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THE HOT SKIN OF PROMINENCE STRUCTURES

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Abstract. We observe various emission lines in solar prominences and compare the widths of He II 4686 Å, He I 4472 Å (triplet) and He I 5015 Å (singlet) with those of the optically thin Hγ and Mg b_2 lines. The latter two yield a thermal line broadening of $9000 < T_{kin} < 11\,000$ K, which fits the width of He I 5015 Å (singlet). However, He I 4471Å (triplet) shows an excess of 1.11 indicating an excitation of the triplet in 1.23 times hotter prominence regions. He II 4686 Å is 1.65 times broader and thus emitted in 2.73 times hotter regions of the prominence-corona transition layer, PCTR. The linear radiance relations He II/He tripl=50 and Hγ/He tripl=11.8 suggest a PCTR between each fine-structure thread and the surrounding hot coronal gas.

Key words: Prominences - helium emissions - transition layer - fine-structure

1. Introduction

In a recent paper (Ramelli, Stellmacher, Wiehr & Bianda 2012) we have shown that the only prominent line of singly ionized helium in the visible spectral range, He II 4686 Å(corrected for atomic fine-structure broadening), is 1.5 times broader than the He I 4471 Å triplet line which, in turn, is 1.1 times broader than the He I 5015 Å (singlet) line. This indicates an origin of the triplet line in 1.2 times and of the singly-charged helium in 2.7 times hotter layers than the singlet line.

The representation of the reduced widths as $v^2 = (c \cdot \Delta\lambda_D/\lambda)^2$ versus the inverse atomic mass $1/\mu$ (cf., Fig. 3) lacked of data for hydrogen. We thus used in our 2011 study a corresponding value for dense and bright prominences, $[\Delta\lambda_D/\lambda]_H = 3.7 \cdot 10^{-5}$, from Stellmacher and Wiehr (1994). If that value was associated with the observed one for Na D_2, the gradient of the $v^2(1/\mu)$ relation gave a thermal broadening of $T_{\rm kin} = 7000$ K; the observed v^2 values of the He I 5015 Å singlet line were always found above that curve, suggesting their origin in apparently hotter regions.

Besides the width, also the integrated emission ('line radiance') gives strong indication for an origin in prominence regions of increasing temperature from singlet to triplet to singly-charged helium. In particular, He II 4686 Å is observed 140 times brighter than predicted by the line radiance ratio He I (triplet)/He II = 7000 from iso-thermal models [$T = 8000$ K and $n_H = 10^{10}\,\mathrm{cm}^{-3}$] by Heasley, Mihalas and Poland (1974). Recent models, however, which include a prominence-corona transition region, PCTR (e.g., Labrosse and Gouttebroze) describe both, the increase of width from singlet to triplet to singly-charged helium, and the low line radiance ratio observed by Ramelli, Stellmacher, Wiehr and Bianda (2012).

2. Observations

Since our former results were based on few examples – the triplet over singlet excess only on three – we try to verify them in order to get a higher statistical significance. For the present measurements we add the Hγ line, which remains optically thin, while Hα largely exceeds $\tau_\alpha^0 = 1.0$ in prominences with sufficient Balmer brightness to also yield significant He II 4686 Å emission; here, even Hβ may reach $\tau_\beta \approx 1$ (cf., Stellmacher & Wiehr, 2005),

We now replace Na D_2 by the similar metallic line Mg b_2 in order to keep the complete spectral range of the observed emission lines as narrow as possible: Hγ 4340 Å through Mg b_2 5172 Å spans about 830 Å thus minimizing the wavelength dependence of both, refraction in Earth's atmosphere and scattering by dust on the telescope optics; it also simplifies the absolute calibration from the disk center continua.

In June 2012, we observed with the Ø=45 cm Gregory-Coudé telescope IRSOL (Ramelli et al., 2006) several prominences (Table 1) with bright but narrow Mg b_2 line profiles, being the tracer for a He II 4686 Å emission well above the noise level (see Ramelli, Stellmacher, Wiehr & Bianda, 2012).

Table I: Date and heliogr. position of the prominences observed.

June, 17	east limb, 23^{o}N	and	east limb, 18^{o}S
June, 27	west limb, 40^{o}N	lower part	upper part
June, 29	west limb, 27^{o}N	and	east limb, 30^{o}S

The CCD camera, available in 2012, introduced interference fringes, which disturb the spectra: while the strong emissions of Hγ and He I 4471 Å (triplet) can well be measured, the medium strong emissions of Mg b_2, He I 5015 Å (singlet) and Fe II 5018 Å are moderately affected, but the faint ones of He II 4686 Å and Ti II 4468 Å almost disappear in the interference fringes. This influence is reduced by averaging the emissions spatially over each prominence. For June 27 the extended prominence is separated into an upper and a lower part; only for the latter He II 4686 Å gives a profile of satisfactory accuracy.

3. Results

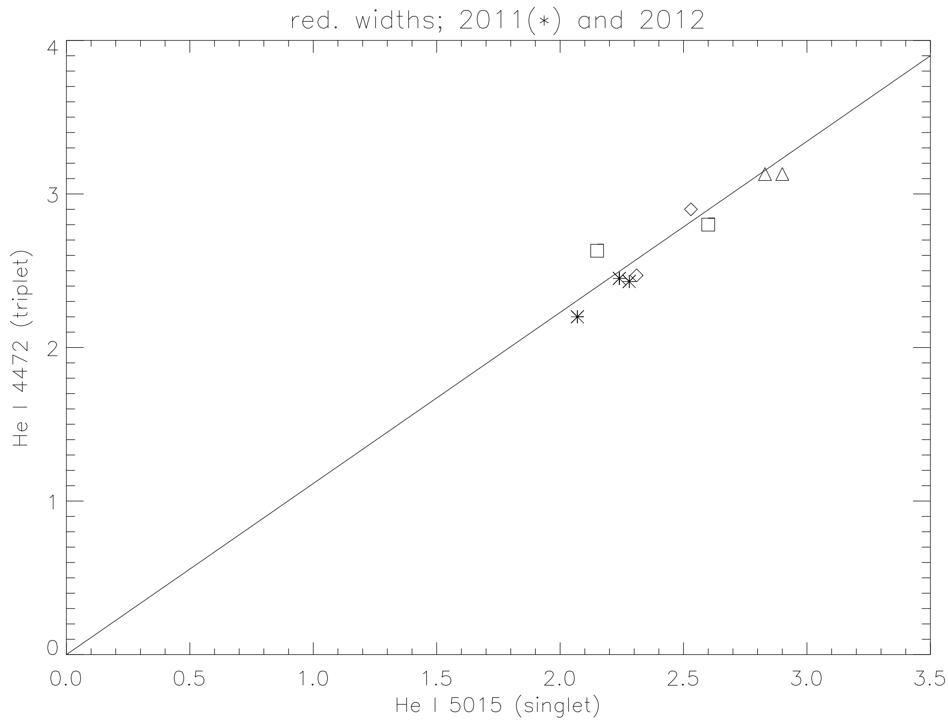

Figure 1: Reduced line widths $\Delta\lambda_D/\lambda$ $[10^{-5}]$ of He I 4471 Å (tripl) and He I 5015 Å (singl); *asterisks*: 2011-data; *squares*: June 17, *triangles*: June 27, *rhombs*: June 29, 2012.

3.1. The helium singlet and triplet lines

With the larger number of observed He I profiles we confirm our 2011 finding of excess widths at a higher statistical significance. The six new data points now yield a slightly larger mean excess 1.11 of the reduced line width $\Delta\lambda_D/\lambda$ as compared to that of 1.09 of our 2011 observations (asterisks in Fig. 1). The line intensity integrated over the emission profile ('line radiance') also gives a slightly larger ratio 9.4 (see Fig. 2) than the 8.7 value from 2011.

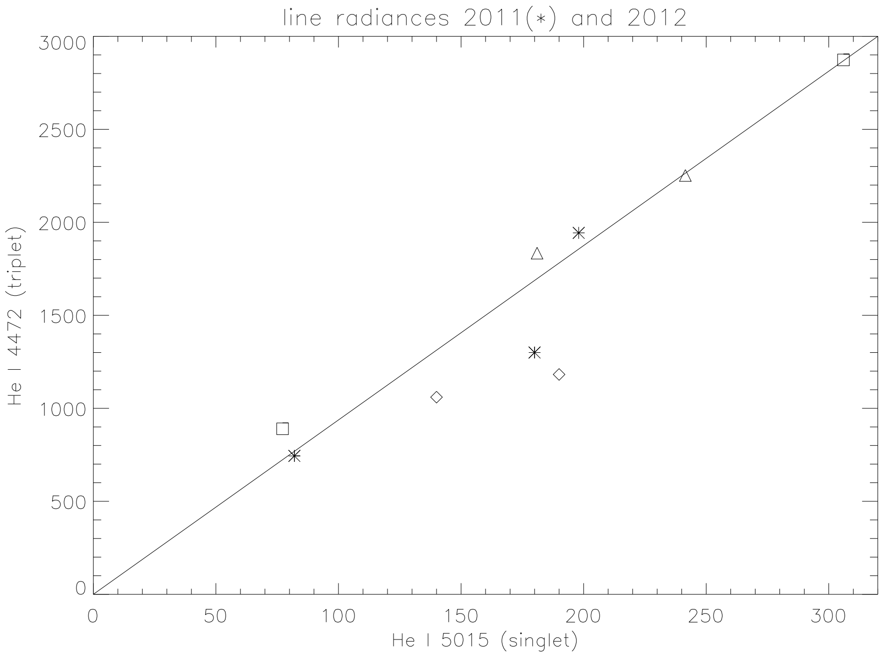

Figure 2: Line radiance $E = \int I\, d\lambda$ [erg/(s cm^2 ster)] of He I 4471 Å (triplet) versus He I 5015 Å (singlet), yielding a mean ratio of 9.4; same symbols as in Fig. 1.

3.2. The Balmer lines

In order to get an idea about the Balmer brightness of the individual prominence, we relate the line radiance of He I 4471 Å (triplet) with that of Hγ, and obtain a mean ratio of 11.8.

On June 16 and 17 we additionally observed the Hα emission, for which we find a maximum radiance value of $E_\alpha = 36 \cdot 10^4\,\mathrm{erg/(s\,cm^2\,ster)}$. The corresponding H$\gamma$ radiance of $2.9 \cdot 10^4$ gives a ratio of $E_\alpha/E_\gamma = 12$, which is much smaller than that of ≈ 30 for the optically thin case (cf., Stellmacher 1967, 1969). This shows that Hα largely saturates in those prominences, we select for sufficient He II 4686 Å brightness. The above Hα radiance value is of the order of the maximum observed by Stellmacher and Wiehr (2005), for which they give $\tau_\alpha^0 \approx 10.0$. We note that the above mean ratio of 11.8 yields for the highest triplet radiance recorded in 2011, 5120 $\mathrm{erg/(s\,cm^2\,ster)}$, an H$\gamma$ radiance of $6 \cdot 10^4\,\mathrm{erg/(s\,cm^2\,ster)}$ and thus $\tau_\alpha^0 > 10.0$

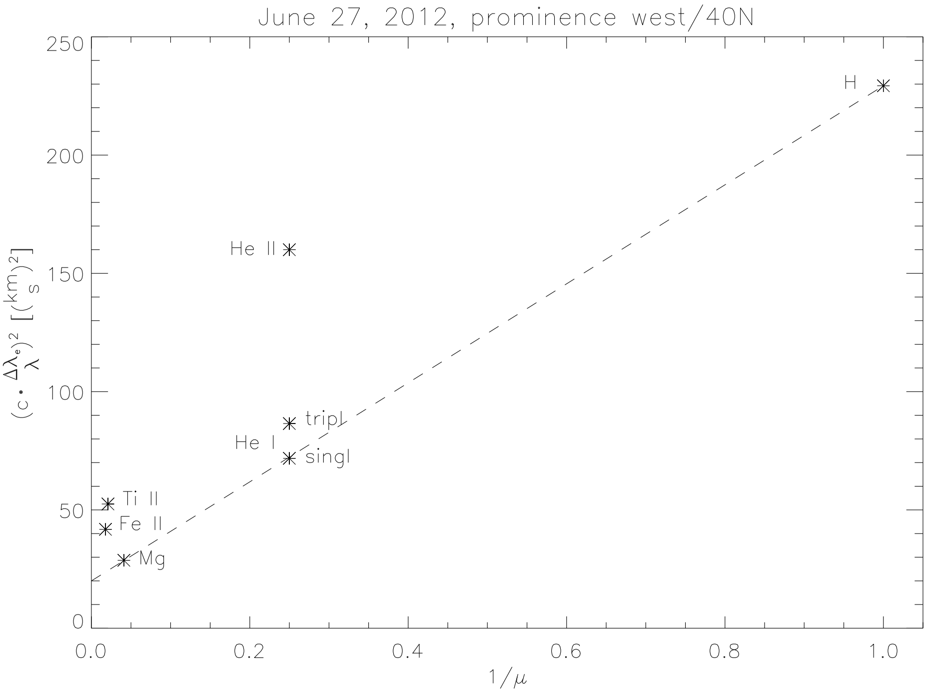

Figure 3: Line width $v^2 = (c \cdot \Delta\lambda_\mathrm{D}/\lambda)^2[(\mathrm{km/s})^2]$ versus inverse atomic mass $1/\mu$ for the emission lines Ti II 4468, Fe II 5018, Mg b_2, He I 5015 (singlet), He I 4471 (triplet), He II 4686 and Hγ 4340 Å; the solid line connects the Mg b_2 and Hγ values, its gradient corresponding to $T_{kin} = 11\,600\,\mathrm{K}$, its ordinate off-set gives $v_{nth} = 4.6\,\mathrm{km/s}$.

3.3. Line broadening parameters

The observation of the (optically thin) Hγ line allows us to deduce the line broadening parameters, T_{kin} and v_{nth}, in the relation $v^2 = (c \cdot \Delta\lambda_{\rm D}/\lambda)^2 = 2RT_{\rm kin}/\mu + v_{\rm nth}^2$. The surprisingly broad $[\Delta\lambda_{\rm D}/\lambda]_H \approx 7 \cdot 10^{-5}$ of the Hγ profiles yield T_{kin} values which give (combined with the respective ones of Mg b$_2$; Fig. 3), a rather high thermal broadening of the order of 10^4 K.

The $v^2_{singlet}$ of He I 5015 Å now fit $[T_{kin}; v_{nth}]$ (dashed line in Fig. 3) within the error limits set by the interference fringes. This indicates the same thermal broadening of singlet as Mg b$_2$ and Hγ. In contrast, the $v^2_{triplet}$ values of He I 4471 exceed that line, confirming our former finding.

A single He II 4686 profile (deduced with some uncertainty between the CCD interference fringes) confirms the large $v^2_{He\,II}$ excess detected by Ramelli, Stellmacher, Wiehr and Bianda (2012). Also their finding that singly-charged metals emit in similar layers as He I 4471 Å is confirmed by the excess of Fe II 5018 Å (and of one profile of Ti II 4688 Å).

4. Discussion

The much smaller value $[\Delta\lambda_D/\lambda]_H = 3.7 \cdot 10^{-5}$ used in our former analysis, was taken from high spatial resolution spectra by Stellmacher and Wiehr (1994). Associating that value with the observed ones of Na D$_2$ we obtained reasonable 7000 K. The $v^2_{singlet}$ values slightly exceeded that $T_{kin} = 7000$ K line in the $v^2(1/\mu)$ relation, suggesting an apparently hotter origin. The present observations, however, indicate $T_{kin} \approx 10\,000$ K and a similar origin of He I 5015 Å (singlet) as Hγ and Mg b$_2$.

These high T_{kin} disagree with former observations of (Balmer-)bright, dense, unstructured prominences (e.g. Stellmacher & Wiehr, 1995). In this study, however, we use spectra of moderate spatial resolution, resulting from the long exposure time (5 sec), required to detect the faint He II emission. The corresponding radiance up to E$\alpha = 36 \cdot 10^4$ erg/(s cm^2 ster) indicates an origin from more than 20 individual threads, assuming for each of them E$\alpha \leq 2 \cdot 10^4$ erg/(s cm^2 ster) (Stellmacher & Wiehr 1994). In that case, the line widths from atoms of different mass can only give *upper limits for the broadening parameters*, since the basic assumption of homogeneous T_{kin} and v_{nth} will not necessarily be valid for a summing-up of various threads (cf., Stellmacher & Wiehr 1981).

Since the $v^2_{singlet}$ values are now found on the dashed line in Fig. 3, we assume that *He I 5015 will be emitted in the same prominence volume as Hγ and Mg b₂ (and Na D₂)*. He I 4471 (triplet), however, is 1.11 times broader than He I 5015 (singlet). The corresponding temperature of the triplet emitting layers can be obtained (e.g. from Figure 3) connecting the ordinate off-set (here $v^2_{nth} = 20$) with $v^2_{triplet}$. The temperature excess then indicates a $(1.11^2 =)1.23$ times hotter origin for the triplet than for the singlet line.

As argued by Ramelli, Stellmacher, Wiehr and Bianda (2012), the helium triplet system can only be populated from the (singlet) ground state by ionization and recombination (or by direct collisions). Evidently, these processes occur in hotter prominence regions than those emitting the Hγ, He singlet and Mg b_2 lines.

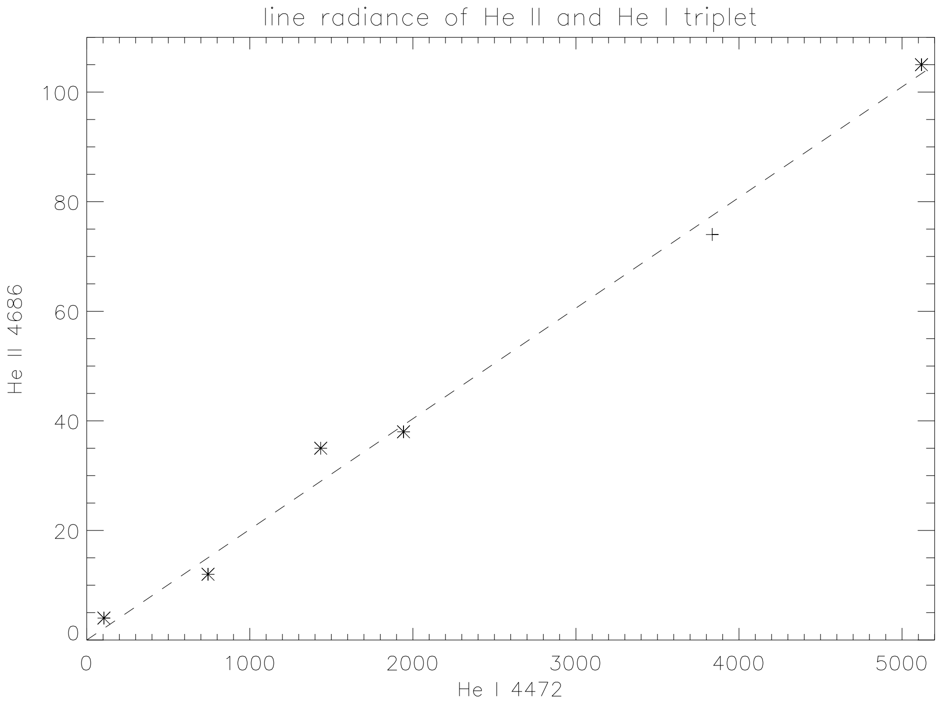

Figure 4: Line radiance $E_{tot} = \int I\, d\lambda$ [erg/(s cm^2 ster)] of He II 4686 Å versus He I 4471 Å (triplet); asterisks give the 2011 data, the cross marks the only 2012 value.

The excess of reduced widths of He II 4686 Å over He I 4471 (1.5) and over He I 5015 ($1.5 \cdot 1.1 = 1.65$) suggests the He II formation in 2.25 and, respectively, 2.72 times hotter layers, representing the prominence-corona transition region, PCTR. This is also indicated from the mean ratio of 50 of the line radiance of He I 4471 Å (triplet) and He II 4686 Å, which can only be explained by prominence models which include a PCTR (e.g., Labrosse and Gouttebroze 2004).

The finding of a *linear relation* of the line radiance of Hγ and He I 4471 Å and, moreover, that of He I 4471 Å (triplet) and He II 4686 Å (Fig. 4), emitted in layers of largely different temperature, favor the existence of PCTRs *around each thread*: If PCTRs were surrounding the prominences as a whole (like huge shells), we would hardly find linearly related radiance values for the variety of prominences observed, since their volumes relate with the third, their 'surfaces' with the second power of their size. The linear relations suggest a PCTR around each individual thread.

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