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Evolution of sunspots seen in molecular lines. II

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Abstract. Utilizing the model atmospheres proposed by Sobotka for umbrae of different sizes and those proposed by Maltby *et al.* for well-developed umbrae, at different phases of solar activity, we examine the molecules C_2, MgH and TiO for a study of sunspot evolution.

Key words : sunspot—spectrum—molecules

1. Introduction

In paper I (Sinha & Tripathi 1991) we have discussed the advantages of simultaneous observations of a spot and photosphere in C_2, MgH and TiO lines. The line intensities of these moleucles in the Stankiewicz (1967) models were shown to behave in a systematic manner in both the photospheric and umbral models with different magnetic fields. This fact, when utilized for structuring model sunspot atmospheres, takes care of the effects of the photospheric stray light on umbral observations.

In the present communication we take up a more comprehensive study of the behaviour of the spot spectrum in several spot models. These models account for the different sizes of the sunspots and the different phases of the solar activity cycle.

2. Method and calculations

The method of equivalent width (EW) calculations and the molecular parameters etc. used in the present study are the same as in paper I. Here we concentrate upon the model atmospheres due to Sobotka (1985) and Maltby *et al.* (1986).

Sobotka (1985) used the solar lines Mg I b_1, Fe I 5434.5 Å and Na I D_2 in the spectra of 48 sunspots of different diameters. Restricting the observations to a study of high quality, only 12 observations were retained and semiempirical models constructed. It is concluded that the model of an umbra varies greatly with an increase in umbral radius up to a limiting value of $r_u = 3.5''$–$4''$, after which the changes are small. For a fixed umbral radius there is no significant difference between the models of sunspots in different phases of their development. Finally Sobotka presents a set of three models called model 13 for the 'cool' well developed sunspot with $r_u = 8''$ and $B = 3100$ G; model 22 for the 'intermediate' with $r_u = 3''$ and $B = 2100$ G and model 12 for the 'hot' $r_u = 2''$ and B = not mentioned (observed at the maximum phase of development). We shall use these three models in the present study.

Maltby *et al.* (1986) utilized the umbra-to-photosphere contrast and its center-to-limb (C-L) variations observed at several continuum windows. The solar activity cycle affects the ratio I_u/I_{ph} in a linear way. The time dependence of the umbral atmosphere in the early, middle and late phases of the solar cycle is represented by the values $t/t_0 = 0.1$, 0.5 and 0.9 respectively. Here t is the time elapsed since the last minimum in the solar cycle, of duration t_0. Clearly 'early' refers to a 'cool' model, and 'late' to a 'hot' model atmosphere. The solar cycle variation of the umbra/photosphere intensity ratio is unlikely to be caused by a variation in the area or intensity of umbral dots. In principle, the solar cycle variation in the umbra/photosphere intensity ratio could be caused by a variation in the photospheric intensity. Also, in a preliminary model calculation (Maltby *et al.* 1984), it has been suggested that the umbral core brightness temperature increases by approximately 300 K from the beginning to the end of each solar cycle.

These authors limit their observations and conclusions to umbral radii greater than 5″ because there seems enough material for the assumption that such spots do not differ much from each other.

In addition to the above six model atmospheres we have used the sunspot models due to Henoux (1969), Zwaan (1974), Stellmacher & Wiehr (1975), Boyer (1980) and Avrett (1981). We have also used the preliminary umbral core model M_L and the photospheric reference model by Maltby *et al.* (1986). Observations for $\cos\theta < 0.3$ introduce uncertainties caused by the large stray light corrections due to perspective foreshortening. However, we give equivalent widths (EWs) for $\cos\theta = 0.2$ to show how they might change in a C-L study.

3. Results and discussion

In figures 1 and 2 we compare Sobotka's (1985) models and Maltby *et al.*'s (1986) models with the other sunspot models to show how they differ from each other. Also plotted in the same figures are the photospheric models.

The molecules C_2

The results of EW calculations for C_2 are presented in table 1. Also included in the table are the EWs obtained with the help of different values of microturbulence. It is evident that the use of a higher value of microturbulence leads to a slightly higher value of EWs. In table 1 the photospheric EWs are seen in agreement with observations. The slightly different values in the two models only point to slightly different model atmospheres.

All the sunspot models for a well developed umbra yield an EW smaller than those from photospheric models (*cf.* table 1). It confirms the observations that the C_2 lines are weakened in sunspots (Harvey 1972). However, the fact that we are getting > 1 mÅ EW in sunspots for the C_2 lines and also that Sotirovski (1971) observed some weak spectral lines in places where C_2 lines could occur may indicate that these lines do not weaken by such a large factor as believed earlier. In the umbral C-L observations, the C_2 lines should vanish at $\cos\theta = 0.2$. This is expected as the line forming region shifts to upper cooler layers of the model atmosphere where CO formation is more dominant.

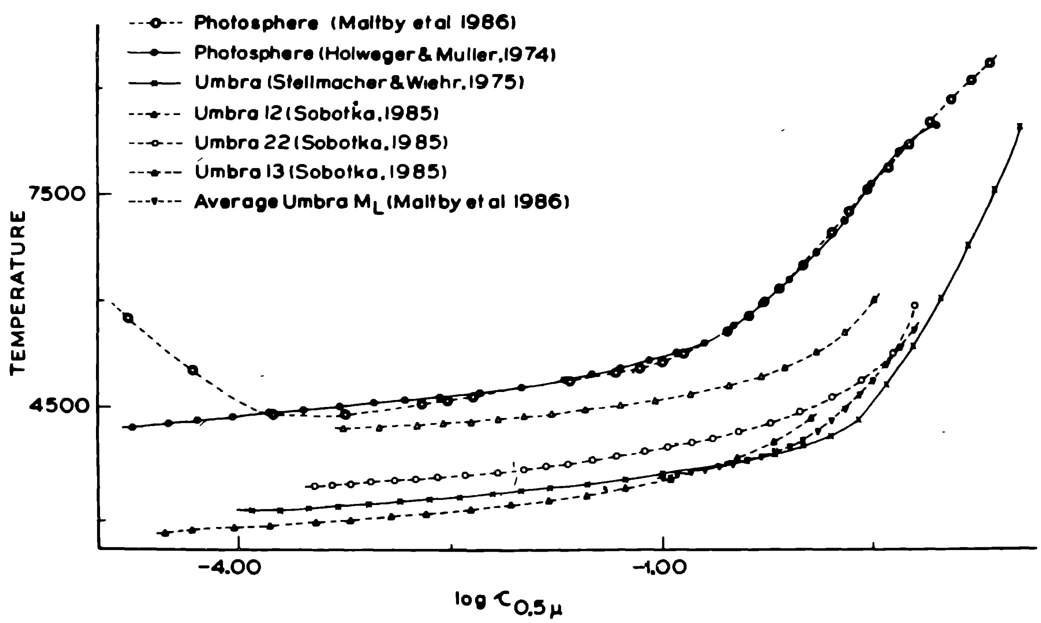

Figure 1. Sobotka's (1985) models 12, 22 and 13 have been plotted for a comparison with the present day photospheric and sunspot model atmospheres.

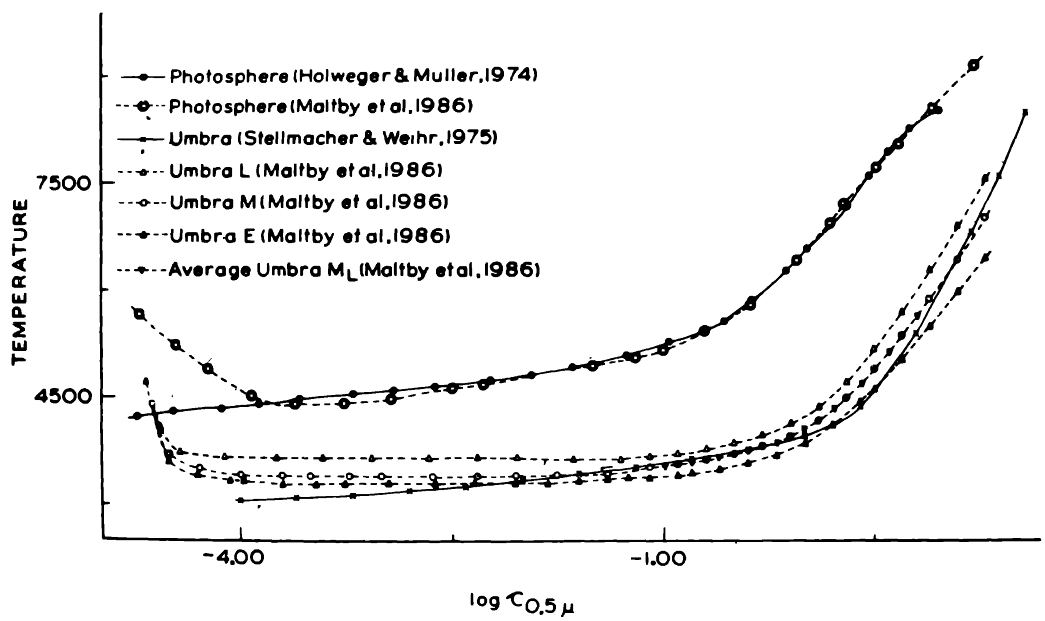

Figure 2. Maltby *et al.*'s (1986) sunspot models for the early, middle and late phases of the solar cycle are presented for a comparison with the present day photospheric and sunspot model atmospheres.

Considering the sunspot models of Maltby *et al.* (1986) it appears that extremely weak C_2 lines can be detected in the spectrum at the centre of the solar disc towards the late phase of the solar cycle.

Sobotka's model 12 is close to quiet photosphere. So we are getting almost photospheric values of EWs. Also the C-L variation which does depend upon the choice of the model atmosphere shows that C_2 lines stay constant in EW towards the limb. This

Table 1. Equivalent widths (mÅ) of some lines of C_2 Swan system (0-0) band in photospheric and sunspot model atmospheres

Wavelength (Å)	5132.360		5136.440		5140.381		5150.558		5159.470 + 5159.453		5160.385	
	R_1 (18)		R_2 (15)		R_3 (12)		P_1 (36) + P_2 (35)		P_1 (28) + P_2 (27)		P_3 (25)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Photosphere												
Observations Sinha (1984)	8.0	12.0	7.5	13.8	4.5	8.0	12.5	20.6	13.8	21.8	6.5	11.5
Holweger & Müller (1974)	7.0	13.1	6.1	11.6	5.1	10.0	15.8	24.8	15.4	24.4	7.7	14.1
	7.1	13.8	6.2	12.2	5.2	10.4	16.4	27.5	16.0	27.1	7.9	14.9
Maltby *et al.* (1986)	7.8	13.7	6.8	12.2	5.7	10.5	17.4	25.4	17.0	25.1	8.6	14.7
Umbra												
Observations	—	—	—	—	—	—	—	—	—	—	—	—
Henoux (1969)	1.1	1.7E-2	1.0	1.5E-2	0.8	1.3E-2	2.0	3.6E-2	2.0	3.7E-2	1.1	1.8E-2
	1.1	1.7E-2	1.0	1.5E-2	0.8	1.3E-2	2.3	3.7E-2	2.2	3.7E-2	1.2	1.8E-2
Zwaan (1974)	3.4	1.1E-2	3.0	1.0E-2	2.6	0 8E-2	6.8	2.4E-2	6.7	2.4E-2	3.7	1.2E-2
	3.5	1.1E-2	3.1	1.0E-2	2.6	0.8E-2	7.4	2.4E-2	7.3	2.5E-2	3.8	1.2E-2
Stellmacher & Wiehr (1975)	1.6	3.0E-3	1.4	2.6E-3	1.2	2.2E-3	3.0	6.3E-3	3.0	6.6E-3	1.7	3.1E-3
	1.7	3.0E-3	1.5	2.6E-3	1.3	2.2E-3	3.4	6.3E-3	3.3	6.6E-3	1.8	3.1E-3
Boyer (1980)	1.0	5.3E-3	0.9	4.6E-3	0.8	3.9E-3	1.9	11.2E-3	1.9	11.6E-3	1.1	5.5E-3
	1.1	5.3E-3	0.9	4.6E-3	0.8	3.9E-3	2.1	11.2E-3	2.1	11 6E-3	1.1	5.5E-3
Avrett (1981)	2.3	6.2E-3	2.1	5.4E-3	1.8	4.6E-3	4.4	13.3E-3	4.3	13.3E-3	2.5	6.4E-3
	2.4	6.3E-3	2.2	5.5E-3	1.8	4.6E-3	4.9	13.0E-3	4.8	13.4E-3	2.6	6.4E-3
Maltby *et al.* (1986)	1.0	4.8E-3	0.9	4.2E-3	0.7	3.5E-3	2.1	10.0E-3	2.1	10.2E-3	1.1	4.9E-3
Model M_L	1.0	4.8E-3	0.9	4.2E-3	0.8	3.5E-3	2.2	10.1E-3	2.2	10.3E-3	1.1	4.9E-3

(Continued)

Table 1. Continued

Wavelength (Å)	5132.360		5136.440		5140.381		5150.558		5159.470 + 5159.453		5160.385	
	R_1 (18)		R_2 (15)		R_3 (12)		P_1 (36) + P_2 (35)		P_1 (28) + P_2 (27)		P_3 (25)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Maltby *et al.* (1986)												
Model E	6.8E-1	5.0E-4	6.0E-1	4.4E-4	5.2E-1	3.7E-4	12.9E-1	10.4E-4	12.8E-1	10.7E-4	7.1E-1	5.1E-4
Model M	1.6	4.0E-3	1.5	3.5E-3	1.2	2.9E-3	3.1	8.3E-3	3.0	8.5E-3	1.7	4.1E-3
Model L	3.1	2.3E-2	2.8	2.0E-2	2.4	1.7E-2	5.8	4.6E-2	5.7	4.7E-2	3.3	2.3E-2
Sobotka (1985)												
Model 12	10.3	10.7	9.1	9.7	7.9	8.6	19.6	17.9	19.5	17.9	11.1	11.3
	10.8	11.8	9.6	10.6	8.1	9.2	21.6	20.6	21.5	20.6	11.7	12.5
Model 22	3.3	0.4	3.0	0.4	2.5	0.3	6.3	0.8	6.2	0.9	3.5	0.4
	3.5	0.4	3.1	0.4	2.6	0.3	6.9	0.9	6.9	0.9	3.8	0.4
Model 13	8.7E-5	1.2E-2	7.7E-5	1.1E-2	6.5E-5	0.9E-2	17.6E-5	2.7E-2	19.0E-5	2.8E-2	8.9E-5	1.3E-2
	8.7E-5	1.2E-2	7.7E-5	1.1E-2	6.5E-5	0.9E-2	17.6E-5	2.7E-2	19.0E-5	2.8E-2	8.9E-5	1.3E-2

$E \pm n = 10^{\pm n}$.
Second entry corresponds to microturbulence velocity = 2.1 km s^{-1}.

Table 2. Equivalent-widths (mÅ) of some lines of MgH Green system (0-0) band in photospheric and sunspot model atmospheres

Wavelength (Å)	5061.536		5085.178		5106.848		5190.561		5202.985		5207.78	
	Q_2 (37)		Q_1 (33)		R_2 (16)		P_2 (29)		P_1 (24)		P_2 (10)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Photosphere												
Observations Lambert *et al.*(1971)	2.9	—	—	—	3.7	—	1.0	—	1.9	—	1.5	—
Holweger & Müller (1974)	1.5	2.6	2.0	3.4	1.7	3.1	1.2	2.0	1.4	2.6	1.1	2.0
	1.5	2.6	2.0	3.5	1.7	3.1	1.2	2.1	1.5	2.6	1.1	2.0
Maltby *et al.* (1986)	1.7	2.9	2.3	3.9	2.0	3.5	1.3	2.3	1.7	2.9	1.3	2.3
Umbra												
Observations Sotirovski (1971)	58	—	59	—	61	—	72	—	61	—	64	—
Henoux (1969)	74.5	42.1	79.3	47.1	83.7	51.7	74.7	43.3	79.0	47.6	79.3	48.4
	102	55.9	109	63.6	115	70.6	103	57.5	109	64.3	109	65.6
Zwaan (1974)	90.5	72.2	98.2	78.5	105	83.6	93.0	75.3	99.8	80.4	101	81.8
	124	100	135	111	146	121	127	105	138	114	140	117
Stellmacher & Wiehr (1975)	76.0	57.6	83.1	64.6	89.6	72.0	77.2	60.0	83.5	66.2	84.6	68.2
	103	77.7	113	88.2	123	99.6	104	81.2	114	90.5	116	93.6
Boyer (1980)	71.6	50.4	78.0	57.0	83.7	63.9	72.3	52.4	78.0	58.2	78.8	59.8
	96.5	67.0	106	76.8	115	87.2	97.5	69.7	106	78.5	107	80.9
Avrett (1981)	83.9	22.2	85.5	22.9	82.5	25.6	83.3	21.6	84.2	22.6	83.3	23.0
	117	33.8	123	32.6	123	34.0	117	32.6	122	31.9	121	32.0
Maltby *et al.* (1986)	51.9	89.8	47.7	80.4	42.0	73.1	50.0	84.3	46.2	77.0	44.7	75.1
Model M_L	77.7	14.6	74.0	12.8	66.5	11.4	75.6	13.6	72.0	12.2	70.0	11.9

(Continued)

Table 2. Continued

Wavelength (Å)	5061.536		5085.178		5106.848		5190.561		5202.985		5207.78	
	Q_2 (37)		Q_1 (33)		R_2 (16)		P_2 (29)		P_1 (24)		P_2 (10)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Maltby *et al.* (1986)												
Model E	86.5	29.4	86.0	33.6	81.2	38.1	85.8	30.2	83.9	34.1	81.9	35.3
Model M	91.6	35.4	94.2	38.7	88.6	43.8	92.4	35.5	92.8	39.0	91.1	40.1
Model L	82.8	27.6	94.2	26.0	98.0	26.3	84.1	26.5	93.6	25.4	93.9	25.3
Sobotka (1985)												
Model 12	10.1	10.4	13.2	13.0	13.2	13.4	8.8	9.4	11.0	11.4	9.3	10.2
	10.6	11.5	14.1	14.7	14.0	15.2	9.1	10.2	11.6	12.6	9.7	11.2
Model 22	60.4	51.0	67.7	57.2	72.5	62.3	60.4	51.7	66.8	57.2	66.3	57.7
	77.5	66.5	88.4	75.9	95.5	83.6	77.4	67.6	86.9	75.8	86.2	76.4
Model 13	62.3	85.3	71.5	93.1	81.7	102	66.5	89.0	74.6	95.8	77.6	98.4
	82.5	119	96.9	131	113	145	88.8	124	102	135	106	139

Table 3. Equivalent widths (mÅ) of some lines of MgH Green system (0-1) band in photospheric and sunspot model atmospheres

Wavelength (Å)	5520.23		5550.68		5555.52		5583.57		5596.76		5603.94	
	R_1 (13)		Q_2 (17)		R_2 (8)		Q_1 (10)		P_1 (22)		P_2 (20)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Photosphere												
Observations	—	—	—	—	—	—	—	—	—	—	—	—
Holweger & Müller	3.4E-2	6.1E-2	6.3E-2	11.1E-2	2.5E-2	4.4E-2	5.5E-2	9.7E-2	3.0E-2	5.3E-2	3.0E-2	5.2E-2
	3.4E-2	6.1E-2	6.3E-2	11.1E-2	2.5E-2	4.4E-2	5.5E-2	9.7E-2	3.0E-2	5.3E-2	3.0E-2	5.2E-2
Maltby *et al.* (1986)	4.0E-2	6.9E-2	7.4E-2	12.5E-2	2.9E-2	5.0E-2	6.4E-2	10.9E-2	3.5E-2	5.9E-2	3.4E-2	5.7E-2
Umbra												
Observations Sotirovski (1971)	16	—	29	—	13	—	24	—	12	—	17	—
Henoux (1969)	26.4	13.4	35.0	17.4	22.2	11.6	34.4	17.3	21.7	11.1	21.9	11.3
	30.2	15.9	42.1	21.2	24.8	13.5	41.2	21.0	24.1	12.8	24.5	13.1
Zwaan (1974)	26.6	27.6	37.6	35.7	21.9	24.0	37.4	36.1	20.6	21.7	21.1	22.4
	29.1	32.2	43.1	43.6	23.6	27.4	42.7	44.1	22.1	24.6	22.6	25.4
Stellmacher & Wiehr (1975)	23.5	17.4	31.5	23.2	19.7	14.9	31.1	23.2	18.8	13.7	19.1	14.1
	26.7	20.1	37.4	27.6	21.9	17.0	36.8	27.7	20.9	15.5	21.3	15.9
Boyer (1980)	21.8	13.5	29.6	18.2	18.2	11.5	29.0	18.2	17.5	10.7	17.8	10.9
	24.6	15.5	34.9	21.5	20.1	12.9	34.1	21.4	19.3	12.0	19.7	12.3
Avrett (1981)	23.7	11.6	33.5	15.0	19.4	9.9	32.9	14.8	18.5	9.2	18.8	9.4
	26.1	13.4	38.4	18.3	20.9	11.2	37.6	18.1	19.9	10.4	20.2	10.6
Maltby *et al.* (1986)	21.8	8.5	30.0	10.2	18.0	7.4	29.3	10.1	17.3	7.0	17.6	7.1
Model M_L	24.2	10.2	35.1	13.1	19.6	8.7	34.3	13.0	18.8	8.2	19.1	8.3

(Continued)

Table 3. Continued

Wavelength (Å)	5520.23		5550.68		5555.52		5583.57		5596.76		5603.94	
	R_1 (13)		Q_2 (17)		R_2 (8)		Q_1 (10)		P_1 (22)		P_2 (20)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Maltby *et al.* (1986)												
Model E	29.3	13.6	37.4	17.6	25.2	11.7	37.2	17.7	23.7	10.6	24.1	10.9
Model M	24.7	16.0	33.7	21.8	20.5	13.5	33.3	21.8	19.5	12.3	19.9	12.6
Model L	16.9	8.6	24.6	12.0	13.6	7.1	23.9	11.8	13.3	6.6	13.5	6.8
Sobotka (1985)												
Model 12	3.1E-1	4.1E-1	5.6E-1	7.3E-1	2.3E-1	3.0E-1	5.0E-1	6.5E-1	2.6E-1	3.4E-1	2.6E-1	3.3E-1
	3.2E-1	4.1E-1	5.6E-1	7.3E-1	2.3E-1	3.0E-1	5.0E-1	6.6E-1	2.6E-1	3.4E-1	2.6E-1	3.4E-1
Model 22	8.1	9.8	13.0	14.6	6.3	7.9	12.4	14.2	6.3	7.6	6.4	7.8
	8.4	10.5	13.7	16.1	6.4	8.3	13.0	15.7	6.5	8.1	6.6	8.2
Model 13	8.5	36.2	14.0	45.2	6.8	32.0	14.6	45.8	5.4	29.2	5.7	29.9
	8.4	43.6	14.1	56.6	6.7	37.7	14.7	57.3	5.2	34.1	5.6	35.0

Table 4. Equivalent widths (mÅ) of some lines of TiO Alpha system (0-0) band in photospheric and sunspot model atmospheres

Wavelength (Å)	5189.80		5199.01		5199.82		5211.77		5213.03		5249.03	
	P_2 (31)		P_3 (39)		R_3 (60)		R_1 (70)		P_1 (50)		R_2 (90)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Photosphere												
Observations	—	—	—	—	—	—	—	—	—	—	—	—
Holweger & Müller (1974)	1.7E-4 1.7E-4	4.3E-4 4.3E-4	2.0E-4 2.0E-4	4.9E-4 4.9E-4	2.3E-4 2.3E-4	5.6E-4 5.6E-4	2.2E-4 2.2E-4	5.3E-4 5.3E-4	2.2E-4 2.2E-4	5.5E-4 5.5E-4	1.7E-4 1.7E-4	4.2E-4 4.2E-4
Maltby *et al.* (1986)	2.3E-4	5.5E-4	2.6E-4	6.4E-4	3.0E-4	7.2E-4	2.9E-4	6.9E-4	2.9E-4	7.0E-4	2.3E-4	5.4E-4
Umbra												
Observations Sotirovski (1971)	10	—	12	—	18	—	17	—	18	—	12	—
Henoux (1969)	26.3 33.5	18.5 25.6	27.7 36.0	19.4 27.0	28.0 36.4	19.4 27.0	26.5 33.9	18.4 25.5	28.4 37.2	19.7 27.5	21.3 25.7	15.3 20.4
Zwaan (1974)	54.8 83.9	51.3 88.5	56.1 86.9	51.7 89.8	55.8 86.0	51.8 89.4	54.0 81.7	51.4 87.4	56.6 87.8	51.9 90.3	47.1 66.4	48.8 79.2
Stellmacher & Wiehr (1975)	40.6 56.3	43.8 67.0	42.2 59.3	44.9 69.2	42.0 59.0	44.5 68.4	39.9 55.2	42.9 65.2	42.7 60.4	45.2 69.8	32.9 42.6	37.3 54.3
Boyer (1980)	29.0 36.8	31.0 43.3	30.6 39.5	32.2 45.5	30.7 39.7	32.0 45.1	28.9 36.7	30.3 42.2	31.3 40.7	32.6 46.2	22.7 27.3	24.9 33.0
Avrett (1981)	39.2 51.1	17.2 27.8	41.1 54.6	17.3 28.5	41.2 54.8	17.3 28.5	39.1 50.9	17.1 27.6	41.9 56.1	17.3 28.8	31.3 38.2	15.9 23.8
Maltby *et al.* (1986) Model M_L	24.9 34.9	7.2 13.8	25.8 36.9	7.0 13.8	25.9 37.2	7.1 13.8	25.1 35.1	7.3 13.8	26.1 37.8	7.0 13.7	21.4 27.5	7.7 13.2

(Continued)

Table 4. Continued

Wavelength (Å)	5189.80		5199.01		5199.82		5211.77		5213.03		5249.03	
	P_2 (31)		P_3 (39)		R_3 (60)		R_1 (70)		P_1 (50)		R_2 (90)	
Model	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$	$\mu = 1.0$	$\mu = 0.2$
Maltby *et al.* (1986)												
Model E	42.2	19.4	42.5	20.0	42.6	19.8	42.5	18.8	42.6	20.2	39.8	16.1
Model M	44.6	20.6	46.2	20.7	46.2	20.7	44.2	20.6	46.8	20.7	36.6	21.1
Model L	15.2	12.5	16.5	13.3	16.8	13.4	15.4	12.5	17.1	13.7	11.3	9.5
Sobotka (1985)												
Model 12	4.3E-3	7.9E-3	4.9E-3	9.0E-3	5.5E-3	10.0E-3	5.2E-3	9.3E-3	5.4E-3	9.9E-3	4.0E-3	7.0E-3
	4.3E-3	7.9E-3	4.9E-3	9.0E-3	5.5E-3	10.0E-3	5.2E-3	9.3E-3	5.4E-3	9.9E-3	4.0E-3	7.0E-3
Model 22	3.2	7.9	3.6	8.7	3.7	8.8	3.3	8.0	3.8	9.0	2.3	5.6
	3.3	8.4	3.7	9.3	3.8	9.5	3.4	8.6	3.9	9.8	2.3	5.9
Model 13	53.6	68.7	54.8	69.5	54.1	69.2	52.0	67.9	55.1	69.8	44.7	63.1
	82.7	116	85.3	118	83.7	117	79.3	114	85.9	118	64.1	103

model also presents the possibility that in small spots, C_2 lines can be observed. The results for model 22 are about the same as in other spot models discussed above. We somehow suspect model 13 as it does not extend to atmospheric layers below log $\tau = 0.06$ which contribute to continuum in large amounts. Also since in spots C_2 forming layers are shifted deeper, such models should yield smaller EW. We repeated our calculations for Zwaan's (1974) model, excluding the layers below log $\tau = 0.0$ and found results similar to those from Sobotka's model 13.

The molecules MgH

Like C_2, the MgH lines in photosphere are in agreement with the calculations. They all intensify as we move to sunspot spectrum. The effect of higher microturbulent velocity is to yield larger EW and it is seen more in saturated lines. In photosphere, the lines strengthen towards the limb but in sunspot spectrum they are seen to weaken except in model M_L. The results are presented in table 2.

In Maltby *et al.*'s (1986) models the (0-0) band remains strong during the entire solar activity cycle and it may be difficult to sense the changes in line intensity. In C-L behaviour, all these lines are seen to weaken towards the solar limb.

In Sobotka's models 12, 22 and 13, the lines are seen to gain in intensity as we move to cooler sunspot models. In C-L behaviour model 12 shows that the lines remain practically unaltered in intensity, model 22 shows that the lines weaken and model 13 shows that the lines are strengthened towards the limb.

Since the (0-0) band of the green bands of MgH is saturated and hence less sensitive to changes in the physical conditions of the umbra, we present results of EW calculations in table 3 for the (0-1) band.

These lines are too weak for detection in photospheric spectrum, but sufficient in strength in umbrae (*cf.* table 3). In umbra they weaken towards the limb (*cf.* table 3). In Sobotka's (1985) models as well as in Maltby *et al.*'s (1986) models these lines strengthen as the models cool. In C-L behaviour the lines weaken towards the limb throughout the activity cycle. However, an increase towards the limb is noticed in Sobotka's (1985) models.

The molecules TiO

The results of EW calculations are presented in table 4. These lines are too weak for detection in the photospheric spectrum and increase in intensity in the umbral spectrum. In the umbral atmospheres the lines show a decrease in intensity towards the limb except in models due to Zwaan (1974) and Stellmacher & Wiehr (1975).

In Maltby *et al.*'s (1976) models a strengthening in line intensity is noticed as we move from late to early phase of the solar cycle but unlike in Sobotka's models these lines show a weakening towards the solar limb.

In Sobotka's models all the chosen TiO lines show an increase in intensity as the model atmospheres cool. This also happens as one moves towards the limb in observations.

The effect of choosing a slightly different Titanium abundance i.e., $\epsilon(\mathrm{Ti}) = 4.99$ (Grevesse *et al.* 1989) is shown in table 5. A comparison of tables 4 and 5 indicates that for the purpose of the arguments developed here, the slightly different Titanium abundance leads to inconsequential changes.

Table 5. Equivalent widths (mÅ) of some lines of TiO Alpha system (0-0) band in photospheric and sunspot model atmospheres at $\mu = 1.0$, $\epsilon(\text{Ti}) = 4.99$

Wavelength (Å)	5189.80	5199.01	5199.82	5211.77	5213.03	5249.03
	P_2 (31)	P_3 (39)	R_3 (60)	R_1 (70)	P_1 (50)	P_2 (90)
Model	$\mu = 1.0$	$\mu = 1.0$	$\mu = 1.0$	$\mu = 1.0$	$\mu = 1.0$	$\mu = 1.0$
Photosphere						
Observations	—	—	—	—	—	—
Holweger & Müller (1974)	1.4E-4	1.6E-4	1.8E-4	1.8E-4	1.8E-4	1.4E-4
Maltby *et al.* (1986)	1.9E-4	2.1E-4	2.4E-4	2.3E-4	2.4E-4	1.9E-4
Umbra						
Observations Sotirovski (1971)	10	12	18	17	18	12
Henoux (1969)	23.5	25.0	25.2	23.8	25.7	18.7
Zwaan (1974)	58.4	59.6	59.4	57.8	60.0	51.7
Stellmacher & Wiehr (1975)	37.3	39.0	38.8	36.7	39.6	29.6
Boyer (1980)	25.9	27.5	27.6	25.8	28.2	19.9
Avrett (1981)	35.4	37.4	37.5	35.3	38.2	27.6
Maltby *et al.* (1986) Model M_L	23.2	24.2	24.3	23.4	24.6	19.3
Maltby *et al.* (1986)						
Model E	41.5	42.0	42.1	41.5	42.2	37.7
Model M	41.3	43.0	42.9	40.8	43.7	32.9
Model L	12.9	14.1	14.4	13.2	14.7	9.6
Sobotka (1985)						
Model 12	3.5E-3	4.0E-3	4.5E-3	4.2E-3	4.4E-3	3.2E-3
Model 22	2.6	2.9	3.0	2.7	3.1	1.9
Model 13	50.9	52.2	51.4	49.3	52.5	41.7

4. Conclusion

We conclude that a simultaneous observation of photosphere and sunspots for the Swan bands of C_2, Green bands of MgH, and alpha bands of TiO does sense changes in model atmospheres. The changes may be either because of the development of the sunspots (Sobotka 1985) or due to the solar cycle (Maltby *et al.* 1986). Also the choice of the above molecular lines tends to account for the scattered photospheric light also hence the evolution of sunspots and structuring an umbral model atmosphere can be achieved in a better way.

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