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MODELLING OF HELIUM SPECTRUM IN SOLAR PROMINENCES

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ABSTRACT

We present new non-LTE calculations for the neutral and ionized helium spectrum in quiescent solar prominences. We investigate the formation of helium lines and continuum within the frame of one dimensional, isothermal and isobaric static slab models. In a previous work (Labrosse & Gouttebroze 1999) we have shown the effects of three parameters of our numerical code (the electron temperature, the gas pressure, and the slab width) on the emerging helium spectrum. In the following we compare our results with former computations by Heasley, Mihalas and Poland (Heasley et al. 1974) and by Heasley and Milkey (Heasley & Milkey 1976).

Our conclusion is that there is a reasonable agreement between our results and those former computations. However there exist some discrepancies which may be attributed to different boundary conditions in hydrogen spectrum computations.

Key words: helium:lines; Sun:prominences.

1. INTRODUCTION

In this work we present our results from new computations of hydrogen and helium spectrum. We do comparisons with Heasley, Mihalas and Poland models (Heasley et al. 1974, hereafter HMP), and Heasley and Milkey models (Heasley & Milkey 1976, hereafter HM2; see also Heasley & Mihalas 1976, Heasley & Milkey 1978, Heasley & Milkey 1983). They calculated the hydrogen and neutral helium spectrum for a consistent prominence model. HMP models have temperatures of 7000 K and 8000 K, a slab width of 6000 km and total hydrogen densities (neutral plus ions) of $n_H = 10^{10}$ and 10^{11}. The HM2 models have temperatures of 7500 and 9500 K, central gas pressures of 0.065 and 0.26 dyn cm^{-2} and no microturbulent velocity.

The comparison of HMP and HM2 results with ours concerns population densities, optical depths and integrated intensities. We focus on helium results since some papers have been already published for hydrogen (Gouttebroze et al. 1993, hereafter GHV, and Heinzel et al. 1994) using the numerical code established by Gouttebroze.

2. MODELLING

2.1. Prominence Model

Our prominence model is the same as described in Labrosse & Gouttebroze 1999. It consists in plane-parallel slabs standing vertically above the solar surface. Observations are made in a direction perpendicular to the slab surface. The prominence is illuminated on both surfaces by an incident radiation field which determines the boundary conditions for the resolution of the radiative transfer equations. This radiation field comes from the photosphere, the chromosphere and the corona and is deduced from observations of the solar disk. The models are defined by the temperature, the gas pressure, the microturbulent velocity and the thickness of the slab. The first three quantities are supposed to be constant throughout the slab.

2.2. The Model Atom

The hydrogen atom is the same as in Labrosse & Gouttebroze 1999 and is described in details in GHV. We have improved the helium model atom with two more levels for the ionized helium. So we have 13 bound levels for He I, 4 bound levels for He II, and the continuum. Thus we obtain 3 resonance and 20 subordinate lines for He I, and 3 resonance and 3 subordinate lines for He II. Departures from Local Thermodymanic Equilibrium (LTE) are allowed for each level. All lines and continua are treated in non-LTE. The energy levels and the incident radiation for helium line transitions have been taken in HMP (see Tables 1 and 2 in their paper). Though our numerical code allows Partial Redistribution studies (necessary for the resonance lines), we made the computations in Complete Redistribution in order to stay as close as possible to HMP and HM2 models. Collisional ionization rates are calculated as in Mihalas & Stone 1968, and collisional excitation rates are taken from Avrett 1994.

2.3. Computational Procedure

The computations are first made for hydrogen in order to obtain along with the hydrogen spectrum

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the level populations, the electron densities and the mean intensities at different wavelengths for different depths inside the slab. Then the radiative transfer and statistical equilibrium equations are solved for helium with the incident radiation field in neutral and ionized helium lines wavelengths from HMP, and taking into account the radiation field in the slab due to hydrogen. The statistical equilibrium equations are solved by iteration. The radiative transfer equations in optically thick transitions are solved by the Feautrier method with variable Eddington factors. The helium-to-hydrogen number ratio is 0.1.

3. COMPARISONS

The prominence model is the same in each case (1D isothermal and isobaric static slabs). Some differences appear in the hydrogen model atom (our model atom includes more bound levels). We use accurate observed incident radiation profiles for hydrogen. The statistical equilibrium equations are solved here by iterations, but by the complete linearization scheme for HMP and HM2. Nevertheless we use atomic data for helium which are very close to those used in HMP and HM2. Tables 1 and 2 show comparisons of respectively physical and optical properties between our results and those from Heasley, Mihalas and Poland. We have computed four models with two different temperatures of 7000 and 8000 K, two different total hydrogen densities of 10^{10} and 10^{11} cm^{-3}, and no microturbulent velocity. In Tables 3 and 4 we show also comparisons for physical and optical properties of the model prominences between our results and those of Heasley and Milkey. Again we have computed four models corresponding to two different temperatures T (7500 and 9500 K) and two different central gas pressures P (0.065 and 0.26 dyn cm^{-2}) with no microturbulent velocity. The first thing we can see in these comparisons is that the slab width is different in our computations from HM2 computations. This comes from the differences in boundary conditions.

In Table 1 we report optical depths and population ratios for HMP models. Optical depths are in good agreement, but for the continuum edge of ionized helium (227 Å), our optical depth is smaller than for HMP. Ratios n(He II)/n(He I) are similar at slab surface but at slab center ours are smaller than for HMP. Ratios n(He III)/n(He II) are very similar. We observe a weak helium ionization at slab center.

In Table 2 we show integrated intensities for several neutral and ionized helium lines. There is a good agreement with HMP results. We can note that at 584 Å our integrated intensities are smaller than those of HMP.

In Table 3 population ratios n(He II)/n(He I), electron densities and optical depths are shown. The ratios are quite similar at slab surface, but ours are much smaller at slab center. The ionizing radiation field does not penetrate deep enough in the slab to ionize helium. The electron densities are of the same order, but ours are smaller. At slab center the difference between our results and HM2 results is larger than at slab surface, which confirms the weak ionization in our computations. Our Lyman continuum opacity is larger than for HM2. This acts as well against the helium ionization at slab center. Opacities for He I resonance continuum edge (504 Å) and He I λ584 Å are of the same order in each computations.

In Table 4 we report the integrated intensities for several hydrogen and neutral helium lines. We can see that our helium integrated intensities are of the same order than for HM2.

4. CONCLUSIONS

In this work we have presented comparisons between computations made by Heasley, Mihalas and Poland in 1974 and Heasley and Milkey in 1976, and our new non-LTE computations. Slight discrepancies are found but they may come from some differences in the boundary conditions especially for hydrogen spectrum computations.

We stress that in order to stay as close as possible to HMP and HM2 computations we have considered only Complete Redistribution. However our numerical code allows Partial Redistribution in the hydrogen and helium resonance lines which can have significant influence on the emergent profiles and the opacities.

After introducing the most recent atomic and spectroscopic helium data and more realistic incident profiles we will present in a future work some comparisons with helium lines profiles obtained with SUMER and CDS instruments of SoHO. Our numerical code will be used as a diagnostic tool to analyze helium lines observations.

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Table 1: *Comparison of physical properties (HMP models).*
Units: electron temperature T(°K); total hydrogen density n_H(cm^{-3}).

Model	T	n_H	Optical Depth (total slab)				n(He II)/n(He I)		n(He III)/n(He II)	
			$\tau(\lambda912)$	$\tau(\lambda504)$	$\tau_0(\lambda584)$	$\tau(\lambda227)$	slab surface	slab center	slab surface	slab center
HMP 4	7000	10^{10}	2.50	3.6	1.9+4	0.8	0.44	0.37	2.-4	1.-4
here			17	4.1	4.4+4	0.07	0.26	0.04	2.-4	2.-4
HMP 5	7000	10^{11}	116	66	2.6+5	10.4	0.05	2.-6	2.-5	1.-7
here			367	49	5.2+5	0.02	0.05	8.-8	3.-5	1.-5
HMP 7	8000	10^{10}	2.30	3.4	1.7+4	0.8	0.53	0.46	2.-4	1.-4
here			18	4.5	4.5+4	0.08	0.27	0.03	2.-4	2.-4
HMP 8	8000	10^{11}	54	54	2.6+5	9.4	0.06	8.-6	2.-5	1.-7
here			319	48	4.9+5	0.01	0.05	1.-7	3.-5	6.-6

Table 2: *Comparison of optical properties (HMP models): Integrated helium line intensities (ergs cm^{-2} s^{-1} sr^{-1}).*
Units: electron temperature T(°K); total hydrogen density n_H(cm^{-3}).

Model	T	n_H	λ (Å)												
			304	522	537	584	1640	3889	5015	5876	6678	7065	7281	10830	20581
HMP 4	7000	10^{10}	381	1.49	8.15	356	0.172	246.9	28.9	1937	60.1	234	7.79	8866	39.7
here			374	1.44	5.93	58.2	0.168	157.9	12.8	1404	6.74	176	4.09	6766	12.8
HMP 5	7000	10^{11}	224	1.06	5.08	96	0.102	180.3	11.5	1408	25	170	3.18	6474	14.6
here			267	1.40	5.51	54	0.287	105.9	22.1	902	9.9	124	11.96	4268	11.4
HMP 7	8000	10^{10}	424	1.64	8.86	370.4	0.186	258.9	29.39	2032	60.9	245	7.90	9300	40.1
here			393	1.53	6.32	61.6	0.175	168.6	14.1	1496	7.3	188	4.51	7184	13.8
HMP 8	8000	10^{11}	245	1.20	5.73	122.7	0.111	236.5	17.5	1846	39.3	223	5.02	8463	23.8
here			282	1.49	5.86	58.0	0.804	110.4	36.1	902	15.8	138	21.8	4206	14.5

Table 3: *Comparison of physical properties (HM2 models).*
Units: total column-mass density M(g cm^{-2}); central gas pressure P(dyn cm^{-2}); electron temperature T(°K); slab width D(km).

Model	M	P	T	D	n(H II)/n(H I)		n(He II)/n(He I)		n(el)		Optical Depths				
					slab surface	slab center	slab surface	slab center	slab surface	slab center	Ly-c	Ly-α	H-α	504 Å	584 Å
HM a5	3.0-5	.065	7500	3800	2.4	3.6	.16	.03	2.47+10	2.62+10	18.8	2.0+5	.65	12.50	5.4+4
here				2750	0.7	0.3	.10	.002	1.76+10	1.12+10	57.3	1.1+6	.83	9.19	9.5+4
HM b2	1.2-5	.26	7500	320	.8	1.2	.05	.02	7.27+10	8.32+10	15.6	1.7+5	.56	6.68	2.2+4
here				255	.3	.2	.04	.005	4.45+10	3.11+10	26.2	5.0+5	.53	3.69	3.8+4
HM c4	4.0-5	.065	9500	7000	4.3	12.8	.29	.07	2.13+10	2.28+10	9.2	1.0+5	.70	12.84	6.8+4
here				5650	1.1	1.2	.14	.0008	1.62+10	1.67+10	47.4	8.1+5	1.99	12.30	1.1+5
HM d4	1.6-5	.26	9500	670	1.7	6.5	.08	.04	7.25+10	8.75+10	6.8	7.6+4	1.00	6.08	3.0+4
here				530	.5	.8	.05	.003	4.53+10	5.79+10	23.9	4.1+5	2.00	4.98	4.6+4

Table 4: *Comparison of optical properties (HM2 models).*
Same units as for Table 3.

Model	M	P	T	D	Integrated intensities ($ergs/(cm^2.s.sr)$)											
					Ly-α	H-α	H-β	P-α	3889 Å	5016 Å	5876 Å	6678 Å	7065 Å	7281 Å	10830 Å	20581 Å
HM a5	3.0-5	.065	7500	3800	4.21+4	5.79+4	8.34+3	2.38+3	2.81+2	1.68+1	2.20+3	3.53+1	2.65+2	4.54+0	1.01+4	2.10+1
here				2750	1.41+4	3.92+4	4.16+3	1.17+3	1.24+2	1.22+1	1.09+3	6.15+0	1.38+2	4.40+0	5.26+3	1.06+1
HM b2	1.2-5	.26	7500	320	3.92+4	5.08+4	7.17+3	2.04+3	1.57+2	5.91+0	1.22+3	1.32+1	1.47+2	1.66+0	5.66+3	6.77+0
here				255	1.35+4	2.60+4	2.67+3	7.49+2	8.29+1	7.89+0	7.20+2	5.05+0	8.99+1	1.88+0	3.47+3	8.80+0
HM c4	4.0-5	.065	9500	7000	5.59+4	6.26+4	9.13+3	2.61+3	5.52+2	6.17+1	4.33+3	1.33+2	5.22+2	1.72+1	1.97+4	8.73+1
here				5650	3.14+4	9.68+4	1.14+4	3.30+3	1.57+2	2.47+1	1.36+3	1.19+1	1.79+2	1.12+1	6.48+3	1.71+1
HM d4	1.6-5	.26	9500	670	8.42+4	8.63+4	1.32+4	3.81+3	3.58+2	2.70+1	2.70+3	6.33+1	3.37+2	8.04+0	1.28+4	3.90+1
here				530	4.34+4	9.91+4	1.17+4	3.37+3	8.79+1	1.38+1	7.36+2	9.56+0	9.54+1	5.00+0	3.54+3	1.29+1