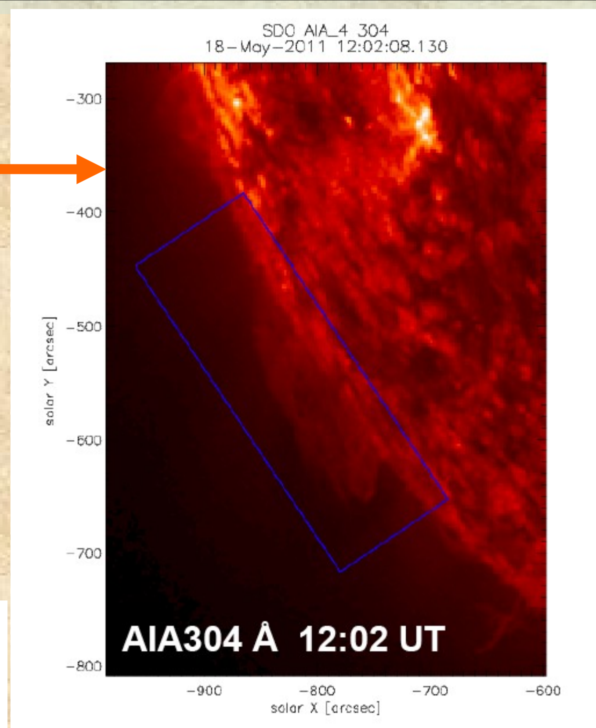
Is it possible to use the green coronal line instead of X rays to cancel an effect of the coronal emissivity deficit in estimation of the prominence total mass from decrease of the EUV-corona intensities?

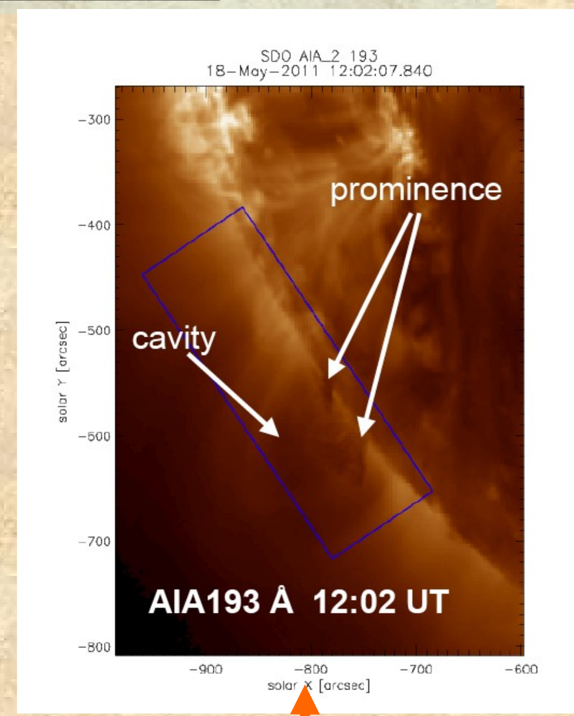
P. Schwartz[1], P. Heinzel[2], S. Jejčič[3], J. Rybák[1], P. Kotrč[2], F. Fárník[2], Yu. A. Kupryakov[2,4], E. E. DeLuca[5], L. Golub[5], P.R. Jibben[5], U. Anzer[6], A.G. Tlatov[7], S.A. Guseva[7]

[1]Astronomický ústav SAS, Tatranská Lomnica;
[3]Astronomický ústav ASCR, Ondřejov;
[2] University of Ljubljana
[5] CfA, Cambridge, MA, USA
[6] Max-Planck Institut für Astrophysics, Garching, Germany
[7] Kislovodsk Mountain Astronomical Station of the Pulkovo observatory, Russia

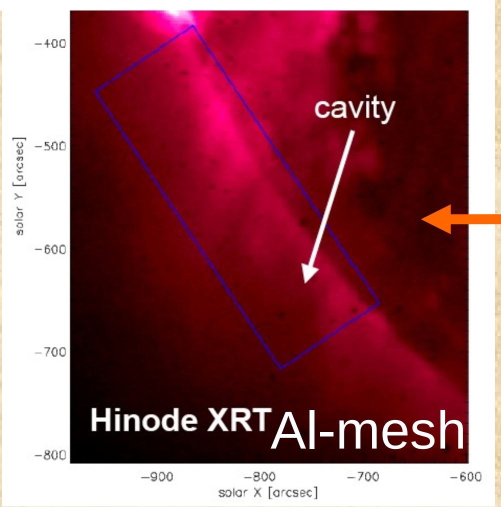
Prominence of 18 May 2011

scattering of the chromosph. emission





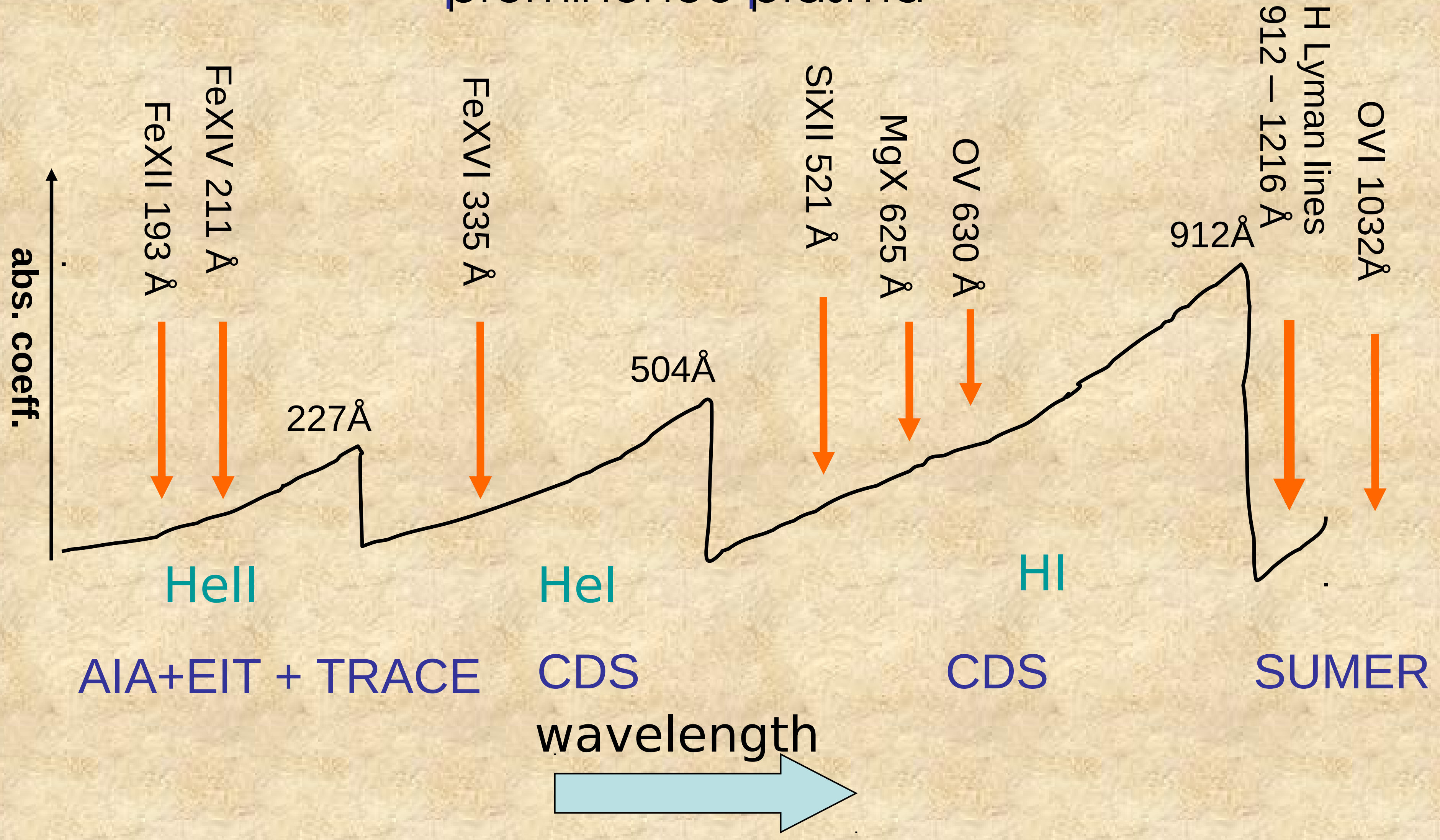
absorption + coronal emissivity deficit



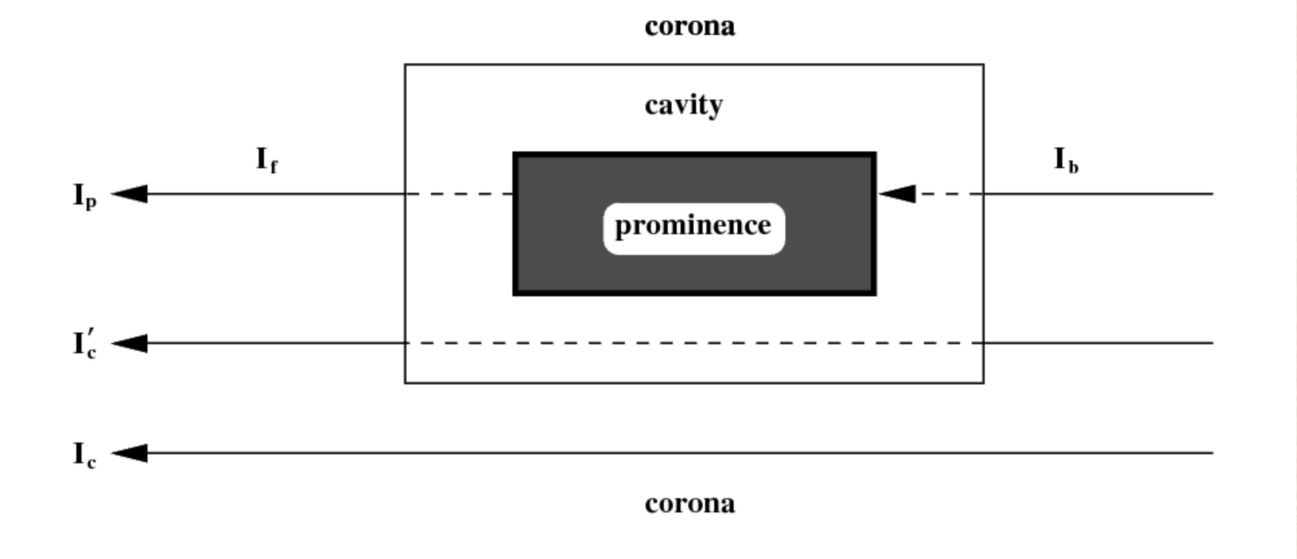
coronal emissivity deficit only

observations with Al-mesh filter was used, because it has max of transmission closer to temperatures around log(T)=6 than Ti-poly

Absorption of EUV coronal and TR line radiation by resonance hydrogen & helium continua in a cool prominence plasma

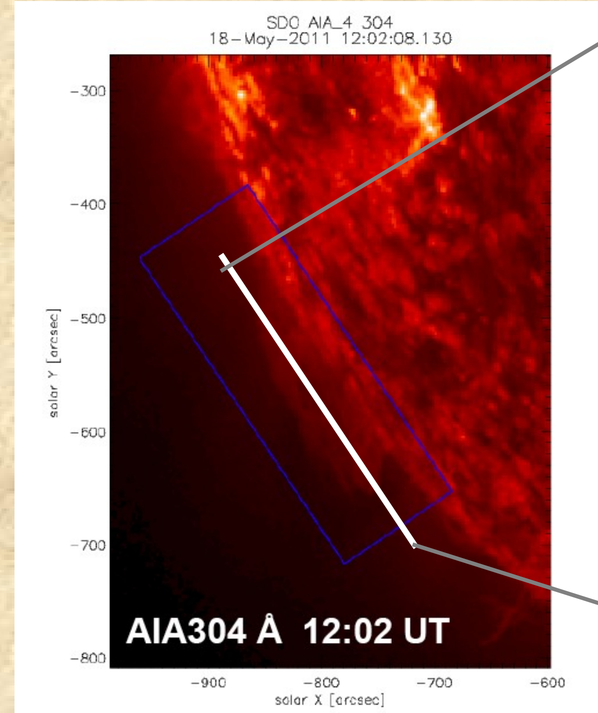


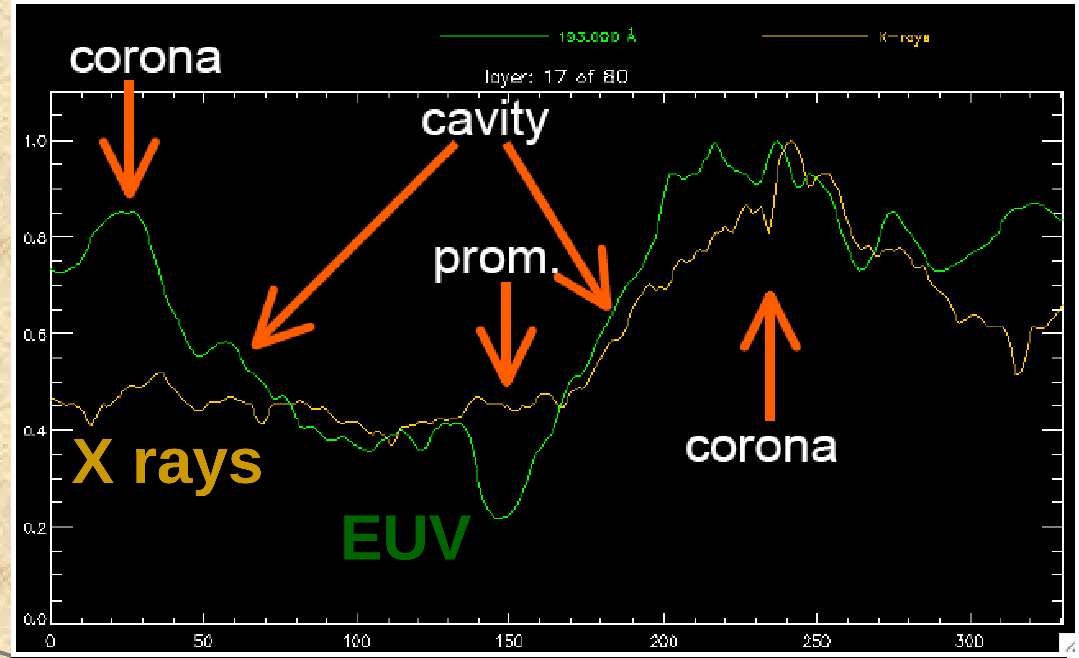
Spectroscopic method



I_p is the intensity of the EUV line with $\lambda \leq 912$ Å observed at the prominence location, decreased by both absorption and emissivity deficit. $I_b = \alpha\, I_{cp}$ and $I_f = (1-\alpha)\, I_{cp}$, where I_{cp} is I_p for X-rays (no absorption). α is the parameter of asymmetrical distribution of the coronal emission ($\alpha = 0.5$ for symmetrical corona). Outside the prominence I_c(XRT) and I_c(EUV) are similar (except for a multiplicative factor).

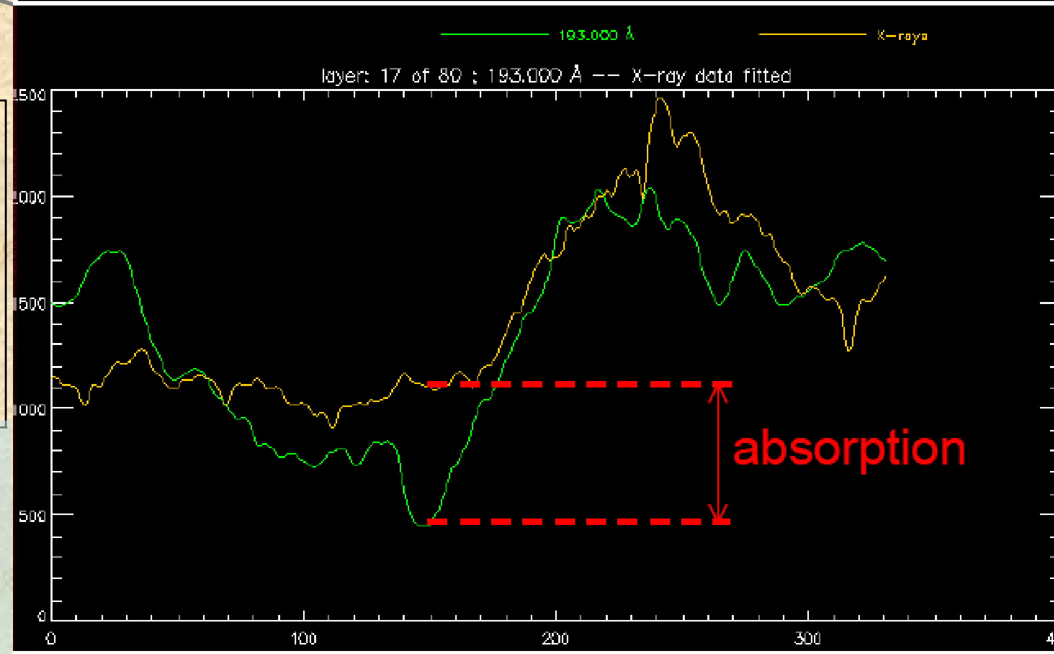
(Heinzel et al. 2008, Apj 686, 1383)



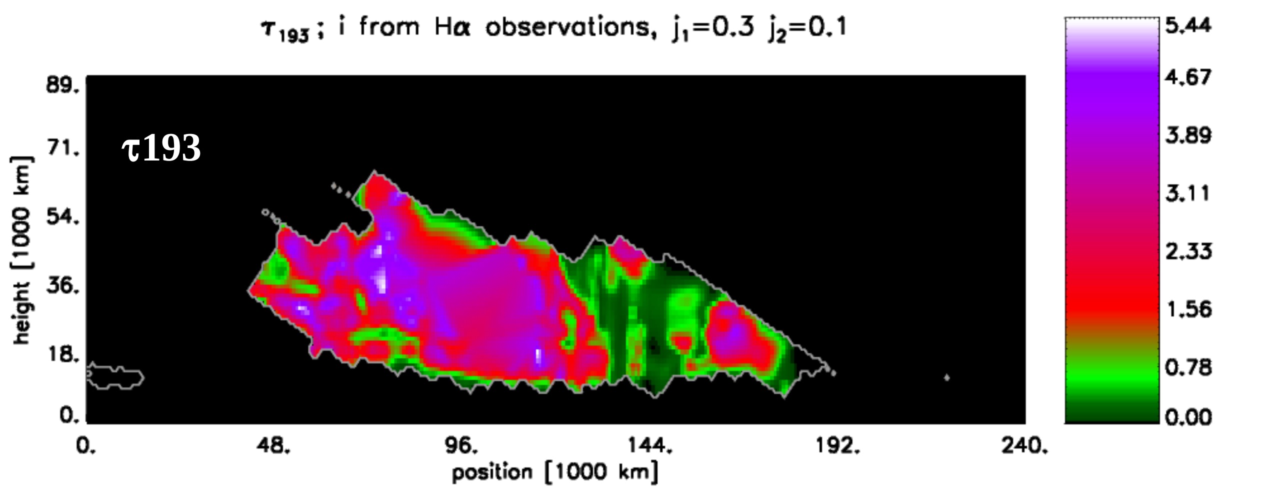


after multiplication of the X-ray intensity distribution to fit that of the EUV outside the prominence

cancellation of an effect of the emissivity blocking



Results for prominence of 18 May 2011



the total mass: 1.7×10^{12} kg

avg α=0.29

avg plasma density: $\approx 4\times10^{-14}$ g cm^{-3} for D ~ 10000 km

$$\tau_\lambda = -\ln\left(1+\frac{r'_\lambda-1}{\alpha}\right)$$

(Heinzel et al. 2008, Apj 686, 1383)

$$\tau_\lambda = N(\mathrm{H})\Big\{(1-i)\,\sigma_{\mathrm{H}}(\lambda) + r_{\mathrm{He}}\left[(1-j_1-j_2)\,\sigma_{\mathrm{He\,I}}(\lambda) + j_1\,\sigma_{\mathrm{He\,II}}(\lambda)\right]\Big\},$$

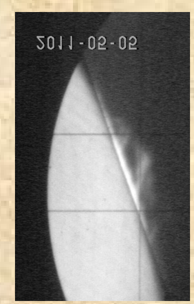
(Anzer&Heinzel 2005, ApJ, 622, 714)

Total masses of five quiescent prominences observed during the campaign from April through June 2011

19 Apr 2011

M=2.9×10^{11} kg
avg N(H)=9.5×10^{18} cm^{-2}

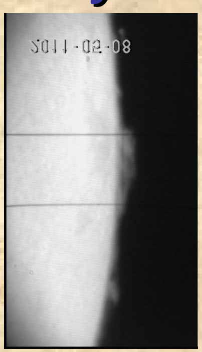
5 May 2011



M=6.7×10^{11} kg
avg N(H)=3.8×10^{18} cm^{-2}

M=3.6×10^{11} kg
avg N(H)=5.5×10^{18} cm^{-2}

8 May 2011



M=1.1×10^{12} kg
avg N(H)=7.0×10^{18} cm^{-2}

18 May 2011

M=1.7×10^{12} kg
avg N(H)=1.6×10^{19} cm^{-2}

total masses:
$2.9\times10^{11} – 1.7\times10^{12}$ kg

avg hydrogen column densities:
$3.8\times10^{18} – 1.6\times10^{19}$ cm^{-2}

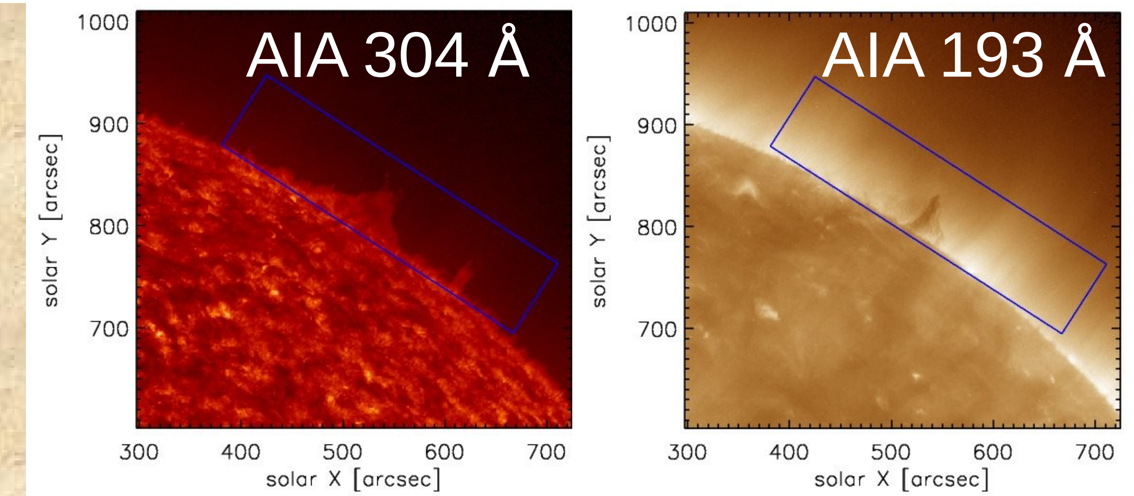
(Schwartz et al. 2014, A&A, 574, A62)

But are prominences really transparent in X-rays?

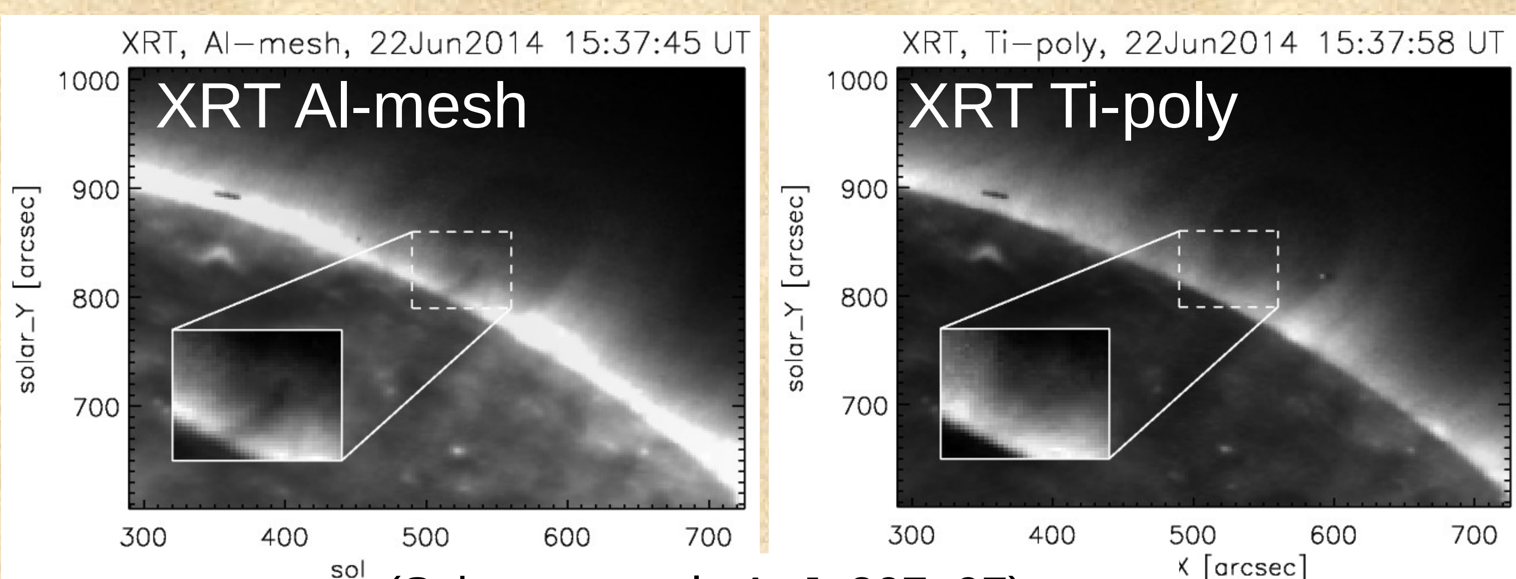
Anzer et al (2007, Sol. Phys. 242, 43) shown that optical thickness of hydrogen and helium plasma of a prominen-ce at 50 Å is around 0.05 what is negligible. Maximum transmission of the XRT filters is around 10 Å where this optical thickness is eve lower.

But at wavelengths below 50 Å also the absorption in con-tinua of other elements occur!!!

Prominence of 22 Jun 2010



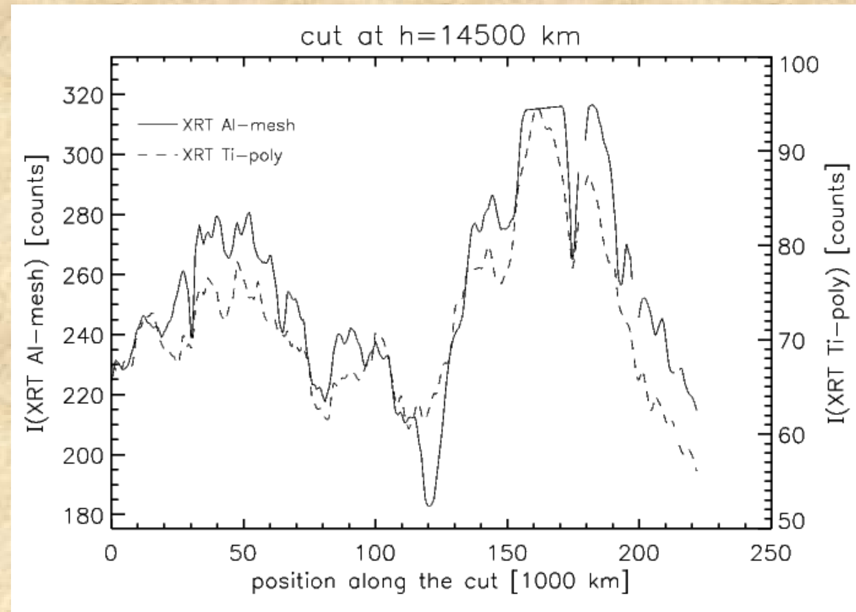
(Gunár et al. 2004, A&A 256, A123)

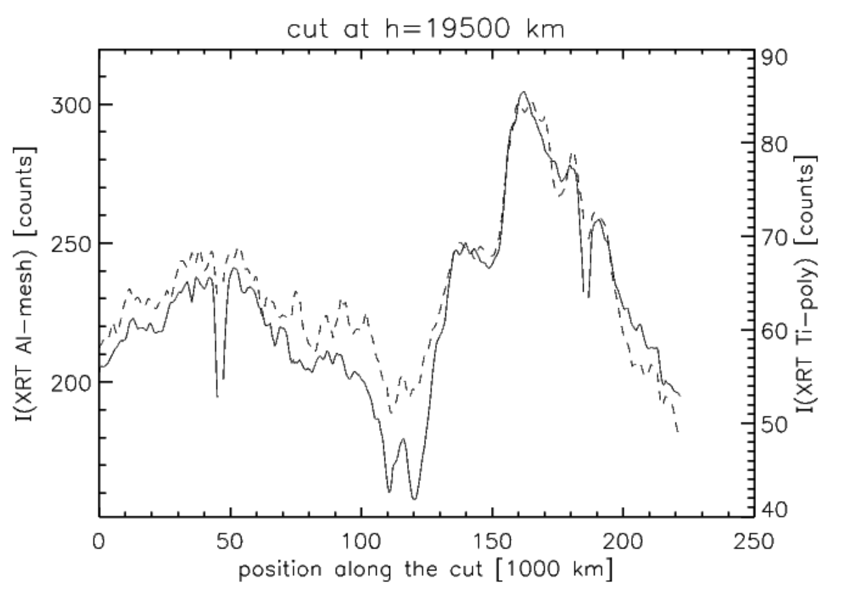


(Schwartz et al., ApJ, 807, 97)

Cuts tangentially to the limb at different heights

Dip at the prominence position in both Al-mesh and Ti-poly data, although in Ti-poly shallower





solid line – Al-mesh, dashed line – Ti-poly

Absorption of X-rays at 10 Å

hydrogen and helium (Anzer&Heinzel 2005, ApJ 622, 714):

$$\tau_\lambda = N(\mathrm{H})\,\{(1-i)\,\sigma_{\mathrm{H}}(\lambda) + r_{\mathrm{He}}\,[(1-j_1-j_2)\,\sigma_{\mathrm{HeI}}(\lambda) + j_1\,\sigma_{\mathrm{HeII}}(\lambda)]\}$$

other elements, such as C, N, O, Ne, Mg, Si, S, Fe:

$$\tau_\lambda = N(\mathrm{H}) \sum_i \sigma_i(\lambda)\,A_i$$

(Gouttebroze et al. 1993, A&AS, 99,513)

A_i is the element abundance according to hydrogen.

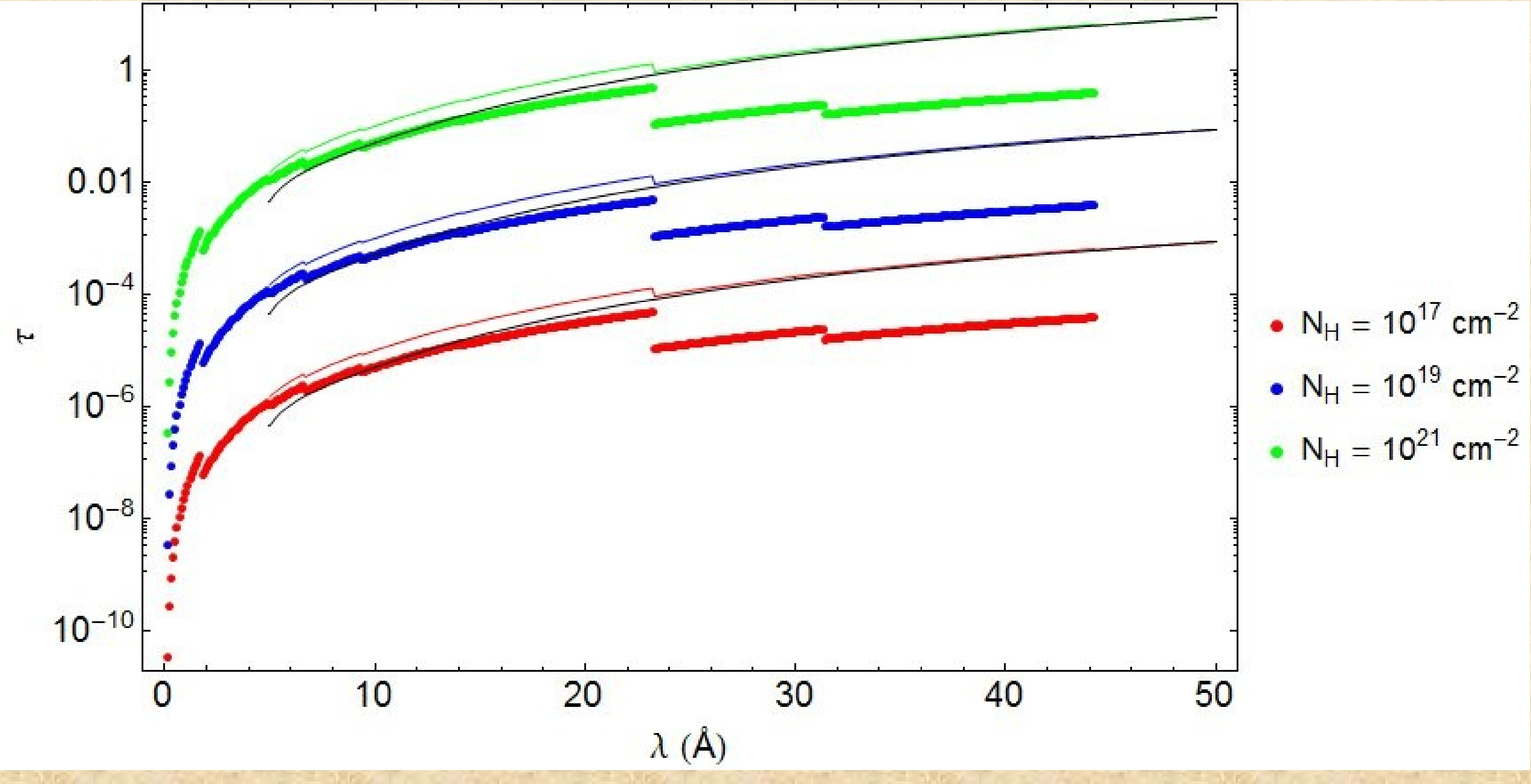
Phosospheric values are used for prominences.

Empirical dependence of the crossection on energy of photons

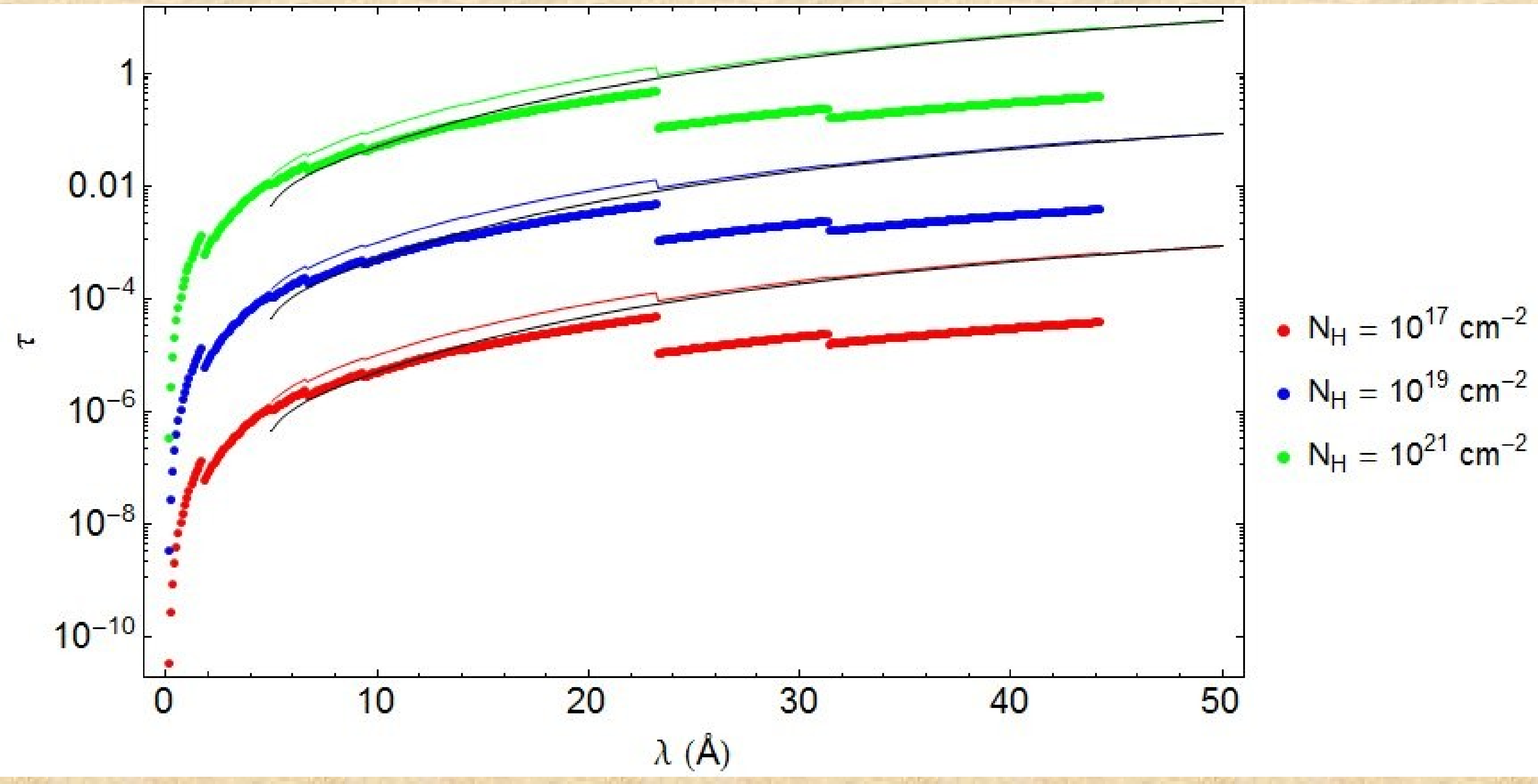
$$\sigma(E) = \sigma(E_{\mathrm{T}})\left[a\left(\frac{E_{\mathrm{T}}}{E}\right)^3 + (1-a)\left(\frac{E_{\mathrm{T}}}{E}\right)^4\right],$$

where for $E < E_{\mathrm{T}}$ the crossection $\sigma(E) = 0$, a is parameter chosen to match the slope near the threshold.

(London et al. 1981, ApJ, 243,970)



Plot of the optical thickness due to other elements as a function of wavelength marked with thick colored disconnected lines. From 5 Å we also mark the optical thickness due to partially ionized hydrogen/helium mixture (with $i = 0.5$, $j_1=0.3$, $j_2= 0$) marked with thin black lines. The total contribution of all elements is marked by thin colored lines.



avg hydrogen column densities for our five prominences

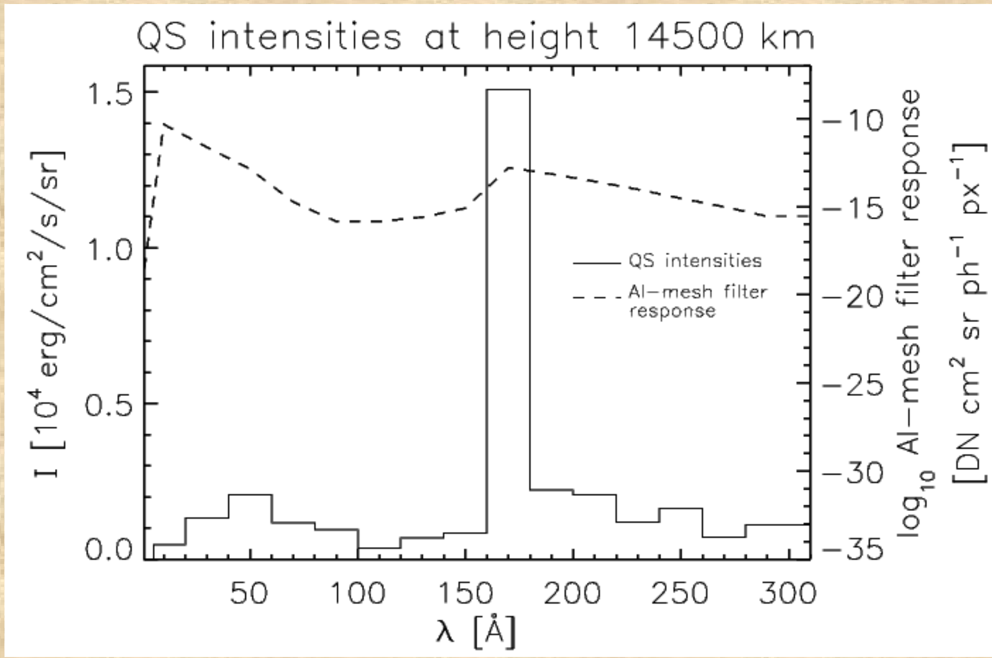
$N(H) \sim 10^{18} – 10^{19}\ cm^{-2}$

Thus absorption at 10 Å is negligible even when also other elements (except of H and He) are included

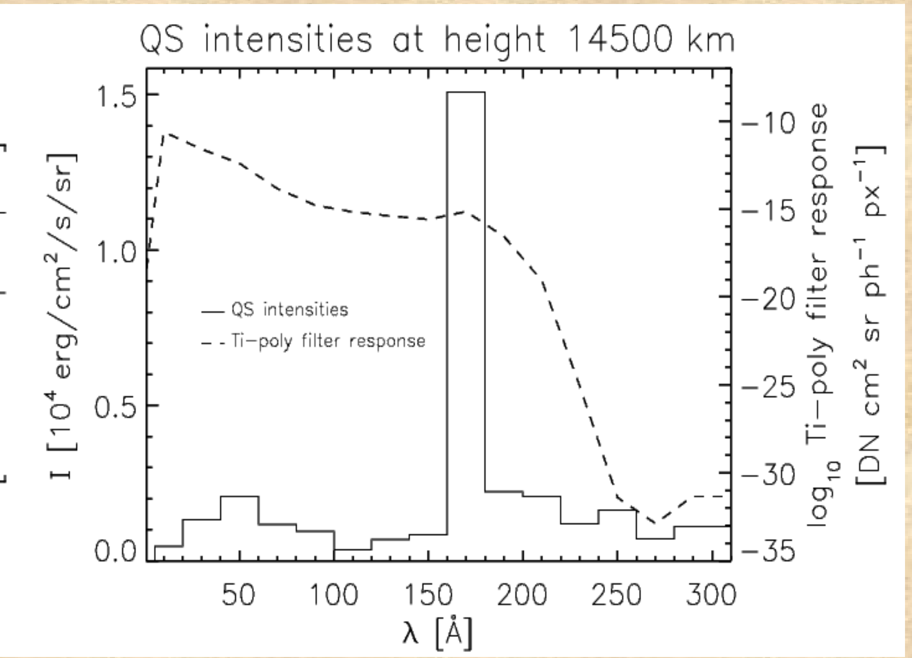
EUV contamination

The XRT Al-mesh Ti-poly filters have secondary maximum around 171 Å.

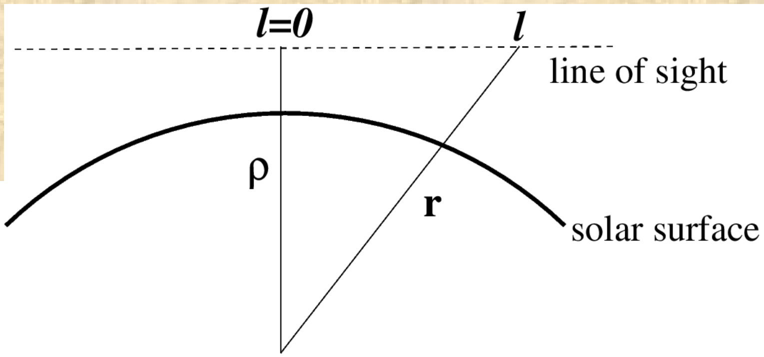
the Al-mesh filter



the Ti-poly filter



For spherically symmetric corona:



$$I_{QS}(\lambda) = 2 \int_0^{\infty} C_\lambda(n_e(r), T(r)) \frac{n(\mathrm{H})}{n_e} n_e^2(r)\, dl\,.$$

Position along the line of sight can be expressed as follows:

$$l = \sqrt{r^2 - (R_{\mathrm{Sun}} + h)^2}$$

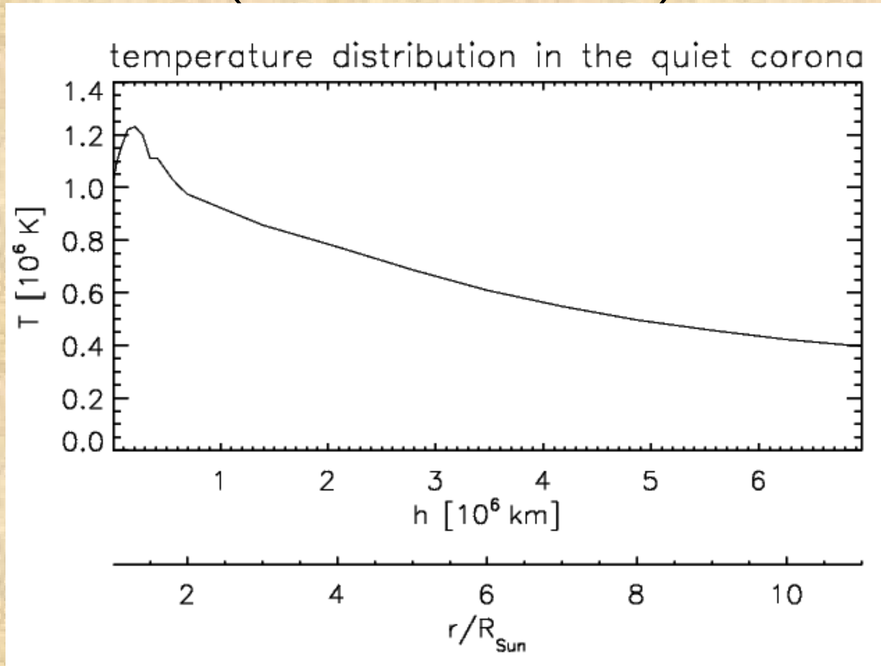
where R_{Sun} is solar radius, h is height above the limb. Contribution function for transition between levels j and i of ion in ionisation state $+m$ of the element X is calculated using formula

$$C(n_e, T) = \frac{h\,c}{4\pi\,\lambda_{ij}} \frac{A_{ij}}{n_e} \frac{n_j(\mathrm{X}^{+m})}{n(\mathrm{X}^{+m})} \frac{n(\mathrm{X}^{+m})}{n(\mathrm{X})} \frac{n(\mathrm{X})}{n(\mathrm{H})}\,,$$

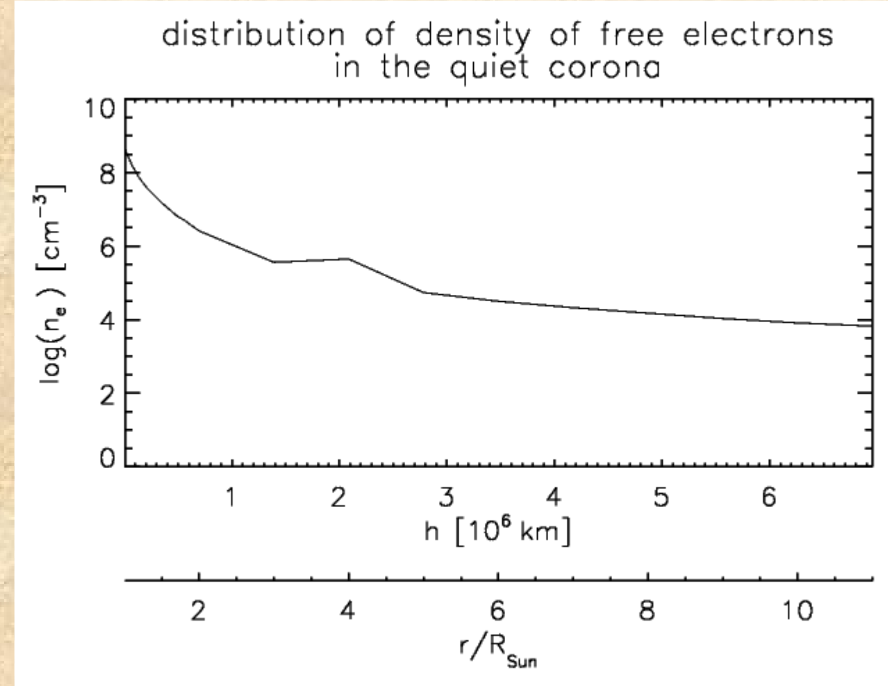
where h is Planck constant, c speed of light in vacuum, λ_{ij} is wavelength of radiation emitted by the transition from the level j to i. A_{ij} is the Einstein's coefficient of spontaneous emission. Ratio $\frac{n_j(\mathrm{X}^{+m})}{n(\mathrm{X}^{+m})}$ is dependent only on temperature while the $\frac{n(\mathrm{X}^{+m})}{n(\mathrm{X})}$ ratio depends on both temperature and density of free electrons. Ratio $\frac{n(\mathrm{X})}{n(\mathrm{H})}$ is abundance of the element X according to hydrogen. The contribution function was calculated using the statistical equilibrium and CHIANTI atomic database version 7.

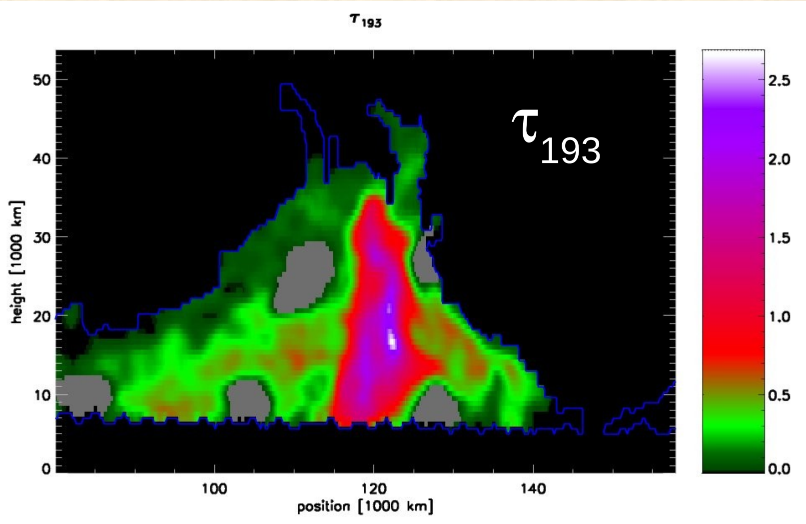
(CHIANTI – Landi et al. 2012, ApJ 744, 99)

(Lemaire 2011 ArXiv)



(Saito et al. 1970, Ann.Tok. AO 12,53)





(Gunár et al. 2004, A&A 256, A123)

For the most simple case: coronal emissivities in front of and behind the prominence are equal, without emissivity deficit:

$$I_{\rm prom}(\lambda) = \frac{1}{2} I_{\rm QS}(\lambda) \left[1 + \exp(-\tau_\lambda)\right] ,$$

Signal that would be measured by XRT is obtained by integration along wavelengths of both I_{QS} and I_{prom} multiplied by transmissions of the filters.

h	observed contrast		maximum τ_{193}	calculated contrast	
[km]	Ti-poly	Al-mesh		Ti-poly	Al-mesh
14 500	0.83	0.77	2.01	0.99	0.95
17 000	0.82	0.79	2.67	0.99	0.95
19 500	0.81	0.76	2.13	0.99	0.95
31 000	0.78	0.78	1.40	1.00	0.96

Table 1: Comparison of observed and calculated contrast at the prominence spine at heights h of the four cuts for the Al-mesh and Ti-poly filters. Influence of the emissivity deficit was not taken into account in the calculations.

Absorption of EUV causes small decrease of measured Al-mesh signal only by several percent (EUV contribution Around 10% in QS up to h=30000 km, only around 7% at the prominence spine) and has negligible influence on Ti-poly data

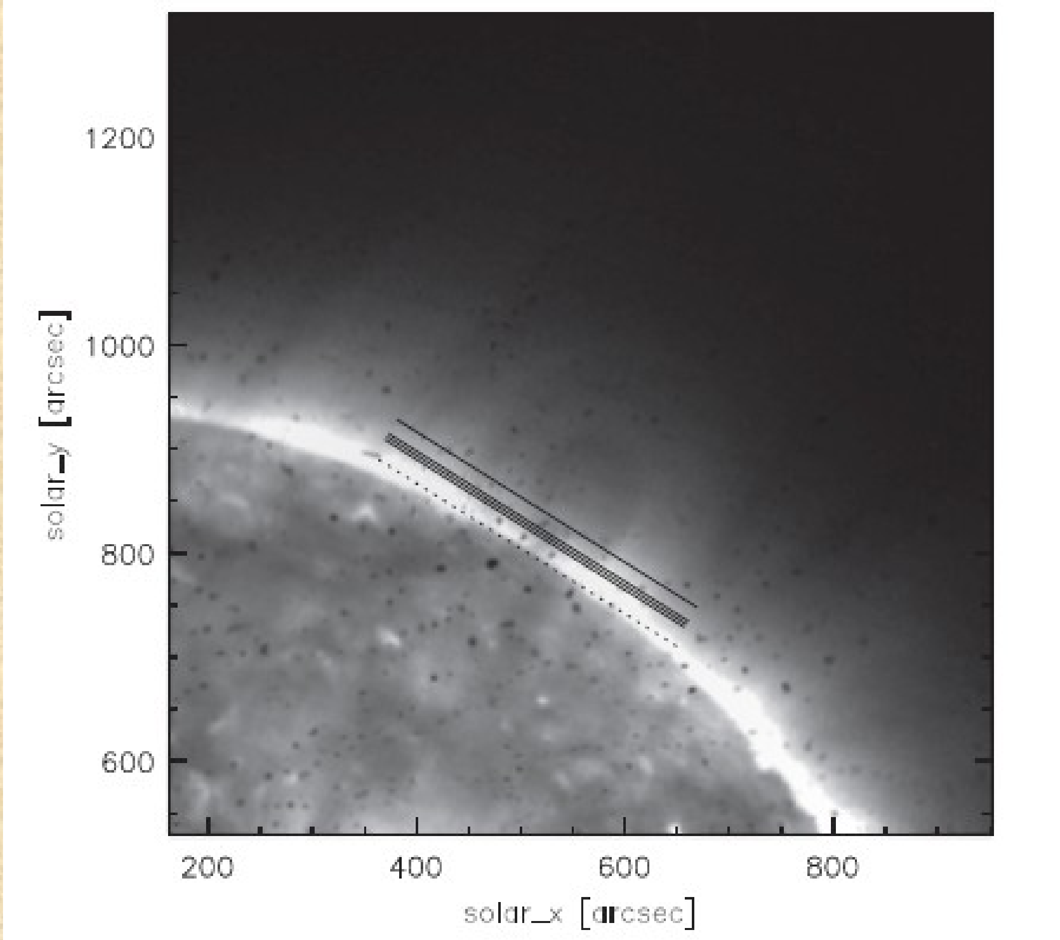
XRT data obtained using the Ti-poly filter are almost unaffected by the EUV absorption. Therefore, contrast at a prominence can be used for estimation of prominence geometrical thickness.

h [km]	observed contrast Ti-poly	observed contrast Al-mesh	D_{geom} $[10^4\,km]$	maximum τ_{193}	calculated contrast Ti-poly	calculated contrast Al-mesh
14 500	0.83	0.77	7.8	2.01	0.83	0.80
17 000	0.82	0.79	8.3	2.67	0.82	0.79
19 500	0.81	0.76	8.9	2.13	0.81	0.78
31 000	0.78	0.78	10.0	1.40	0.78	0.76

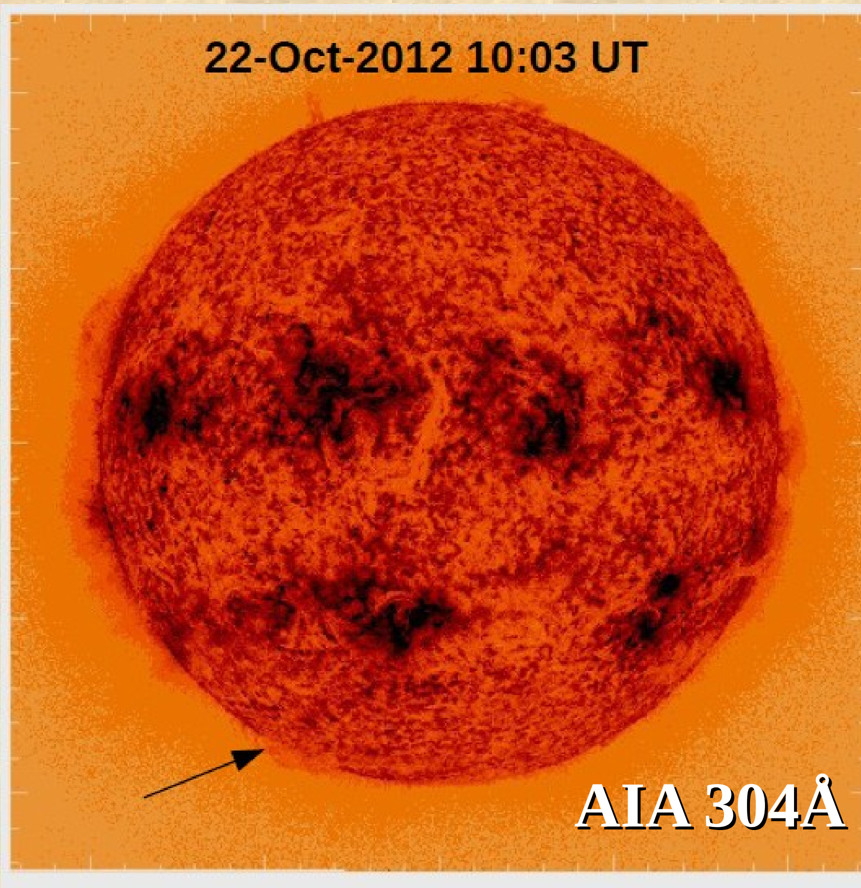
Table 2: Comparison of observed and calculated contrast at the prominence spine for the Al-mesh and Ti-poly filters with the emissivity deficit taken into account. Contrast at heights of the four cuts for both filters was calculated using values of the geometrical thickness D_{geom} and maximum optical thickness τ_{193} listed in the fourth and fifth columns of the table, respectively.

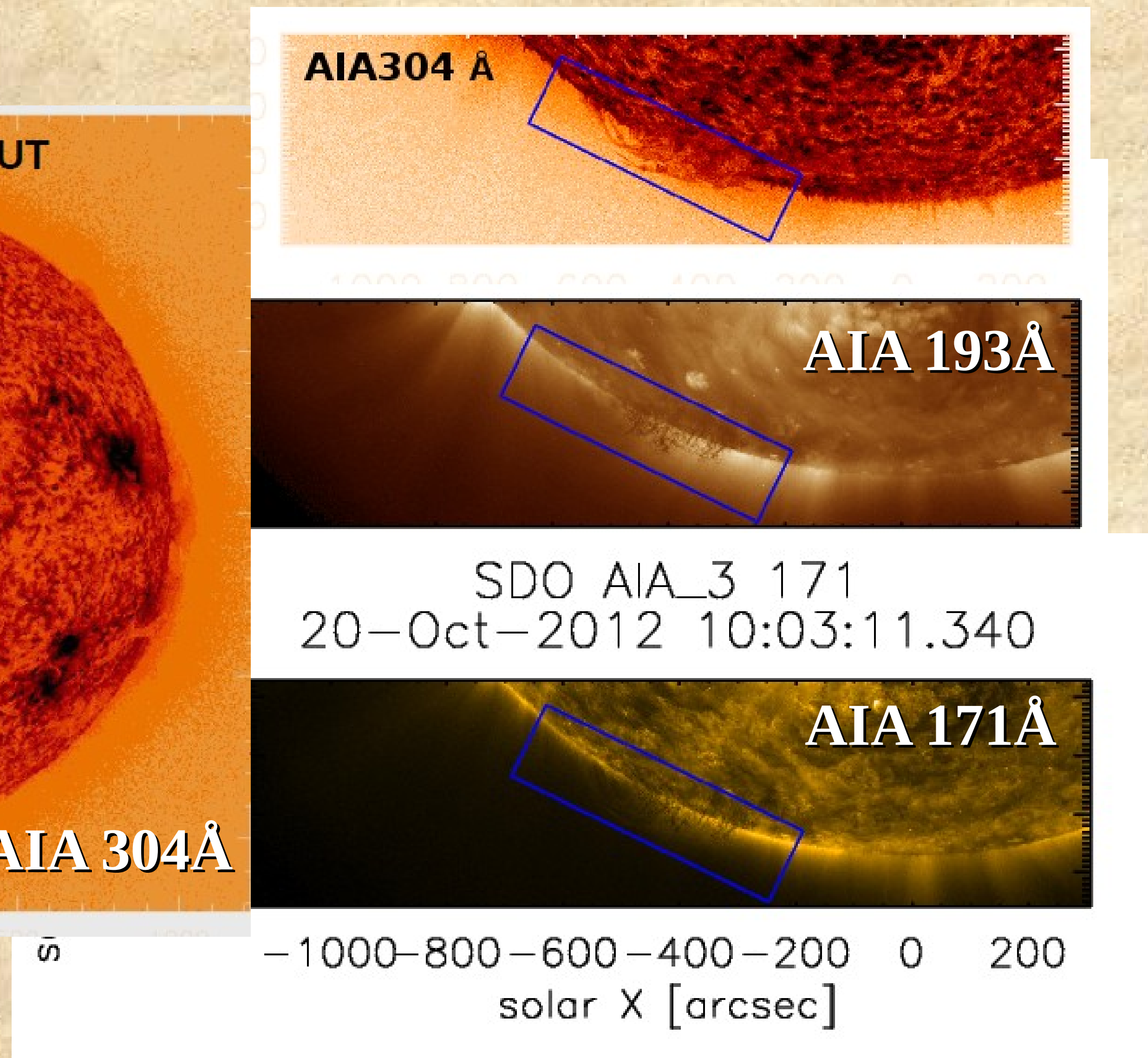
Good agreement between observed and calculated contrast
is achieved only when the emissivity deficit is taken into account

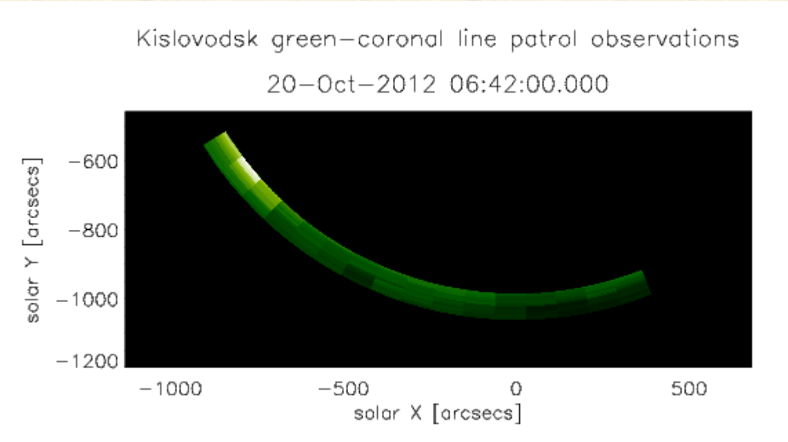
XRT filters are degrading and more contamination spots are gradually appearing in the XRT X-ray data (Narukage et al., 2014, SoPh, 289, 1029)

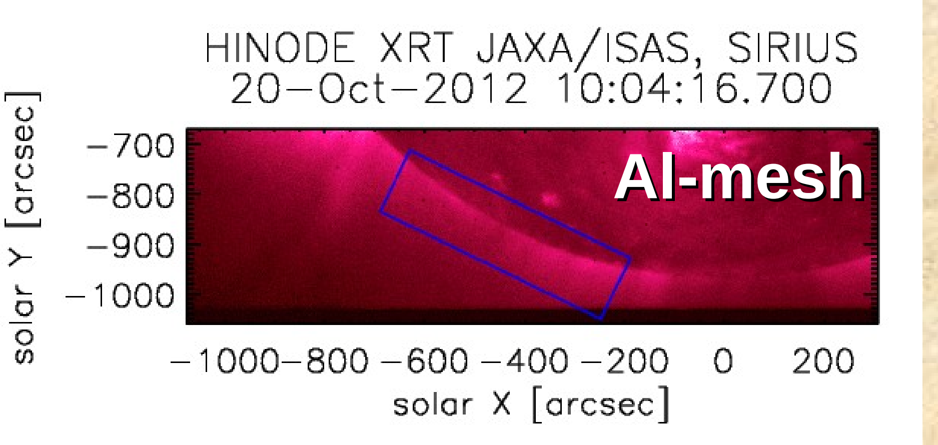


Prominence observed on October 22, 2014

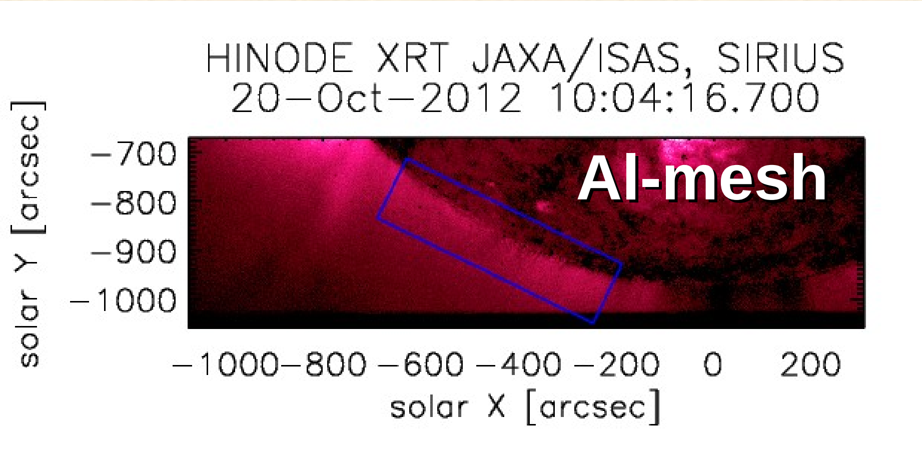


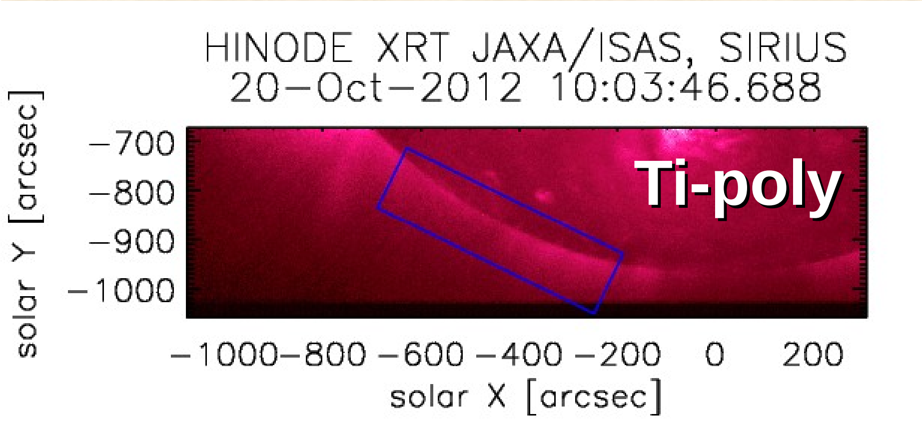




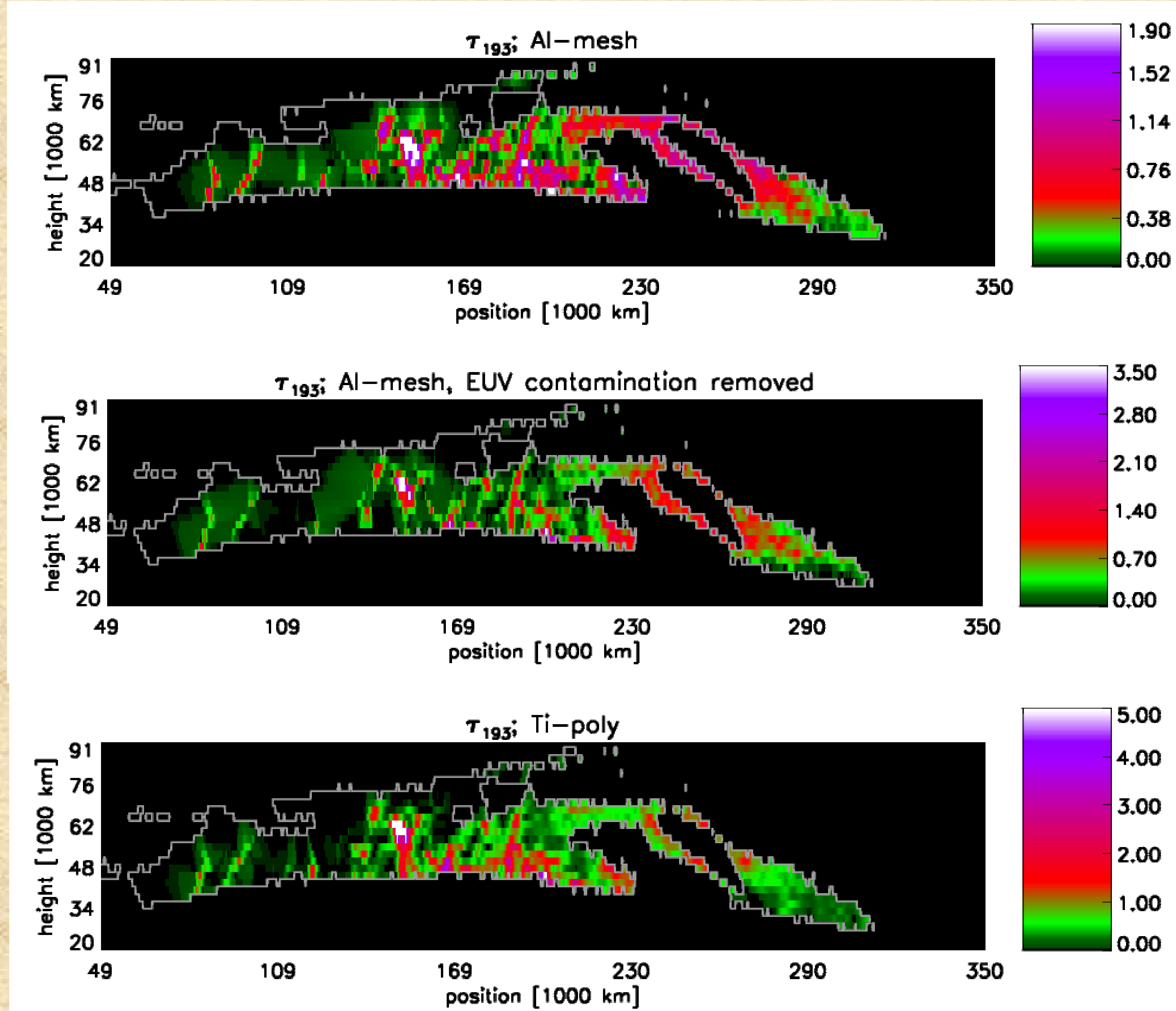


Total emisson of the green coronal line from 20-Oct-2012 06:42 UT (Makarov, V. I. et al. 2006, SoPh, 237, 201)

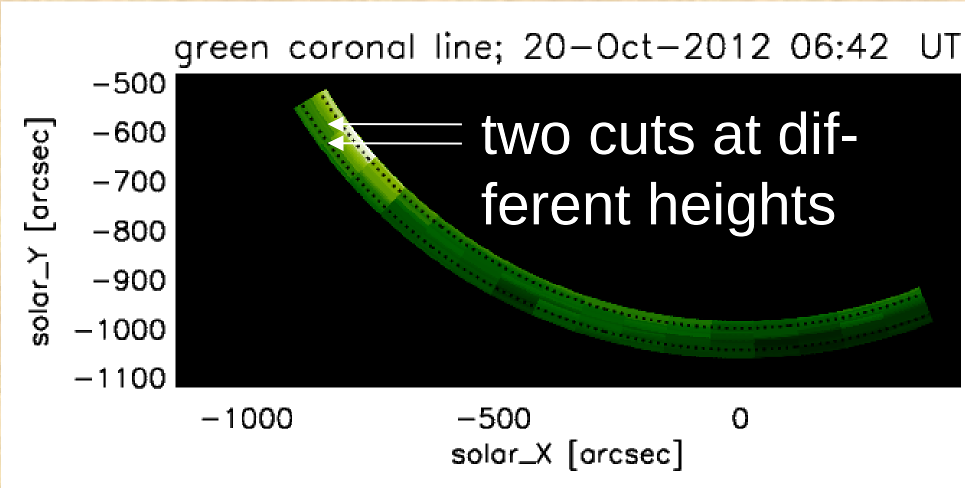


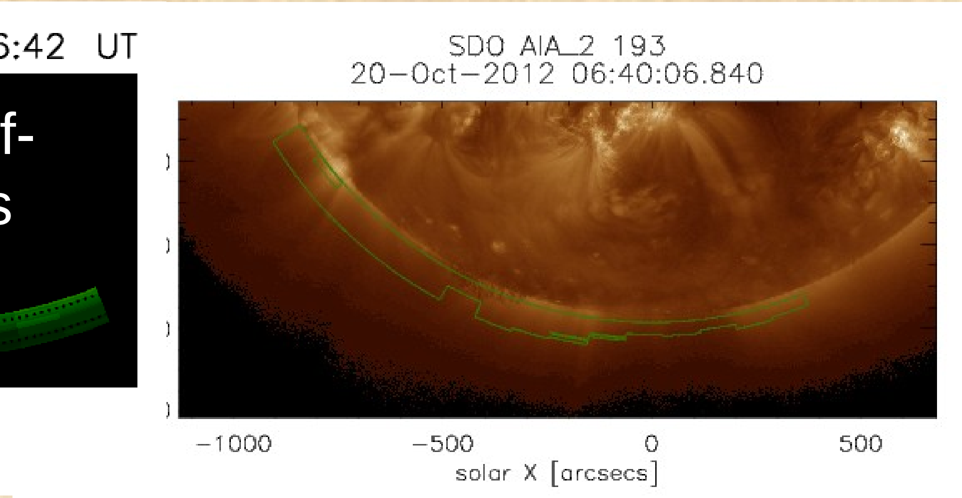


EUV contamination removed


τ193; Al–mesh
τ193; Al–mesh, EUV contamination removed
τ193; Ti–poly
height [1000 km]
91
76
62
48
34
20
position [1000 km]
49
109
169
230
290
350
1.90
1.52
1.14
0.76
0.38
0.00
3.50
2.80
2.10
1.40
0.70
0.00
5.00
4.00
3.00
2.00
1.00
0.00

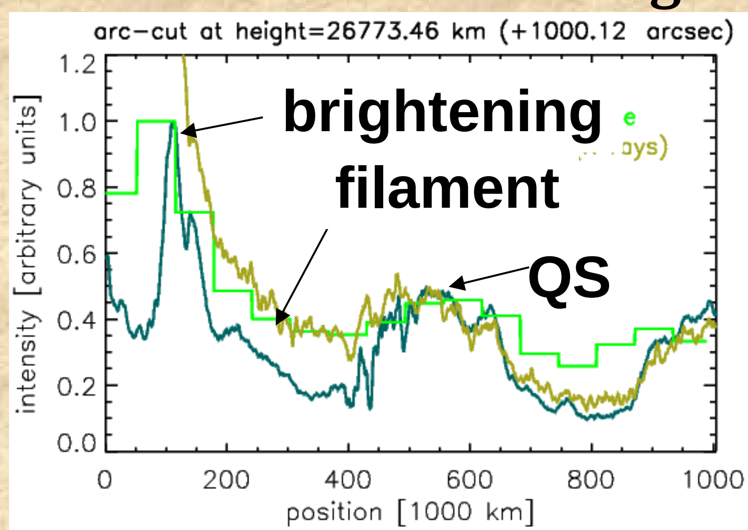
When using the green coronal line instead of the X rays

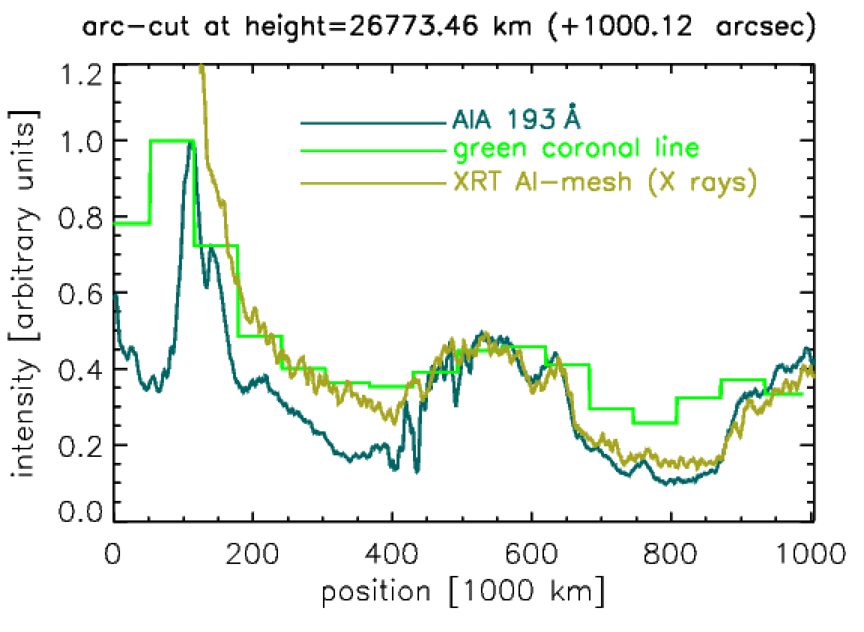


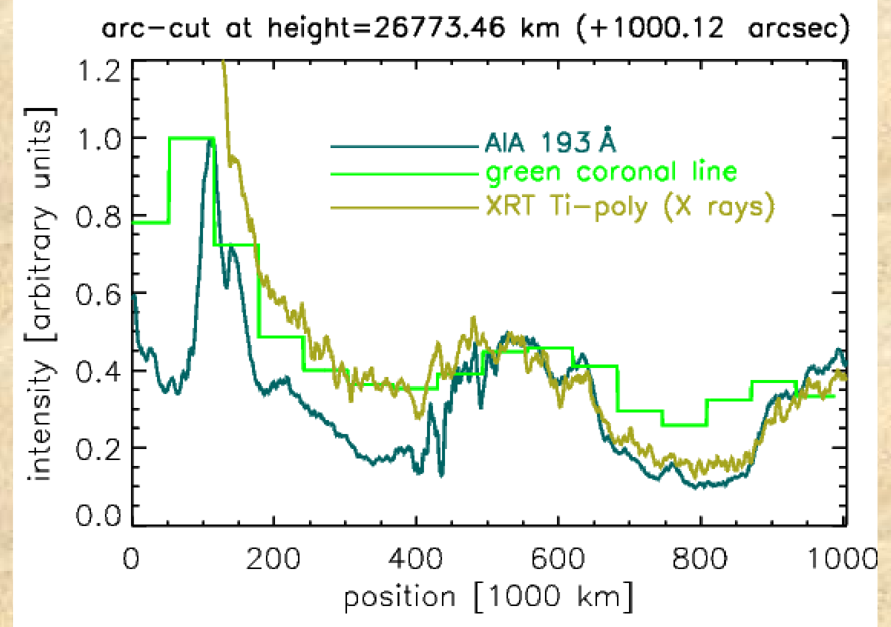


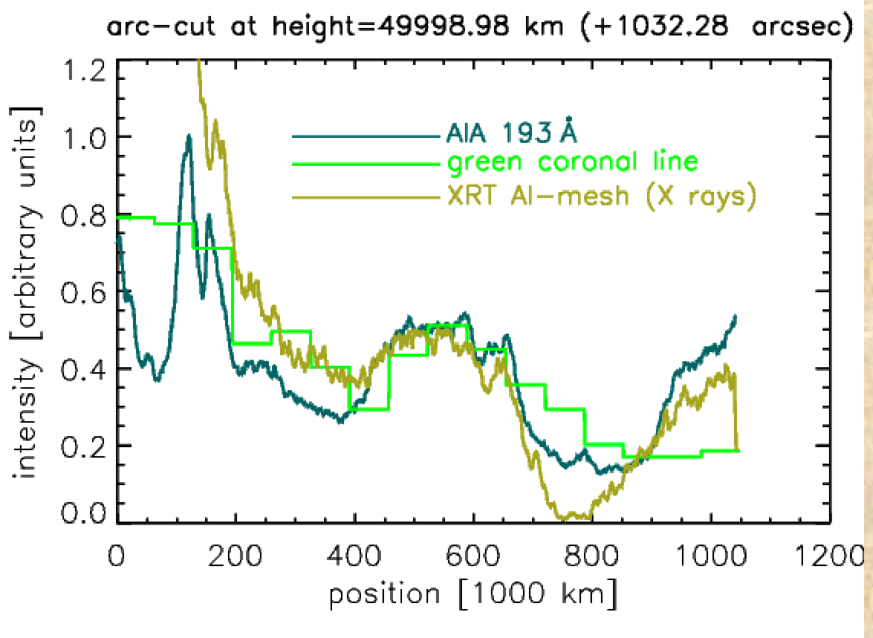
Total green-coronal line emission from Kislovodsk

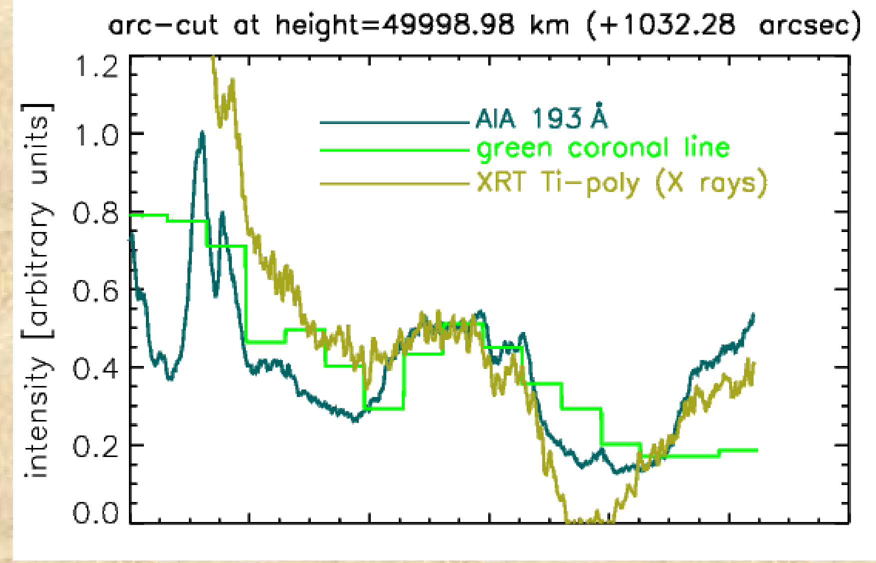
Co-alignment with AIA 193 Å image











estimated avg τ_{193}~ 1 – 2

CONCLUSIONS

– values of mass of the five quiescent prominences observed in EUV and X-ray during observing campaign from April through June 2011 are between $2.9 \times 10^{11} – 1.7 \times 10^{12}$ kg
– avg hydrogen column densities for the five prominences are of the orders $10^{18} – 10^{19}$ cm^{-2}. Thus, absorption of X-rays by the prominence plasma (H, He and other elements) should be negligible. But, our values of hydrogen column densities are limited by an effect of saturation – in some parts of the prominences the hydrogen column densitie can reach up to much higher values for which absorption in X rays cannot be neglected

CONCLUSIONS – continuation

– EUV contamination of XRT Al-mesh data causes only a small decrease of measured intensity at a prominence. Errors in the mass estimations caused by the EUV contamination for the five prominences observed during the campaign in 2011 do not exceed errors caused by noise in the data themselves. But errors caused by the EUV contamination can be much larger for some of other prominences, as it was shown for prominence from 20 October 2012. Therefore it is much better to use XRT X-ray data obtained with the Ti-poly filter for which the EUV contamination is negligible. Now, data of green coronal line are available only from a very limited FOV, but already showed that it could be used instead of XRT Ti-poly images. Observations of the green coronal line obtained at the Lomnicky Peak Observatory in much larger FOV can approve this much better.

– mainly coronal emissivity deficit is responsible for manifestation of the prominence of 22 Jun 2010 spine as dark structure in XRT X-ray data, not absorption. Effect of the EUV contamination on signal obtained with Al-mesh filter data is only several percent.

Thank you for your attention