Solar prominences with Na and Mg emissions and centrally reversed Balmer lines

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Abstract. We observed bright solar limb prominences with significant emission of NaD2 and Mgβ2 simultaneously with the Hα, Hβ, HeD3, He4+4685, and the He5+ singlet 5015 Å lines, using the THEMIS telescope on Tenerife. We find that most prominences with significant NaD2 and Mgβ2 emissions show pronounced centrally reversed Hα profiles, and occasionally even of Hβ; the strongest emissions reach integrated intensities Eβ > 16 × 104 [erg/(cm2 s str)]. The centrally reversed profiles are well reproduced by semi-infinite models. The source function reaches S0 ≈ 36 × 104 [erg/(cm2 s str Å)] corresponding to an excitation temperature T exc ≈ 3950 K; here, the optically thickness of Hα amounts τα ≈ 10. The line widths of the NaD2, Mgβ2, and HeD3 profiles yield kinetic temperatures 7000 ≤ T kin < 8000 K and non-thermal broadening vth = 5 km s−1.

Key words. Sun: prominences – radiation mechanisms: non-thermal – line: formation

1. Introduction

The simultaneous emission of resonance lines with low ionization potential, like Mgβ2 and NaD2, and of hydrogen and helium with much higher excitation and ionization energies, illustrates the large deviations from LTE in atmospheres of solar prominences. However, only a few comprehensive data sets of such emissions have so far been published, e.g., Yakovkin & Zel’dina (1964), Kim (1987). High precision data of spectral prominence photometry show for faint emissions (Eβ ≤ 1 × 104 erg/(cm2 s str), corresponding to τα ≤ 1) a unique empirical relation between Hα and Hβ independent on the individual prominence atmospheres (Stellmacher & Wiehr 1994b). For higher emissions, this relation depends on the individual prominence atmospheres (Stellmacher & Wiehr 1995). They allow a determination of upper limits of the source function of Hα as well as a quantitative analysis of the centrally reversed Hα profiles and their representation by models.

2. Observations and data reduction

We simultaneously observed with the French-Italian solar telescope THEMIS the emission lines Hα, Hβ, NaD2, Mgβ2, HeD3, He4+4685, and He5+ singlet 5015 Å with seven CCD-cameras on October 18 and 23, 2000. Entrance slits of 0.5 arcsec and 0.75 arcsec widths for the two data sets were oriented parallel to the direction of atmospheric refraction. Exposure times of a few seconds yielded about 2000 counts for the brightest Hα, and 300 counts for the faintest Mgβ2 emissions.

The CCD-images were corrected for the dark and the gain matrices; the underlying stray-light aureole was subtracted using spectra from locations adjacent to the corresponding prominence. For the calibration of the prominence emissions, we took disk-center spectra and used the absolute intensities of Labs & Neckel (1970): I (6563 Å) = 2.86, I (5890 Å) = 3.34, I (5876 Å) = 3.36, I (5173 Å) = 3.93, I (5015 Å) = 4.06, I (4861 Å) = 4.16, I (4685 Å) = 4.3 [10^3 erg/(cm^2 s str Å)].

We determine the total emission E of a line as the intensity integrated over the whole emission profile: E = \int I \, dλ [erg/(cm^2 s str)]; we give I and E in units of 10^4 to enable an easy comparison with former data. Hα solar survey images of the prominences analyzed (Fig. 1) show that these low solar latitude objects (φ < 32°) occurred under various aspect angles between “face-on” and “end-on”. An example of simultaneously observed CCD spectra is displayed in Fig. 2.

3. Results for the Hα and Hβ lines

3.1. The Hα versus Hβ emission relations

Our observed Hα and Hβ emissions, given in Fig. 3, reach integrated intensities of up to Eβ = 16 × 10^4, being four times higher than the maximum values by Stellmacher & Wiehr (1994b, their Figs. 2 and 3). Comparably high values were published by Yakovkin & Zel’dina (1963; shown in Fig. 3).

For faint emissions, our data perfectly match those from Stellmacher & Wiehr (1994b) who found for Eβ ≤ 1 × 10^4...
October 18, 2000

Fig. 2. CCD spectra of the Balmer lines Hα (upper left), Hβ (upper right), both with central reversions, and the simultaneously observed HeD3 (lower left), NaD2 (lower right) in the prominence at E/22N on Oct.18; each sub-image: 41′′ × 2.5 Å.

October 23, 2000, SE

October 25, 2000, SE

Fig. 1. Hα solar survey images from the Meudon observatory with the observed prominences at E/22N and W/24S (upper panel) and at E/5N, E/15S, E/23S, and E/32S (lower left panel), together with the corresponding disk filaments two days later (lower right panel) showing the different aspect angles.

3.2. Centrally reversed Hα

We observe distinct central reversions (double peaks) of the Hα line profile for integrated intensities $E_β > 5 \times 10^4$. An example of centrally reversed Hα and Hβ profiles is shown in Fig. 4 together with profiles of other simultaneously observed lines. We find the most prominent central reversions in the strongest, yet narrow emission profiles. In Fig. 5 we give the observed relations in comparison to corresponding curves deduced from the comprehensive set of Hα emission...
profiles calculated by GHV for thick slabs of models with $T_{\text{kin}} = 6000$–$8000$ K and $v_{\text{tu}} = 5$ km s$^{-1}$, acting as semi-infinite layers. We find that profiles with the most prominent central reversals are markedly narrow; their values (filled circles in Fig. 5) well follow the calculated relations and can, hence, be explained by pure line-saturation. Data that deviate from the calculated curves (open circles) are derived from broader line profiles; stronger broadening (e.g., by macro velocities or superpositions) will readily lead to a deterioration of the pure saturation effect.

The mean Doppler widths of our simultaneously observed lines amount to $\Delta \lambda_{D}^{\text{He}D_{2}} \leq 160$, $\Delta \lambda_{D}^{\text{Na}D_{2}} \approx 95$, and $\Delta \lambda_{D}^{\text{Mg}b_{2}} \approx 82$ mÅ; (the latter two being obtained from plots $E_{\text{Na}, \text{Mg}} = f_{\text{Na}, \text{Mg}}^{\text{He}} \Delta \lambda_{D} \cdot \sqrt{\tau}$). These widths set an upper limit for the broadening parameters of the observed prominence lines of $7000 \leq T_{\text{kin}} < 8000$ K with a non-thermal (Maxwellian) velocity of $5$ km s$^{-1}$.

The fact that the bright and rather unstructured prominences show strikingly narrow lines was already mentioned by Stellmacher & Wiehr (1994b). We consider the central reversions as a signature of emission in semi-infinite dense layers. No evident relation is found between the intensity difference of the two emission peaks and the line-center wavelength. Here, non-LTE transfer calculations should be considered, including “spatially correlated velocity fields” as suggested by Magnan (1976).

### 3.3. Central Intensities and source function $S_{\alpha}$

The double peaked Hα emissions originate from thick layers $r_{\text{ex}}^{\text{H}} \gg 1$, for which the line center intensities become $I_{\text{ex}}^{\alpha} = I_{\text{H}}^{\alpha}(1 - e^{-r_{\text{ex}}}) \approx S_{\alpha}$ allowing us to directly deduce the source function. For the stronger emissions, we find $r_{\text{ex}}^{\alpha} > 5$ (following the method described by Stellmacher & Wiehr (1994b; Sect. 4). If we express the relative level population of the Hα transition by the Boltzmann formula: $(n_{0.3 \ 90.3})/(n_{0.2 \ 90.2}) = \exp[-hc/(\lambda_{\alpha} k T_{\text{ex}}^{\alpha})]$, and insert this into the general equation for the source function, we obtain the corresponding Planck formula for the excitation temperature $T_{\text{ex}}^{\alpha}$:

$$S_{\alpha} = (2 \ h \ c^{2} / \lambda_{\alpha}^{3} / (\exp[-hc/(\lambda_{\alpha} k T_{\text{ex}}^{\alpha})] - 1) = B(T_{\text{ex}}^{\alpha})$$

($B$ being the Planck function).

The mean upper values $I_{\text{ex}}^{\alpha} = 36 \times 10^{4}$ (Fig. 6) correspond to an excitation temperature $T_{\text{ex}}^{\alpha} \approx 3950$ K. Fainter prominences analyzed by Stellmacher & Wiehr (1994b) gave smaller mean upper values $I_{\text{ex}}^{\alpha} \approx 26.5 \times 10^{4}$ corresponding to $T_{\text{ex}}^{\alpha} \approx 3700$ K. GHV obtain for their models with $T_{\text{kin}} = 6000$ K and $v_{\text{tu}} = 5$ km s$^{-1}$ a source function $S_{\alpha} = 36 \times 10^{4}$ at $r_{\text{ex}}^{\alpha} = 10$, in good agreement with the present observations (Fig. 6).

The intensity peaks of the centrally reversed profiles reach values near $I_{\text{ex}}^{\alpha} = 43 \times 10^{4}$ (cf., Fig. 5) which correspond to $T_{\text{ex}}^{\alpha} = 4000$ K. These peaks outside the line center arise from smaller $r_{\text{ex}}$ values, their higher intensity then indicates an increase of the source function towards the prominence interior (see also Yakovkin & Zel’dina 1964). The model calculations GHV (1994; their Fig. 18) indicate a rise of $S_{\alpha}$ beyond $0.16 \times I_{\text{phot}}$, i.e. $46 \times 10^{4}$; this does not seem to be observed in prominences, and it would disagree with their visibility as dark filaments on the disk. Such high $S_{\alpha}$ may be valid for spicules and eruptive objects.
Fig. 6. Observed relation between the integrated intensity \( I_e \) and the central intensity \( \dot{E}_e \); filled circles mark \( \text{H}_\alpha \) profiles with prominent central reversions, filled squares denote values with centrally reversed \( \text{H}_\beta \) profiles.

Fig. 7. Integrated intensities of \( \text{HeD}_3 \) and \( \text{H}_\beta \); emissions corresponding to prominent \( \text{H}_\alpha \) reversions are marked by filled circles; full lines trace emission ratios of 0.5, 0.4, 0.3, and 0.2.

4. The helium emissions

The simultaneously observed \( \text{HeD}_3 \) and \( \text{H}_\beta \) lines show distinct branches in their intensity relation (Fig. 7): Emissions from prominence locations with prominent \( \text{H}_\alpha \) reversions show ratios \( E_{\text{HeD}_3}/E_\beta \approx 0.2-0.5 \), while less thick prominences follow branches with ratios 0.4–0.5. This confirms earlier results by Stellmacher & Wiehr (1994a, 1995) who found from analysis of He 3889 and H 3888, and of He D3 and \( \text{H}_\beta \), that the emission ratios of the He-triplet and the Balmer lines show for individual prominences typical mean values, in the sense that prominences with stronger Balmer emissions (known to be cooler, less structured, and denser; cf., Introduction) yield lowest Helium-to-Balmer ratios.

The ratio of the \( \text{HeD}_3 \) fine-structure components is a measure of the optical thickness, as was shown by Stellmacher et al. (2003) for the analogous case of the triplet \( \text{He} \) 10830 Å. In contrast, the \( \text{HeD}_3 \) triplet does not allow us to determine the ratio of the faint red and the (not separated) two blue components with similar reliability, due to the much smaller spectral separation of its components. We find ratios above 1/6, indicating that \( \text{HeD}_3 \) begins to saturate, for emissions \( E(\text{HeD}_3) \geq 0.6 \times 10^{4} \).

Our instrumental set-up also allowed the simultaneous observation of the lines He II 4685.7 and He I 5015.7 (singlet). We did not find any significant He II emission in the prominences observed, which may be too cool and dense for sufficient He II excitation. The faint He I singlet line was only measurable in one prominence, its width is quite similar to that of \( \text{HeD}_3 \): \( (\Delta \lambda_{\text{D}}/\lambda_{\text{He}})_{\text{He}} \approx 3 \times 10^{-3} \). The integrated intensity \( E(\text{He} 5016) \approx 0.05 \times 10^{4} \) gives an emission ratio with \( \text{HeD}_3 \) of \( E_{\text{singl}}/E_{\text{tripl}} \approx 0.016 \). Other line combinations, including the stronger singlet line He 6678, might be useful to extend the study of singlet-to-triplet ratio by Stellmacher & Wiehr (1997).

5. Emissions of the metal lines NaD2 and MgB2

The integrated intensities \( E(\text{Mgb}_2) \) and \( E(\text{NaD}_2) \) show a linear relation (with a gradient of 0.7; Fig. 8), indicating that the emissions of both lines are closely related. Their integrated intensities strongly depend on the prominence thickness, as can be seen from the relation with \( \text{H}_\beta \) in Fig. 9. We observe reliable emissions of \( \text{NaD}_2 \) only if \( \dot{E}_\beta > 3 \times 10^{4} \). The strongest \( \text{NaD}_2 \) emissions, up to \( E(\text{NaD}_2) \approx 0.78 \times 10^{4} \), are observed at prominence locations where the \( \text{H}_\beta \) profiles are saturated or even centrally reversed (i.e., \( \dot{E}_\beta > 10 \times 10^{4} \)).

The narrow widths of these turbulence-sensitive metal lines (\( \Delta \lambda_{\text{NaD}_2} \approx 95 \text{ mÅ}, \Delta \lambda_{\text{Mgb}_2} \approx 82 \text{ mÅ} \)) imply rather cool emission layers with line broadening parameters \( T_{\text{kin}} \approx 7000 \text{ K} \) and \( v_{\text{los}} \approx 5 \text{ km s}^{-1} \) (see Sect. 3.2). Similarly narrow profiles of \( \text{Mgb}_2 \) were reported by Landman (1985). Comparison with model calculations by Kim (1987; Fig. 7) indicates that these observations can only be reproduced with high total number densities \( N \geq 10^{12} \text{ cm}^{-3} \).

6. Conclusion

The present spectro-photometry extends former analysis (Stellmacher & Wiehr 1994b, 1995) to four times higher \( \text{H}_\beta \) emissions. Our observed bright prominences are low latitude
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objects, i.e. at $\phi \leq 32^\circ$. We find prominent central reversions of H\(\alpha\) and occasionally of H\(\beta\) for integrated intensities $E_\beta > 5 \times 10^4$ [erg/(cm$^2$ s str)]. These centrally reversed profiles can well be modeled assuming semi-infinite layers, as is seen from a comparison with model calculations by Gouttebroze et al. (1993). The emitting layers should then consist of densely wound fibers forming massive ropes or wicks (cf., Engvold 1997).

THEMIS proved to be a powerful instrument for multi-line spectral photometry, also useful for solar prominences. Due to its low stray-light level (seen in the rather faint aureoles in our spectra) and its low instrumental polarization, one may extend these observations to filtergram techniques (cf., Stellmacher & Wiehr 2000) for a study of the dynamics of small-scale prominence structures inclusive their magnetic field as, e.g., done by Wiehr & Bianda (2003).

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