the response of both filters to SXR is rather similar (peaked around 10 Å), an additional darkening in the Al-mesh image is most probably caused by a secondary peak in its transmittance function—we address this effect in the present paper.

3. SOFT X-RAY VISIBILITY OF PROMINENCES

In order to investigate darkening in the SXR images in detail, we made cuts tangentially to the limb in both Al-mesh and Ti-poly images taken at 15:37:45 and 15:37:58 UT, respectively, at four different heights as shown in Figure 4. Heights above the limb at which the cuts were made were chosen so that they would not intersect any contamination spot at least at places of the prominence location and its vicinity. Three cuts were made close to each other at heights 14,500, 17,000, and 19,500 km, and the fourth one at a larger height of 31,000 km. Resulting intensity plots along cuts are shown in Figure 5. A noticeable decrease in the intensity occurs at the position of the prominence spine in the Al-mesh filter in all four cuts. In Ti-poly along the four cuts a decrease also occurs at the position of the dark prominence structure, but somewhat shallower than in the case of Al-mesh data.

There are two known mechanisms that can be responsible for the darkening: absorption of background coronal radiation by the cool prominence plasma and/or the so-called coronal emissivity deficit (formerly called volume or emissivity blocking). Although Anzer et al. (2007) already showed that there is a negligible amount of absorption in the hydrogen and helium prominence plasma at wavelengths around 50 Å (they used the Yohkoh observations), we can expect some additional opacity due to metals around 10 Å, where both XRT filters have their peaks in the X-ray domain. Moreover, the line of sight (LOS) crosses an extended volume occupied by a cool prominence plasma not emitting in SXR, which can cause lower intensities in the corona—the coronal emissivity deficit.

However, the two filters we used have quite different responses to the EUV part of the spectrum. While the Ti-poly transmittance has mainly one peak around 10 Å, the Al-mesh filter has two transmittance maxima, one also around 10 Å and the other one around 171 Å. This then means that apart from the absorption and emissivity deficit, a more pronounced darkening in Al-mesh can be explained by a contamination from the secondary EUV peak of the filter. In the following subsections we first estimate the total prominence opacity in the X-ray domain, taking into account several important metals, and then explain the darkening in Ti-poly alone. In the last
subsection we show how the Al-mesh images are affected by the secondary EUV transmittance peak.

4. MECHANISMS OF PROMINENCE SXR DARKENING

4.1. Soft X-Ray Absorption

The absorption of X-ray background coronal radiation is caused by hydrogen and helium resonance continua and by continua of some metals (the process called photoionization). The cross sections and total optical thickness at resonance continua of the hydrogen and helium mixture have been calculated by Anzer & Heinzel (2005) for cool gas located at the corona. Cross sections of neutral hydrogen and singly ionized helium at a given wavelength ($\lambda$) of the resonance continuum are proportional to $\lambda^3$,

$$\sigma_{H I}(\lambda) = \sigma_0 \sigma_{H I}(\lambda) \left(\frac{\lambda}{912}\right)^3$$

(1)

and

$$\sigma_{He II}(\lambda) = 16 \sigma_0 \sigma_{He II}(\lambda) \left(\frac{\lambda}{912}\right)^3,$$

(2)

Figure 1. Prominence observations made by the AIA instrument are shown in its three wavelength channels: 304 Å (the left upper panel), dominated by the $\text{He}^\text{n} \text{Ly}$ line; 193 Å (the right upper panel), where mainly radiation of the $\text{Fe}^{xx}$ and $\text{Fe}^{xxv}$ lines is detected; and 171 Å (the lower panel), where the $\text{Fe} \text{x}$ and $\text{Fe} \text{x}$ lines contribute. In the 304 Å channel image the whole prominence is seen well in emission, while in 193 and 171 Å images mainly its spine is seen as a dark structure. Prominence barbs are seen in emission in the 171 Å channel owing to the $\text{Fe} \text{x}$ line formed in PCTR.
Figure 2. Prominence observed as a filament at 304 Å by the EUVI instrument on board the STEREO-A satellite. The image was made close in time to XRT and AIA observations. Filament structures are so faint and geometrically thin that the area in which the filament occurs has been marked by a white border. Nevertheless, the long spine on one end of the filament and two barbs on the other are well distinguishable.

where 912 presents the Lyman limit of the neutral hydrogen in units of Å. Here \( \sigma_0 = 7.91 \times 10^{-18} \text{cm}^2 \), \( g_{\text{He}} \) is the hydrogen Gaunt factor (see Karzas & Latter 1961), and 
\( g_{\text{He} \, n}(\lambda) = g_{\text{He}}(4 \lambda) \). The cross section of neutral helium is obtained from Figure 2 in Brown & Gould (1970).

The optical thickness of the hydrogen and helium mixture at the SXR spectral range (see Anzer & Heinzel 2005) is given by

\[
\tau_{\text{H}+\text{He}}(\lambda) = N_{\text{H}} \left\{ \left( 1 - i \right) \sigma_{\text{H}}(\lambda) + N_{\text{He}} \times \left[ \left( 1 - j_1 - j_2 \right) \sigma_{\text{H}}(\lambda) + j_1 \sigma_{\text{He} \, 1}(\lambda) + j_2 \sigma_{\text{He} \, 2}(\lambda) \right] \right\},
\]

(3)

where \( N_{\text{H}} \) is the total hydrogen column density (\( N_{\text{H}} = N_{\text{H} \, i} + N_{\text{H} \, s} \)), \( N_{\text{H} \, i} \) and \( N_{\text{H} \, s} \) are neutral hydrogen and proton column densities, respectively, \( i \) is the ionization degree of hydrogen defined as the ratio between the proton and total hydrogen column density, \( N_{\text{He}} \) is the abundance of the helium relative to hydrogen (\( N_{\text{H} \, i} / N_{\text{H} \, s} \)), and ionization degrees of neutral and singly ionized helium \( j_1 \), \( j_2 \), respectively, are defined as

\[
j_1 = N_{\text{He} \, i} / N_{\text{He} \, s}, \quad j_2 = N_{\text{He} \, i} / N_{\text{He} \, s},
\]

(4)

where \( N_{\text{He}} = N_{\text{H} \, i} + N_{\text{He} \, i} + N_{\text{He} \, m} \). For three typical values of \( N_{\text{H}} \) (\( 10^{17}, 10^{19}, 10^{21} \text{cm}^{-2} \)) taken from Gouttebroze et al. (1993), hydrogen and helium mixture with \( N_{\text{He}} = 0.1, i = 0.3, j_1 = 0.3, \) and \( j_2 = 0 \), the optical thickness is calculated between 5 and 50 Å as shown in Figure 6 (thin dashed lines for various \( N_{\text{H}} \)).

X-ray absorption by hydrogen and helium at 50 Å was computed already by Anzer et al. (2007). Here we extend the wavelength range below 50 Å and add contributions of eight metal continua, i.e., C, N, O, Ne, Mg, Si, S, and Fe. Photoionization cross sections of these eight abundant metals are computed using an approximate formula that depends on the energy \( E \) (see London et al., 1981),

\[
\sigma(E) = \sigma_T \left[ a \left( \frac{E_T}{E} \right)^3 + \left( 1 - a \right) \left( \frac{E_T}{E} \right)^4 \right],
\]

where \( E_T \) and \( \sigma_T \) are the threshold energy and threshold cross section, respectively, and \( a \) is a parameter chosen to match the slope near the threshold (see Table 3 in London et al., 1981)

Comparison of cross sections of metals between the approximate formula given by London et al. (1981) and Figure 2 in Brown & Gould (1970), which is mostly cited in the literature, gives a difference of the order of 10%. The best agreement is for Si (1%), and the worst for S (21%). Optical thickness of metals is expressed in the form

\[
\tau_i = N_{\text{H} \, i} \sum_{E} \sigma(E) A_i,
\]

(5)

where \( A_i \) represents the abundance of a chosen metal marked by subscript \( i \) given in Table 3 of London et al. (1981). Optical thickness is calculated for all eight abundant metal elements under the condition \( E \geq E_T \); otherwise, \( \sigma(E) = 0 \). Note that in our calculations we used the photospheric abundances of metals; the coronal abundances would lead to even smaller opacities. Note here that the metallic opacity is not sensitive to the ionization degree of individual metals, because we are dealing here only with the inner-shell electrons (see also London et al., 1981).

Figure 6 presents the optical thickness versus wavelength below 50 Å for three values of \( N_{\text{H}} \). Contribution of metals is marked with thin solid lines. Small “jumps” on the curves occur when metals stop to contribute above a certain wavelength (their \( E_T \)). The total contribution of the hydrogen and helium mixture and of all metals is presented by thick solid lines. Above 20 Å the contribution of metals is negligible compared to the hydrogen and helium mixture. It is well seen that the total \( \tau_i \) (hydrogen, helium, and metals all together) is practically negligible in the SXR domain.

From the amount of EUV coronal emission at wavelengths below 912 Å absorbed by the hydrogen and helium prominence plasma, Kucera et al. (1998) and Golub et al. (1999) found the hydrogen column density \( 10^{18} \text{cm}^{-2} \) in quiescent prominences. The hydrogen column densities in the same range were estimated also by Schwartz et al. (2015) from observations of six quiescent prominences in EUV, SXR, and Hz. Even if one considers a limiting value \( 10^{21} \text{cm}^{-2} \), which, for example, would correspond to hydrogen density \( 10^{11} \text{cm}^{-3} \) and the prominence extension of \( 10^7 \) km, the optical thickness around 10 Å (where both Al-mesh and Ti-poly filters have the maximum responsibility) is below 0.02. Therefore, the absorption mechanism cannot explain the observed darkening, and we must turn our attention to the effect of emissivity deficit.

4.2. Emissivity Deficit

In EUV and SXR, the prominence will appear dark in the coronal line/continuum emitted at temperatures higher than \( 10^6 \)K. We assume that this is due to the absorption and emissivity deficit, i.e.,

\[
I_{\text{prom}}(\lambda) = I_{\text{bg}}(\lambda) + I_{\text{bg}}(\lambda) \exp(-\tau_i),
\]

where \( I_{\text{bg}}(\lambda) \) and \( I_{\text{bg}}(\lambda) \) are intensities of the radiation emitted by the corona in front and beyond the prominence, respectively. Assuming the most simple case when these intensities
are equal (symmetric corona), we can write
\[
I_{\text{prom}}(\lambda) = I_c(\lambda)[1 + \exp(-\tau_0)],
\]
where \(I_0 = I_{bg}\).

In this paper we express the prominence darkening in terms of the intensity ratio \(R\), which we define as
\[
R = \frac{I_{\text{prom}}}{I_0},
\]
where \(I_0\) is the coronal intensity measured close to the prominence. In the case of a negligible absorption, \(R = 2L_c/I_0\), which demonstrates the effect of emissivity deficit, i.e., the lack of hot coronal emission at the volume occupied by the cool prominence material—see below. Sometimes it is also useful to express the prominence darkening in terms of the contrast, which can be defined as \(C = 1 - R\). C is zero in the case of no prominence visibility. If there is a negligible absorption, \(C = 1 - 2L_c/I_0\); on the other hand, for large \(\tau\), \(C = 1 - L_c/I_0\). In the case of \(L_c = I_0/2\) (no deficit effect), the latter will give \(C = 1/2\).

The coronal intensity \(I_c\) at the prominence location is obtained by integration of the coronal emissivity along the LOS, from the middle of the (symmetrical) cool structure positioned at the limb to coronal boundaries
\[
I_c(\lambda) = \int_0^\infty C_\lambda(n_e, T) \frac{n(H)}{n_e} n_e^2 \, dl,
\]
where \(l\) is the position along the LOS expressed as
\[
l = \sqrt{R^2 - (R_{\text{Sun}} + h)^2}.
\]

Here \(r\) is the radial position in the corona, \(R_{\text{Sun}}\) the solar radius, and \(h\) the height above the limb. \(n_e\) and \(n_H\) are the electron and hydrogen densities, respectively, \(T\) is the kinetic temperature, and \(C_\lambda\) is the contribution function calculated using the statistical equilibrium and CHIANTI atomic database version 7 (Dere et al. 1997; Landi et al. 2012). For the ratio \(n(H)/n_e\), a common coronal value 0.83 is adopted. Distributions of the temperature and electron density with height above the solar surface in the quiet corona were taken from Lemaire (2011) and Saito et al. (1970), respectively. In Equation (9) we first integrate from the middle of the cool prominence structure up to its boundary \(D_{\text{geom}}/2\) (where \(D_{\text{geom}}\) represents the total LOS extension of the prominence); this automatically accounts for the emissivity deficit because \(C_\lambda\) is there essentially zero. From the coronal part we get the actual \(I_c\). In the quiet corona outside...
the prominence, this integral gives simply \( I_0/2 \). Finally, the signal measured by XRT is calculated by the integration of \( I(\lambda) \) multiplied by the filter response function \( f(\lambda) \) over the wavelength range of the filter,

\[
E = \int I(\lambda)f(\lambda)d\lambda, \tag{11}
\]

where \( I(\lambda) \) is either \( I_{\text{prom}} \), \( I_c \), or \( I_0 \). Response functions \( f(\lambda) \) for both Al-mesh and Ti-poly filters are shown in plots in Figure 7.

Length \( 1.8 \times 10^5 \) km of the prominence spine in projection on the solar disk was measured in the image in Figure 2, made at 304 Å with the EUVI instrument on board STEREO-A, which observed the prominence as a filament. But the real length of the spine can be larger. Moreover, it can be possible for the prominence on-limb observations that the LOS was not passing along the whole length of the spine or part of the spine could be hidden behind the limb. Therefore, length estimated according to STEREO-A observations cannot be used as \( D_{\text{geom}} \). For correct derivation of \( D_{\text{geom}} \) a view from a minimum of three angles is necessary, and only two are available (edge-on viewed from Earth direction and from above). Unfortunately, STEREO-B was positioned by 75° from Earth in the opposite direction of STEREO-A, and therefore the whole prominence was behind the limb for STEREO-B. Thus, we used Ti-poly observations to estimate \( D_{\text{geom}} \) at four heights where the cuts have been made. \( D_{\text{geom}} \) was optimized in order to achieve the best fit between the observed and computed ratio \( R \). Note that in the case of the Ti-poly filter, the latter is equal to \( 2E_c/E_0 \) because the absorption at 10 Å is considered to be quite negligible and the contribution of EUV radiation to the

![Figure 5](image-url)  
**Figure 5.** Intensity distributions along the four cuts made at heights 14,500, 17,000, 19,500, and 31,000 km above the limb in the Al-mesh and Ti-poly images taken at 15:37 UT. Depression at the prominence spine (positions along the cuts 110,000–120,000 km) is seen well in data from both filters in all four heights, although it is much shallower in the Ti-poly data. For estimation of the quiet-corona intensities the averages from positions around 50,000 km outside contamination spots were used.

![Figure 6](image-url)  
**Figure 6.** Plot of the optical thickness due to metals as a function of wavelength is marked with thin solid lines. Lower set of curves is for \( N_H = 10^{17} \) cm\(^{-2} \), middle for \( N_H = 10^{19} \) cm\(^{-2} \), and upper for \( N_H = 10^{21} \) cm\(^{-2} \). From 5 Å we also mark the optical thickness due to the partially ionized hydrogen and helium mixture (with \( n_e = 0.1, i = 0.3, j_1 = 0.3, j_2 = 0 \)) with thin dashed lines. The total contribution of hydrogen, helium, and metals between 5 and 50 Å is marked with thick solid lines.
measured signal is under 1%. The resulting $D_{\text{prom}}$ are shown in Table 1 and are used in the next subsection to evaluate the darkening in the Al-mesh images, where the filter has a secondary peak in EUV, which contributes to the integral in Equation (11). All resulting values of $D_{\text{prom}}$ are of order of magnitude of $10^7\text{ km}$, which is close to the length of the spine measured in the EUVI image (Figure 2) from STEREO-A. It must also be noted that none of them exceed the measured spine length.

### 4.3. Extreme-ultraviolet Contribution from the Al-mesh

#### Secondary Extreme-ultraviolet Peak

To evaluate the intensity ratio $R$ in the case of the Al-mesh filter, we proceed in the same way as in the previous subsection. The only difference is that we cannot neglect the absorption because in the EUV domain around 170 Å, the secondary peak of the Al-mesh filter contributes to the measured signal (see Figure 7), the absorption of coronal radiation by cool hydrogen and helium prominence plasma can be significant. Although the response for the Al-mesh filter around 170 Å is almost three orders of magnitude lower than at 10 Å, as shown in Figure 7, the quiet corona in EUV around 170 Å is approximately 40 times as large as those at 10 Å. Thus, the contribution of the EUV radiation from wavelengths around 170 Å to the measured signal is around 11%, which cannot be neglected. A similar EUV contribution was calculated for the quiet corona also at heights 17,000 and 19,500 km, while at height 31,000 km the contribution was only 9%. On the other hand, the response at 170 Å for the Ti-poly filter is four orders of magnitude lower than at 10 Å; thus, the EUV contribution to the measured signal is under 1%.

#### Table 1

| $h$ (km) | $R$ from the XRT observations | $D_{\text{prom}}$ ($10^7\text{ km}$) | Maximum $\tau_{93}$ | $R$ from the calculations |
|---------|-------------------------------|-----------------------------------|---------------------|---------------------------|
| 14,500  | 0.83                          | 0.77                              | 7.8                 | 2.01                      |
| 17,000  | 0.82                          | 0.79                              | 8.3                 | 2.67                      |
| 19,500  | 0.81                          | 0.76                              | 8.9                 | 2.13                      |
| 31,000  | 0.78                          | 0.78                              | 10.0                | 1.40                      |

SDO/AIA observations in the 193 Å channel (upper right panel of Figure 1), SXR data from XRT (Figure 4), and the method of Schwartz et al. (2015). Because of the assumption of symmetrical distribution of the coronal emissivity, a factor of the coronal asymmetry $\alpha$ equal to 0.5 was used. The $\tau_{93}$ map is shown in Figure 8. The position and shape of an area with $\tau_{93}$ above 2 correspond well to the dark radial structure of the prominence visible in the AIA 193 Å and XRT Al-mesh images. Thus, the minimal $R$ of the XRT data for both filters corresponds well with the maximum $\tau_{93}$ at all heights above the limb. They can be transformed to other wavelengths by multiplying with the $\tau_{93}(193\text{ Å})/\tau_{93}$ ratio obtained from Equation (3) for estimation of the theoretical optical thickness of hydrogen and helium plasma $\tau_{93}(193\text{ Å})$; see, e.g., Anzer & Heinzel (2005). In calculations of $\tau_{93}(193\text{ Å})$ in the wavelength range from 1 to 300 Å (from X-rays up to EUV) we adopted the same values of helium abundance and ionization degrees ($n_{\text{He}} = 0.1$, $i = 0.3$, $j_1 = 0.3$, and $j_2 = 0$) as in Section 4.1. The resulting ratio is plotted in Figure 9. Maximum values of $\tau_{93}$ occurring at the prominence spine are within an interval 1.4–2.7 for heights 14,500–31,000 km, which corresponds to optical thickness at wavelengths around 170 Å of approximately 0.8–2.2. Such an optical thickness produces a remarkable decrease of intensity and subsequently smaller EUV contribution (only 7%–8%) to signal measured at the prominence spine using the Al-mesh filter than for the quiet corona (the contribution of 11% at heights 14,500–19,500 km, 9% at the height 31,000 km). Then again the signal $E_{\text{prom}}$ registered at the prominence by the Al-mesh filter is calculated by integration along the wavelength of $I_{\text{prom}}(\lambda)$ multiplied by...
the instrument response \( f(\lambda) \) (see Figure 7), similarly as in the case of Ti-poly. Finally, the theoretical intensity ratio \( R = E_{\text{prom}}/E_0 \) at the prominence position is calculated. Note that the emissivity deficit is properly accounted for by using the values of \( D_{\text{geom}} \) obtained in the previous subsection.

For the Al-mesh filter we compare the observed values of \( R \) with those calculated assuming the EUV contamination in Table 1. For values of \( D_{\text{geom}} \) of the order of \( 10^5 \) km and maximal \( \tau_{93} \) between 1.4 and 2.67 a good agreement between calculated and observed values of \( R \) was achieved for the four selected heights above the limb—see Table 1.

5. DISCUSSION AND CONCLUSIONS

In this paper we studied SXR visibility of the prominence observed on 2010 June 22 during the coordinated campaign. We noticed that a dark structure resembling the prominence spine is well visible in \textit{Hinode}/XRT images obtained with Al-mesh and Ti-poly filters. Positions of the dark structure at all heights above the limb correspond to the maximal \( \tau_{93} \) as estimated by Gunár et al. (2014) for the same prominence. We examined three possible mechanisms of SXR prominence darkening: absorption of X-ray radiation around 10 Å by the resonance continua of hydrogen, helium, and selected metals; influence of the coronal emissivity deficit; and the effect of a contamination by the secondary EUV peak in the case of the Al-mesh filter.

Comparison was made for four heights above the limb—three close to each other cutting the prominence spine somewhere in the middle between its bottom (at the limb) and top, and the fourth close to its top. For the theoretical calculations, distributions of electron densities and temperature in the quiet corona were used, and for the absorption of EUV radiation by hydrogen and helium plasma, maximal \( \tau_{93} \) values for the four heights calculated for this prominence by Gunár et al. (2014) were scaled. Then, calculated intensities were integrated along wavelength using the XRT filter responses in order to obtain a signal that should be measured by the XRT instrument.

We found that both absorption in resonance continua of hydrogen and helium of EUV radiation that contaminates SXR data and EUV emissivity deficit would lower \( R \) at the prominence spine when using the Al-mesh filter. In the case of the Ti-poly filter, lowering of \( R \) due to absorption of EUV radiation is negligible.
As for absorption of X-ray radiation by prominence hydrogen and helium plasma, it is totally negligible at 10 Å. But when also continua of other elements (metals) such as C, N, O, Ne, Mg, Si, S, and Fe are taken into account, total optical thickness cannot be neglected for hydrogen column density exceeding 10^{21} cm^{-2}. For the prominence studied here we estimated the hydrogen column density at hydrogen and helium ionization degrees \( i = 0.6, j_1 = 0.5, \) and \( j_2 = 0 \) from the \( \tau_{93} \) map constructed by Gunár et al. (2014), and we found a maximum column density of hydrogen of \( 2 \times 10^{19} \) cm^{-2} for this prominence. It means that absorption of X-rays at 10 Å can be neglected for the prominence studied here. Only when assuming that the LOS at the prominence location is passing through a volume occupied by the cool prominence plasma not emitting in EUV and X-rays, the contrast comparable to observations is achieved due to the coronal emissivity deficit. For simplicity the position of the prominence exactly at the limb was assumed. For the geometrical thickness \( D_{\text{geom}} \) of the prominence spine along the LOS of the order of 10^3 km, calculated intensity ratios comparable to those obtained from observations were obtained for all four selected heights (Table 1) for both Al-mesh and Ti-poly filters. Although \( D_{\text{geom}} \) is increasing with height, its variations are not exceeding 20%. Thus, it can be just due to noise in the XRT Ti-poly data. But an increase of \( D_{\text{geom}} \) with height could also be a real effect of the prominence shape. Unfortunately, observations of the prominence only in two viewing angles are available—edge-on on the limb and viewed as a filament projected on the disk from STEREO-A. Therefore, it is not possible to infer reliably its 3D shape and subsequently geometrical thickness of the prominence at the four heights. Thus, it is not possible to distinguish whether the increase of \( D_{\text{geom}} \) with height is caused by noise in the data or by the shape of the prominence. However, such behavior of the geometrical thickness might conform a loop-like shape of the prominence where at smaller heights the LOS is passing through its vertical parts while in larger heights the LOS is passing along its horizontal part. In the case of the Al-mesh filter also the EUV transmittance peak that contaminates the measured signal was taken into account. The calculated EUV contribution to the signal in the case of the Al-mesh filter for the quiet corona is 11% at heights 14,500–19,500 km. The EUV contribution at the prominence spine is 7%–8% in all four heights. This difference in EUV contributions causes a decrease of the measured XRT signal at the prominence spine, together with the emissivity deficit. Comparing the contribution to the signal from quiet-Sun radiation in X-rays (main peak of the Al-mesh filter transmittance within wavelength interval 1–30 Å) and EUV (secondary peak at 160–210 Å), it was found that the contribution of EUV to depression of the measured signal in the quiet corona decreases steeply with height. At the height of 31,000 km the EUV contribution to the signal in the quiet corona is lower—only 9%—while at the prominence spine the contribution is the same as at lower heights. Thus, lower EUV contribution to the measured signal in the quiet corona at \( h = 31,000 \) km causes notably less dramatic intensity decrease at the prominence for this height than at lower heights, as can be seen in Figure 5. Although mainly the coronal emissivity deficit is responsible for visibility of this prominence in XRT images, in the case of the Al-mesh filter a fraction of 16%–25% of the total darkening comes from the EUV contamination. Therefore, depression of the measured signal at the prominence in the case of the Al-mesh filter is more prominent, and its variations with height are larger than in the case of the Ti-poly filter. In contrast, the contamination of the Ti-poly signal by the EUV radiation is negligible, and thus the emissivity deficit only causes depression at the prominence spine in XRT observations made with the Ti-poly filter.

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