Astron. Astrophys. 319, 669–672 (1997)

ASTRONOMY AND ASTROPHYSICS

The helium singlet-to-triplet line ratio in solar prominences

G. Stellmacher[1] **and E. Wiehr**[2]

[1] CNRS; Institut d'Astrophysique, 98bis Bd.Arago, F-75014 Paris
[2] Universitäts Sternwarte Göttingen, D-37083 Göttingen, Germany

Received 24 May 1996 / Accepted 1 August 1996

Abstract. The emissions of the He singlet line at 6678Å and the He triplet line at 4471Å are simultaneously observed in three solar prominences. For two of them, the line pairs He-D_3/H_β and Ca^+8662/H_β were also observed. Comparisons with model calculations show that the emission line ratios require low densities ($n_H \approx 3 \cdot 10^{10} cm^{-3}$), low gas pressures ($P_g \approx$ 0.02 dyn/cm^2), and large physical slab widths. The relative He-to-H number density cannot be much lower than y = 0.1.

Key words: Sun: prominences – lines: formation

1. Introduction

Prominences observed at high spatial resolution show characteristic He-to-H emission line ratios which are related to the mean kinetic temperature, T_k, the non-thermal line broadening, ξ, and the fine-structuring (i.e. the packing of threads; cf. Stellmacher & Wiehr 1994a). The largest He-to-H emission line ratios are found in faint, highly structured prominences, where generally $T_k > 8000$K. Less structured prominences have low He-to-H ratios, and low $T_k \approx 6000$K with correspondingly narrow line profiles (Stellmacher & Wiehr 1994b, 1995). These prominences are generally bright in the Balmer lines: the H_α line is largely saturated with total optical thicknesses up to τ_α=7.0, and occasionally even self-reversed.

The calculations by Heasley et al. (1974) and by Heasley & Milkey (1976) show that the ratio of the singlet He 6687 to the triplet He 4471 line emission is sensitive to the optical thickness in the He 584 Å resonance line which, in turn, depends upon the density n_H. Calculations by Heasley & Milkey (1978) show that the emission ratios of the near infrared Ca^+ lines to H_β are a strong function of the gas pressure, only slightly sensitive to the thermal, and insensitive to the non-thermal line broadening.

In this paper, we present P_g- and n_H- sensitive observations consisting of three simultaneously observed line pairs taken successively with time intervals short enough to yield a homogeneous data set at a hithertoo not achieved spatial resolution and compare them with existing model calculations.

Send offprint requests to: E. Wiehr

2. Observations

The observations were made with the evacuated Gregory Coudé telescope on Tenerife island in July, 1994. The He 6678 and He 4471 emission lines were simultaneously observed in the 10^{th} and the 15^{th} grating order for five slit locations. A few minutes later, the line pair He D_3 and H_β was observed in the 10^{th} and 12^{th} order, and the line pair Ca^+8661 and H_β in the 4^{th} and 7^{th} order at the 'anti-blaze' of the grating. The spectra were taken on two 1024x1024 pixel CCD-cameras binned to 512x512. Exposure times of 1.5, 1.0, and 0.5 sec allowed a resolution of about 1 arcsec corresponding to 3.2 pixels. For the quiet structured hedge-row type prominence from July 22, only the singlet He 6678 and triplet He 4471 lines were observed (cf. Table 1):

Using IDL image processing routines, the raw spectra were correccted for the dark and the gain matrices before the stray-light aureoles were carefully elliminated. The reduced spectra were then calibrated in absolute intensities using our disc centre spectra and the data by Labs & Neckel (1970):

3. Results

3.1. Thermal and non-thermal line broadening

The classical method to determine the kinetic temperature, T_k, and the non-thermal line broadening, ξ, is to compare the observed line widths from elements with different atomic weights. This method is restricted to optically thin lines which are not broadened by the presence of macroscopic motions. For the prominences W-15 and W-25, the range of the measured line widths is rather broad; W-15 even shows a double-peaked distribution. The narrowest emission line profiles yield:

$9000 < T_k < 9500K; 6.5 < \xi < 8.0$ km/s for W-15

$8000 < T_k < 9000K; 6.0 < \xi < 8.0$ km/s for W-25

However, the high mean H_β brightness of both prominences indicates large optical depths and thus the superposition of an appreciable number of macroscopally shifted elements. Hence, the true line broadening parameters may actually be smaller. Conspicuously shifted line profiles occur for prominence W-15

Table 1. Observing dates, rominence position, and observed emission lines

date	position	observed emission lines
July 22	E+25	He singl/tripl
July 25	W-15	He singl/tripl ; He-D_3/H_β ; Ca^+8662/H_β
July 27	W-25	He singl/tripl ; He-D_3/H_β ; Ca^+8662/H_β

Table 2. Absolute intensities [10^6 erg/(cm^2· sec· sr·Å)] for the 5 wavelengths under study

I_{abs} :	4.46	4.16	3.36	2.76	1.68
λ[Å] :	4471	4861	5875	6678	8662

Table 3. He singlet-to-triplet emission line ratios

prominence	mean ratio	max. at low heights
E+25	0.22	–
W-15	0.22	0.28
W-25	0.24	0.28

in the vicinity of a gap-region, in agreement with similar results by Engvold et al. (1978) and by Stellmacher & Wiehr (1973).

For prominence E+25, the distribution of observed line widths is rather narrow. The smallest He profiles have Doppler widths $\Delta\lambda_D/\lambda = 2.2 \cdot 10^{-5}$. For this prominence, a separation of thermal and non-thermal line broadening is not applicable since only the He lines were observed. Considering purely thermal broadening ($\xi = 0$), the smallest profiles yield $T_k > 10700$ K.

3.2. The He singlet-to-triplet ratio

The observed integrated line emissions E=$\int$ I(λ) dλ cover the range 0.1 <E(He4471)< $0.32 \cdot 10^4$ $erg/(cm^2 \cdot sec \cdot sr)$. For the central parts of the prominence one obtains mean singlet-to-triplet ratios, whereas higher values are found at low heights (≈12 arcsec) above the visible limb.

Our observations cannot be directly compared with those by Landman & Illing (1976) since their mean ratios between 0.16 and 0.25 refer to fainter prominences (E(He4471)< $0.05 \cdot 10^4$ $erg/(cm^2 \cdot sec \cdot sr)$, cf. Fig. 1).

For comparison with model calculations by Heasley et al.(1974) and Heasley & Milkey (1976), we converted their given emission values of He5876 into equivalent emissions of He4471 using the factor E(He4471)/ E(He5876) = 0.137 which, following Heasley et al. (1974) and Heasley & Milkey (1976), is insensitive to the model parameters if $T_k < 10000$K. The ratio E(He4471)/E(He5876) corresponds to a Boltzmann distribution with $T_{ex} = 6250$ K between the upper 3d and 4d levels; the lower levels being common to both transitions.

Our lowest values E(He4471) ≈ $0.1 \cdot 10^4$ $erg/(cm^2 \cdot sec \cdot sr)$ are much higher than those in the model calculations by

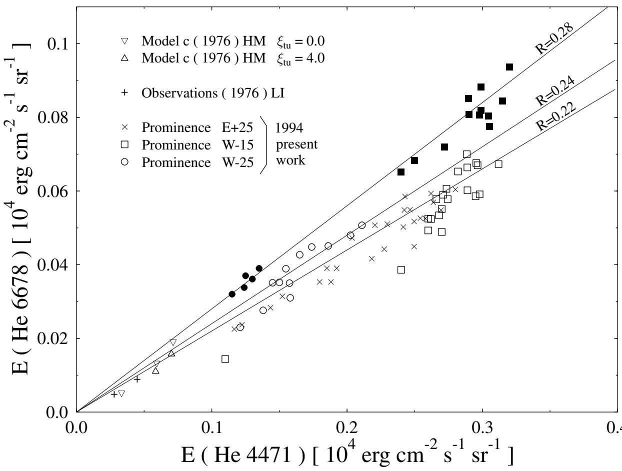

Fig. 1. Observed relations of the integrated line emissions E(He6678) versus E(He4471) to gether calculations by Heasley and Milkey (1976) for two values of non-thermal line broadening. Filled symbols denote emissions from low heights h≈12 arcsec above the limb. Mean slopes of the line emission ratios are indicted

Table 4. He-D_3-to-H_β emission line ratios

prominence	mean ratio	top regions	ejecta
W-15	0.48	0.58	0.9
W-25	0.52	0.65	–

Heasley & Milkey (1976, Tables 1 and 2). A linear extrapolation of our data to smaller emissions indicates that their model C with T_k=9500 K, P_g=0.065 dyn/cm^2, and $\tau_{584} > 1.5 \cdot 10^5$, and low densities $n_H \approx 2.5 \cdot 10^{10}$ cm^{-3} matches our observations.

3.3. The He-D_3-to-H_β ratio

The emission ratios of the lines He-D_3 and H_β were observed for prominences W-15 and W-25. In the central parts of the prominences, He-D_3 is largely linear related with H_β. The slopes in Fig. 2 yield mean ratios near 0.5, few detached regions at the top of the prominences show higher ratios (full symbols in Fig. 2). The faintest emissions from isolated clouds at the top of W-15 show clearly shifted line profiles ('ejecta'), which have significantly higher line ratios.

The observed mean ratio 0.5 agrees with the result of Stellmacher & Wiehr (1995) for prominences with $T_k \approx 8000$ K. The values of E(H_β) < $1.0 \cdot 10^4 erg/(cm^2 \cdot sec \cdot sr)$ overlap with the range calculated for model-c by Heasley & Milkey (1976, Tab.2). At some locations of high emission within W-15, the mean ratios drop to 0.43. These locations correspond to low prominence heights above the limb (h≈12 arcsec) which were found to show high He singlet-to-triplet emission line ratios (see above).

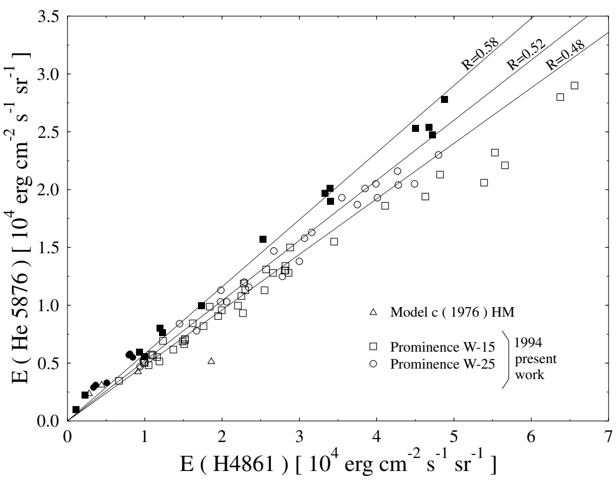

Fig. 2. Observed relations of the integrated line emissions E(He-D_3) versus E(H_β) in comparison with calculations by Heasley & Milkey (1976). Filled symbols denote emissions from detached regions at the top of the prominences. The mean slopes of the emission ratios are indicted

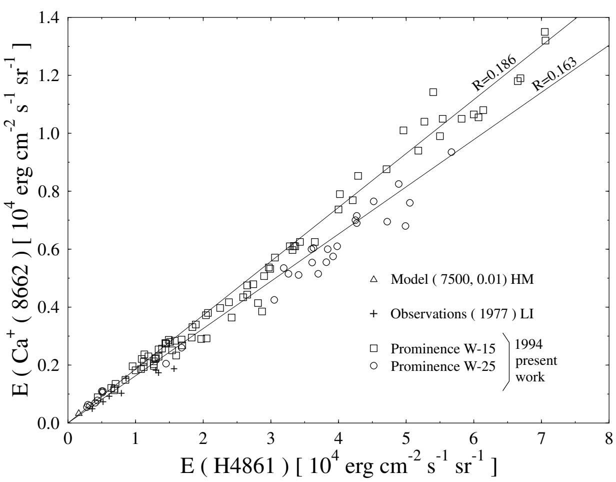

Fig. 3. Observed relations of the integrated line emissions E(Ca^+8662) versus E(H_β) in comparison with calculations by Heasley & Milkey (1978) for model (7500 ; 0.01). The mean slopes of the emission ratios are indicted

Table 5. Ca^+-to-H_β emission line ratios

prom.	Ca+8662/H_β	Ca^+8542/H_β	P_g[dyn/cm^2]
W-15	0.186	0.365	0.020
W-25	0.163	0.320	0.021

3.4. The Ca^+8662-to-H_β ratio

The observed emission line ratios E(Ca+8662) / E(H_β) amount to 0.186 and 0.160, respectively. These values agree with those between 0.12 and 0.18 found by Landman and Illling (1977) for fainter emissions (see Fig.3).

The calculations by Heasley & Milkey (1978) show that the Ca^+-to-H_β ratio depends strongly on the gas pressure, P_g, only slightly on T_k, but not on ξ. Since their Fig.2 only gives calculated ratios of Ca^+8542 to H_β, we converted our observed Ca^+8662 emissions into equivalent emissions of Ca^+8542. For this purpose, we use the factor E(Ca^+8662)/E(Ca^+8542) = 0.51, which Heasley & Milkey (1978) deduced from their model (7500; 0.01) that was adapted to the ratios 0.40 - 0.56 observed by Landman & Illing (1977). We then obtain E(Ca^+8542)/E(H_β) values of 0.365 and 0.32, respectively, which agree with the range 0.2 - 0.42 found by Landman et al. (1977).

Inserting our values into the relation E(Ca^+8542)/E(H_β) vs. P_g by Heasley & Milkey (1978), we finally obtain the gas pressure for W-15 with T_k = 9500K, and for W-25 with T_k =9000 K (cf. Table 5). The low dispersion in the linear emission relations in Fig. 3, indicates that P_g can be assumed to be rather constant over the prominences.

Such low gas pressures correspond to low densities n_H of the order of $2 \cdot 10^{10}$ cm^{-3} in agreement with the values derived from the observed He emission lines and the model calculations by Heasley & Milkey (1976).

4. Discussion and conclusion

When interpreting the observed prominence emission lines, one has to consider that theoretical models generally assume they are optically thin. Thicker prominences are modelled by superpositions of several intrinsically thin slabs, the number of threads along the line-of-sight then determining the final brightness. However, the physical slab width influences e.g. the He singlet-to-triplet ratio. The calculations by Heasley et al. (1974) and by Heasley & Milkey (1976) show that this ratio is sensitive to the optical thickness in the He 584 Å resonance line. In the optically thin case, photons escape in the He 584 line leading to a depopulation of the lower level of the He 6678 transition. In the optically thick case, this depopulation is reduced and the He 6687-to-He 4471 emission ratio increases. Higher non-thermal line broadening, ξ, also increases the escape probability in the He 584 line, thus lowering the singlet-to-triplet ratio.

Comparing our quasi-simultaneous, high resolution obervations with the model calculations by Heasley & Milkey (1976), we find that our largest singlet-to-triplet ratios of 0.25 (filled squares in Fig. 1) require thicker slabs than assumed in the models, explaining the increase of the singlet-to-triplet ratios. Indeed, H_α pictures from the preceeding days indicate that the corresponding filament is rather 'clumpy'. The largest ratios are found in low-lying (h$\approx$ 12 arcsec) regions of prominences W-15 and W-25 (cf. Fig. 1), for W-15 these are regions of highest emission.

The high slab widths are also required to explain the significantly low He-D_3-to-H_β ratios down to 0.43 (cf. Fig. 2) occurring in the brightest parts of prominence W-15 since the calculations by Heasley & Milkey (1976) show a systematic decrease of this relation for increased slab width.

The faint isolated knots at the top of the prominences (ejecta) which exhibit high He-D_3/H_β ratios (up to 0.9), require small physical slab widths, in agreement with their small spatial widths of 1 arcsec. The observed mean singlet-to-triplet ratio E(He 6687)/E(He 4471)$\approx$ 0.22 implies that the He-to-H number ratio cannot be much lower than the value of y=0.1 assumed in the models.

Besides the line ratios, the absolute line emissions, E, of our prominences are much higher than the values calculated by Heasley & Milkey (1976; Tables 1, 2). The theoretical models could achieve higher emissions via larger optical thickness τ_{584} by linear superposition of many elements along the line-of-sight keeping the individual slab width constant and the density low. Their model C (T_k=9500 K, P_g=0.065 dyn/cm^2) with $\tau_{584} = 1.5 \cdot 10^5$ and and n_H=2.5$\cdot 10^{10}$ cm^{-3} could then also match our mean singlet-to-triplet ratios of $\approx$ 0.22 found for large E(He 4471) values. The low densities in that model are also conform with the pressure values $Pg \approx 0.02$ dyn/cm^2 deduced from our observed Ca^+8662-to-H_β ratio.

Acknowledgements. The Gregory Coudé Telescope is operated by the Universitäts Sternwarte, Göttingen, at the Observatorio del Teide of the Instituto de Astrofísica de Canarias.

References

Engvold O., Malville J.M., Livingston W., 1978, SP. 60, 57

Heasley J.N., Mihalas P., Poland A.I., 1974, Ap.J. 192, 181

Heasley J.N., Milkey R.W., 1976, Ap.J. 210, 827

Heasley J.N., Milkey R.W., 1978, Ap.J. 221, 677

Labs D., Neckel H., 1970, SP. 15, 79

Landman D.A., Illing R.M.E., 1976, A&A 49, 227

Landman D.A., Illing R.M.E., 1977, A&A 55,103

Landman D.A., Edberg S.J., Laney C.D., 1977, Ap.J. 218, 888

Stellmacher G., Wiehr E., 1973, A&A 24, 321

Stellmacher G., Wiehr E., 1994a, A&A 286, 302

Stellmacher G., Wiehr E., 1994b, A&A 290, 655

Stellmacher G., Wiehr E., 1995, A&A 299, 921

This article was processed by the author using Springer-Verlag TEX A&A macro package version 4.