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Line emission from the quiet sun and the coronal hole regions

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Abstract. Using Kopp & Orrall (1976) model for the electron density and temperature for the quiet sun and the coronal hole regions, we have computed emission line intensities from Mg VIII, Si X (boron-like); Mg VII, Si IX (Carbon-like) and Si VII, S IX (oxygen-like) ions and compared them with available observational data.

Key words : EUV emission lines—chromosphere-corona transition region—coronal holes

1. Introduction

Skylab ATM observations in x and extreme ultraviolet (EUV) wavelengths have provided valuable information about the morphological features of coronal holes (low emission regions). Apart from having low density and temperature, coronal holes are shown to possess open, diverging magnetic field configurations and are associated with high velocity solar wind streams leading to recurrent geomagnetic activity. Skylab x-ray photographs show very clear signature of coronal holes. For instance, in EUV, Mg X ($T_e \sim 10^6$K) λ 625 Å line, coronal holes appear to be devoid of emission compared to the quiet sun. However, in the low chromosphere-corona transition region lines, the contrast is weak to detect the coronal hole by visual inspection. For further details one may refer to Zirker (1977). Adopting a combined theoretical and observational approach Kopp & Orrall (1976) have set up a temperature and electron density model for the quiet sun and the coronal hole regions. Such a model could be used to estimate the spectrum of various emissions emanating from the quiet sun and coronal hole regions. Estimate of line intensities using a model atmosphere is useful in identifying close lines arising from different ions prevalent in the atmosphere. Such a study provides first hand information to predict for future observation lines which have hitherto not been observed. Moreover, this study could also act as a test or constraint on the model atmosphere when compared with observational data. In our opinion this kind of study might also help to avoid wrong interpretation of the observational data by adjusting atomic parameters in order to match the observations (Vernazza & Mason 1978). However, we need more observations with better spectral resolution than currently available to substantiate our contention (Dwivedi & Raju 1980).

We then report here our detailed computation of line intensities from the ions of boron, carbon and oxygen isoelectronic sequences using the model atmosphere of Kopp & Orrall (1976) for the quiet sun and coronal hole regions. The ions we have considered have a ground state which has more than two sub-levels. As a check on their model atmosphere, Kopp & Orrall (1976) have computed resonance line intensities of ions whose ground configurations contains only a single level.

Table 1. Computed line intensities using Kopp & Orrall (1976) model
Mg VIII ion; N(Mg)/N(H) = 3.16×10^{-5}

Transition	Wave-length (Å)	Intensity at the sun (erg cm^{-2} sterad^{-1} s^{-1})			
		Quiet sun		Coronal hole	
		Calculated	Observed	Calculated	Observed
$2s^23d\ ^2D_{3/2} - 2s^22p\ ^2P^0_{1/2}$	74.86	6.81	11.03*	3.58	—
$2s^23d\ ^2D_{5/2} - 2s^22p\ ^2P^0_{3/2}$	75.03	11.39		5.44	—
	75.09[b]		16.18*		
$2s^23d\ ^2D_{3/2} - 2s^22p\ ^2P^0_{3/2}$	75.04	1.37		0.72	—
$2s^23s\ ^2S_{1/2} - 2s^22p\ ^2P^0_{1/2}$	82.61	1.78	—	0.90	—
$2s^23s\ ^2S_{1/2} - 2s^22p\ ^2P^0_{3/2}$	82.82	3.63	—	1.83	—
$2s2p^2\ ^2P_{3/2} - 2s^22p\ ^2P^0_{1/2}$	311.81	14.79	—	8.25	—
$2s2p^2\ ^2P_{1/2} - 2s^22p\ ^2P^0_{1/2}$	313.74	26.48	—	15.37	—
$2s2p^2\ ^2P_{3/2} - 2s^22p\ ^2P^0_{3/2}$	315.02	76.51	—	42.74	—
$2s2p^2\ ^2P_{1/2} - 2s^22p\ ^2P^0_{3/2}$	317.03	18.74	—	10.86	—
$2s2p^2\ ^2S_{1/2} - 2s^22p\ ^2P^0_{1/2}$	335.23	13.07	—	7.67	—
$2s2p^2\ ^2S_{1/2} - 2s^22p\ ^2P^0_{3/2}$	338.95	17.44	63.72**	10.26	30.42**
$2s2p^2\ ^2D_{3/2} - 2s^22p\ ^2P^0_{1/2}$	430.47	23.47	38.22**	14.32	17.29**
			22.70***		
$2s2p\ ^2D_{5/2} - 2s^22p\ ^2P^0_{3/2}$	436.62	39.06	42.70***	21.60	19.84**
			36.10***		
$2s2p\ ^2D_{3/2} - 2s^22p\ ^2P^0_{3/2}$	436.73	4.00	—	2.44	—
$2s2p\ ^4P_{5/2} - 2s^22p\ ^2P^0_{3/2}$	783.60	1.43	—	0.80	—
$2s2p\ ^4P_{3/2} - 2s^22p\ ^2P^0_{3/2}$	794.20	1.05	—	0.62	—
$2s^22p\ ^2P^0_{3/2} - 2s^22p\ ^2P^0_{1/2}$	3.03+μ	0.08	—	0.10	—

Table 2. Computed line intensities using Kopp & Orrall (1976) model
Si x ion; N(Si)/N(H) = 5.01×10^{-5}

Transition	Wave-length (Å)	Intensity at the sun (erg cm^{-2} sterad^{-1} s^{-1}) Quiet sun Calculated	Quiet sun Observed	Coronal hole Calculated	Coronal hole Observed
$2s^23d\ ^2D_{3/2} - 2s^22p\ ^2P^0_{1/2}$	50.52	31.10	—	5.82	—
$2s^23d\ ^2D_{5/2} - 2s^22p\ ^2P^0_{3/2}$	50.69	15.70	—	1.99	—
$2s^23d\ ^2D_{3/2} - 2s^22p\ ^2P^0_{3/2}$	50.70	6.23	—	1.16	—
$2s^23s\ ^2S_{1/2} - 2s^22p\ ^2P^0_{1/2}$	54.79	4.83	—	0.83	—
$2s^23s\ ^2S_{1/2} - 2s^22p\ ^2P^0_{3/2}$	55.01	9.91	—	1.70	—
$2s2p^2\ ^2P_{3/2} - 2s^22p\ ^2P^0_{1/2}$	253.81	23.48	18.39*	4.39	—
$2s2p^2\ ^2P_{1/2} - 2s^22p\ ^2P^0_{1/2}$	256.58^b	62.28	103.00*	13.49	—
$2s2p^2\ ^2P_{3/2} - 2s^22p\ ^2P^0_{3/2}$	258.39	118.68	99.30*	22.20	—
$2s2p^2\ ^2P_{1/2} - 2s^22p\ ^2P^0_{3/2}$	261.27	51.22	50.00*	11.10	—
$2s2p^2\ ^2S_{1/2} - 2s^22p\ ^2P^0_{1/2}$	272.00	50.00	40.50*	11.10	—
$2s2p^2\ ^2S_{1/2} - 2s^22p\ ^2P^0_{3/2}$	277.27	36.50	34.60*	8.20	—
$2s2p^2\ ^2D_{3/2} - 2s^22p\ ^2P^0_{1/2}$	347.43	85.90	228.80	20.10	61.10**
$2s2p^2\ ^2D_{5/2} - 2s^22p\ ^2P^0_{3/2}$	356.07	40.90	82.10**	6.40	—
$2s2p^2\ ^2D_{3/2} - 2s^22p\ ^2P^0_{3/2}$	356.10	11.70	—	2.80	—
$2s2p^2\ ^4P_{5/2} - 2s^22p\ ^2P^0_{3/2}$	638.00	1.40	0.29**	0.20	—
$2s2p^2\ ^4P_{3/2} - 2s^22p\ ^2P^0_{3/2}$	653.00	2.30	2.47**	0.50	—
$2s^22p\ ^2P^0_{3/2} - 2s^22p\ ^2P^0_{1/2}$	1.43μ	4.60+	—	2.00	—

2. Line intensities

The line emission per unit volume is given by the expression

$$E(j, i) = A_{ji} h\nu_{ij} N_j$$

$$= \frac{1.59 \times 10^{-8}}{\lambda(\text{Å})} \cdot A_{ji} \frac{N_j}{N_{ion}} \cdot \frac{N_{ion}}{N_{el}} \cdot \frac{N_{el}}{N_H} \cdot N_e \cdot \qquad \ldots(1)$$

(erg cm^{-3} s^{-1}),

where $N_H = 0.8\ N_e$ has been used. Integrated line intensity at the sun is given by

$$I(j, i) = 7.95 \times 10^{-2} \int E^*(j, i)\ .\ N_e dh. \qquad \ldots(2)$$

(erg cm^{-2} sterad^{-1} s^{-1}),

where

$$E^*(j, i) = 1.59 \times 10^{-8} A_{ji} \frac{N_j}{N_{ion}} \cdot \frac{N_{ion}}{N_{el}} \cdot \frac{N_{el}}{N_H} \cdot \frac{1}{\lambda(\text{Å})}.$$

N_{ion}/N_{el} is the relative ion abundance and taken from Jordan (1969). Electron density N_e and electron temperature T_e as a function of height have been kindly provided by Kopp (1978, personal communication) in tabular form. The chemical abundance N_{el}/N_H for Mg, Si and S has been taken from Kato (1976). N_j is the level density for the upper level of the transition. The necessary steady state equilibrium equations for various levels accounting for different physical processes as well as the atomic data used here have been the same as reported by Raju & Dwivedi (1978, 1979) and Dwivedi & Raju (1980). Various significant line intensities obtained from these computations have been given in tables 1–6 for Mg VIII, Si X; Mg VII, Si IX, Si VII and S IX respectively.

Table 3. Computed line intensities using Kopp & Orrall (1976) model Mg VII ion; (Mg)/N(H) = 3.16×10^{-5}

Transition	Wave-length (Å)	Intensity at the sun (erg cm^{-2} sterad^{-1} s^{-1})			
		Quiet sun		Coronal hole	
		Calculated	Observed	Calculated	Observed
$2s2p^3\ ^3S^o_1 - 2s^22p^2\ ^3P_0$	276.15	3.46	2.94*	2.86	—
$2s2p^3\ ^3S^o_1 - 2s^22p^2\ ^3P_1$	277.01	9.86	10.30* 66.20$^\Delta$	8.46	—
$2s2p^3\ ^3S^o_1 - 2s^22p^2\ ^3P_2$	278.41	16.70	17.66* 51.50$^\Delta$	14.35	—
$2s2p^3\ ^1P^o_1 - 2s^22p^2\ ^1D_2$	280.74	17.51	—	8.68	—
$2s2p^3\ ^1D^o_2 - 2s^22p^2\ ^1D_2$	319.02	7.70	—	5.30	—
$2s2p^3\ ^3P^o_1 - 2s^22p^2\ ^3P_0$	363.77	4.19	—	3.55	—
$2s2p^3\ ^3P^o_0 - 2s^22p^2\ ^3P_1$	365.24	3.58	—	3.02	—
$2s2p^3\ ^3P^o_2 - 2s^22p^2\ ^3P_1$	365.24	3.23	—	2.74	—
$2s2p^3\ ^3P^o_2 - 2s^22p^2\ ^3P_1$	365.24	4.58	—	4.00	—
$2s2p^3\ ^3P^o_1 - 2s^22p^2\ ^3P_2$	367.67	5.27 }	66.20$^\Delta$	4.49	—
$2s2p^3\ ^3P^o_2 - 2s^22p^2\ ^3P_2$	367.68	2.74 }		2.32	—
$2s2p^3\ ^3D^o_1 - 2s^22p^2\ ^3P_0$	429.13	4.65	—	3.88	—
$2s2p^3\ ^3D^o_1 - 2s^22p^2\ ^3P_1$	431.22	3.58 }	29.43$^\Delta$	3.00	—
$2s2p^3\ ^3D_2 - 2s^22p^2\ ^3P_1$	431.22	8.17 }		6.97	—
$2s2p^3\ ^3D_2 - 2s^22p^2\ ^3P_2$	434.71	2.72 }	73.57$^\Delta$	2.32	—
$2s2p^3\ ^3D_3 - 2s^22p^2\ ^3P_2$	434.92	15.00 }		13.24	—
$2s2p^3\ ^5S^o_2 - 2s^22p^2\ ^3P_1$	851.00	5.44	—	4.79	—
$2s2p^3\ ^5S^o_2 - 2s^22p^2\ ^3P_2$	864.00	14.57	—	12.80	—
$2s^22p^2\ ^1S_0 - 2s^22p^2\ ^3P_1$	1189.82++	14.05	—	9.20	—
$2s^22p^2\ ^1D_2 - 2s^22p^2\ ^3P_2$	2629.47	20.75	—	22.95	—

Table 4. Computed line intensities using Kopp & Orrall (1976) model
Si IX ion; N(Si)/N(H) = 5.01×10^{-5}

Transition	Wavelength (Å)	Intensity at the sun (erg cm^{-2} sterad^{-1} s^{-1}) Quiet sun		Coronal hole	
		Calculated	Observed	Calculated	Observed
$2s2p^3\ {}^3S^o_1 - 2s^22p^2\ {}^3P_0$	223.72	14.96	17.66*	4.42	—
$2s2p^3\ {}^3S^o_1 - 2s^22p^2\ {}^3P_1$	225.03	42.74	33.10*	12.71	—
$2s2p^3\ {}^3S^o_1 - 2s^22p^2\ {}^3P_2$	227.01	68.93	58.12*	20.35	—
$2s2p^3\ {}^1P^o_1 - 2s^22p^2\ {}^1D_2$	227.30	4.13	—	0.96	—
$2s2p^3\ {}^1D_2 - 2s^22p^2\ {}^1D_2$	258.10	10.95	—	2.57	—
$2s2p^3\ {}^3P^o_1 - 2s^22p^2\ {}^3P_0$	290.63	15.77	15.45*	4.90	—
$2s2p^3\ {}^3P^o_0 - 2s^22p^2\ {}^3P_1$	292.83	15.70		4.94	—
$2s2p^3\ {}^3P^o_2 - 2s^22p^2\ {}^3P_1$	292.83	11.72	31.63*	3.55	—
$2s2p^3\ {}^3P^o_1 - 2s^22p^2\ {}^3P_1$	292.83	18.72		5.45	—
$2s2p^3\ {}^3P^o_1 - 2s^22p^2\ {}^3P_2$	296.89	18.69	46.35*	5.83	—
$2s2p^3\ {}^3P^o_2 - 2s^22p^2\ {}^3P_2$	296.19	52.31		15.33	—
$2s2p^3\ {}^3D^o_1 - 2s^22p^2\ {}^3P_0$	342.97	16.29		5.38	—
$2s2p^3\ {}^3D^o_1 - 2s^22p^2\ {}^3P_1$	345.01	12.12	161.77**	4.02	—
$2s2p^3\ {}^3D_2 - 2s^22p^2\ {}^3P_1$	345.10	34.27		10.62	—
$2s2p^3\ {}^3D_2 - 2s^22p^2\ {}^3P_2$	349.77	10.97	133.11**	3.39	—
$2s2p^3\ {}^3D_3 - 2s^22p^2\ {}^3P_2$	349.96	55.69		15.96	—
$2s2p^3\ {}^5S^o_2 - 2s^22p^2\ {}^3P_1$	672.00	3.28	—	1.69	—
$2s2p^3\ {}^5S^o_2 - 2s^22p^2\ {}^3P_2$	696.90	10.73	—	4.16	—
$2s^22p^2\ {}^1S_0 - 2s^22p^2\ {}^3P_1$	949.90	1.46	—	0.43	—
$2s^22p^2\ {}^1D_2 - 2s^22p^2\ {}^3P_1$	1984.88++	1.63	—	0.52	—
$2s^22p^2\ {}^1D_2 - 2s^22p^2\ {}^3P_2$	2149.26++	3.58	—	1.13	—

3. Results and discussion

The computed line intensities indicate that for lower temperature ions in the chromosphere-corona transition region the contrast between the quiet sun and coronal hole regions is not sharp. For higher temperature ions, lines formed in the coronal holes are weaker by a factor of two or more as compared to lines of the same ions in the quiet sun regions. At low temperatures, the relative steepness of temperature gradient in the transition region for the quiet sun, in combination with relative ion abundance (as based on ionization equilibrium calculations), might be

Table 5. Computed line intensities using Kopp & Orrall (1976) model
Si VII ion; N(Si)/N(H) = 5.01×10^{-5}

Transition	Wavelength (Å)	Intensity at the sun (ergs cm^{-2} $sterad^{-1}$ s^{-1})			
		Quiet sun		Coronal hole	
		Calculated	Observed	Calculated	Observed
$2s2p^5\ ^1P_1^0-2s^22p^4\ ^1D_2$	217.83	7.37	—	3.60	—
$2s2p^5\ ^3P_1^0-2s^22p^4\ ^3P_2$	272.64	9.88	5.15*	6.89	—
$2s2p^5\ ^3P_0^0-2s^22p^4\ ^3P_1$	274.18	7.11	m	4.57	—
$2s2p^5\ ^3P_2^0-2s^22p^4\ ^3P_2$	275.35	32.69	14.71*	23.37	—
$2s2p^5\ ^3P_1^0-2s^22p^4\ ^3P_1$	275.67	5.72	2.21*	3.98	—
$2s2p^5\ ^3P_1^0-2s^22p^4\ ^3P_0$	276.84	7.45	3.68*	5.19	—
$2s2p^5\ ^3P_2^0-2s^22p^4\ ^3P_1$	278.45	10.47	m	7.48	—
$2s^22p^4\ ^1S_0-2s^22p^4\ ^3P_1$	1049.26	1.01	—	0.69	—
$2s^22p^4\ ^1D_2-2s^22p^4\ ^3P_2$	2147.75+++	2.41	—	1.90	—
$2s^22p^4\ ^3P_1-2s^22p^4\ ^3P_2$	24825.12	0.11	—	0.16	—

Table 6. Computed line intensities using Kopp & Orrall (1976) model
S IX ion; N(S)/N(H) = 1.99×10^{-5}

Transition	Wavelength (Å)	Intensity at the sun (ergs cm^{-2} $sterad^{-1}$ s^{-1})			
		Quiet sun		Coronol hole	
		Calculated	Observed	Calculated	Observed
$2s2p^5\ ^1P_1^0-2s^22p^4\ ^1D_2$	179.32	2.68	—	0.72	—
$2s2p^5\ ^3P_1^0-2s^22p^4\ ^3P_2$	221.26	8.31	9.56*	2.33	—
$2s2p^5\ ^3P_0^0-2s^22p^4\ ^3P_1$	223.27	1.92	6.62*	0.42	—
$2s2p^5\ ^3P_2^0-2s^22p^4\ ^3P_2$	224.75	33.84	24.28*	10.04	—
$2s2p^5\ ^3P_1^0-2s^22p^4\ ^3P_1$	225.23	4.75	m	1.32	—
$2s2p^5\ ^3P_1^0-2s^22p^4\ ^3P_0$	226.59	6.08	m	1.70	—
$2s2p^5\ ^3P_2^0-2s^22p^4\ ^3P_1$	228.84	10.60	11.77*	3.15	—
$2s^22p^4\ ^1S_0-2s^22p^4\ ^3P_1$	871.82	0.65	—	0.20	—
$2s^22p^4\ ^1D_2-2s^22p^4\ ^3P_2$	1715.12+++	1.98	—	0.61	—
$2s^22p^4\ ^3P_1-2s^22p^4\ ^3P_2$	12520.35ˣ	1.10	—	0.58	—

Notes for the tables **1–6**

- * observed values from Malinovsky & Heroux (1973)
- ** observed values from Vernazza & Reeves (1978)
- *** observed values from Dupree *et al.* (1973)
- \+ line observed by Münch *et al.* (1967); Olsen *et al.* (1971)
- ++ line observed in active region; Sandlin *et al.* (1977)
- +++ line observed by Gabriel *et al.* (1971)
- x line observed by Olsen *et al.* (1971)
- Δ observed values from Behring *et al.* (1976)
- b denotes blend
- m denotes that the line is masked.

responsible for reducing the contrast between quiet sun and coronal hole regions. For higher temperature ions the electron density may be the dominant factor for the significantly lower intensity of lines in the coronal hole regions.

In conclusion the study of line emission from the ions considered could provide supplementary and complementary information leading to a more comprehensive study of the solar atmosphere. With the availability of observational data, which future solar missions might provide, the computed line intensities from the quiet sun and the coronal hole regions, as reported here, may serve as a useful testing ground for the model of Kopp & Orrall (1976).

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