Bull. Astr. Soc. India (1984) 12, 229–232

Model dependence of the rotational temperature of SiO in sunspots

L. M. Punetha and G. C. Joshi
Uttar Pradesh State Observatory, Manora Peak, Naini Tal 263 129

Received 1984 January 25; accepted 1984 April 23

Abstract : Centre-to-limb variation of the rotational temperature of the fundamental band of SiO in different sunspot models has been calculated. The possibility of using these calculations to pick up the true model on the basis of infrared observations is indicated.

Key words : SiO molecule—rotational temperature—sunspot model

1. Introduction

Various sunspot models have been constructed on the basis of studies of line profiles and continuum (*cf.* Zwaan 1965, 1974, 1975; Henoux 1969; Stellmacher & Wiehr 1970, 1975; Kneer 1972; Boyer 1980; Kollatschny *et al.* 1980). These models vary in their atmospheric characteristics. For example, the model by Zwaan (1974) explains continuum intensity in the spectral range $0.5 < \lambda < 4.0$ μm by introducing an additional opacity for $\lambda < 0.8$ μm and also reproduces the infrared Ca^+ lines at 8498, 8542 and 8662 Å (Kollatschny *et al.* 1980). The model by Stellmacher & Wiehr (1975) reproduces the line profiles of Fe 5434 and Na D_2. Boyer (1980) has altered the temperature stratification of the Stellmacher & Wiehr (1975) sunspot model to reproduce the observed equivalent widths of TiO lines in sunspots in the spectral range 6100–7100 Å. Kollatschny *et al.* (1980) have also altered the temperature stratification of Stellmacher & Wiehr (1975). With the inclusion of additional opacity as suggested by Zwaan (1974), the Stellmacher & Wiehr (1975) sunspot model as corrected by Kollatschny *et al.* (1980) has been able to explain the lines of Fe 5434, Na D_2, Ca^+ (8498, 8542 and 8662 Å), K 7699 and the continuum contrast.

With a view to selecting a model for representing sunspots in the infrared, we have calculated the centre-to-limb variation of the rotational temperature of the (2–1) fundamental band of SiO around 8 μm. The molecule SiO in the infrared was picked up because (i) the element Si gets easily ionized and SiO can be used to sense the temperature variation in the infrared with the same sensitivity as

TiO; (ii) LTE is a safe assumption in case of vibration-rotation transitions; (iii) SiO is abundant in the umbral atmosphere as per the dissociation equilibrium calculations; and (iv) SiO lines are not expected to be contaminated by photospheric radiation, since SiO vibration-rotation bands are not present in the photospheric spectrum. The predicted temperatures turn out to be widely different and may provide a suitable criterion for selecting a representative model.

2. Calculations

Twenty six lines (from $J'' = 25$ to $J'' = 50$) of the P branch of the fundamental band (2–1) arising from the ground electronic state $X^1\Sigma^+$ of $Si^{28}O^{16}$ were selected for equivalent width calculations at five disc positions in the following six models : $M_1 \equiv$ Henoux (1969); $M_2 \equiv$ Stellmacher & Wiehr (1970); $M_3 \equiv$ Kneer (1972); $M_4 \equiv$ Zwaan (1974); $M_5 \equiv$ Stellmacher & Wiehr (1975) as corrected by Boyer (1980); and $M_6 \equiv$ Stellmacher & Wiehr (1975) as corrected by Kollatschny *et al.* (1980).

Equivalent widths of some lines of the above mentioned band of $Si^{28}O^{16}$, $Si^{29}O^{16}$ and $Si^{30}O^{16}$ have been calculated by Gaur *et al.* (1978) and Pande & Joshi (1978). We have adopted the same procedure in the present investigation also, except that the molecular line haze opacity (Joshi *et al.* 1979) has also been accounted for along with that due to H^-. The rotational temperature was calculated using (Herzberg 1950)

$$\log (W_\mu/S_J) = \text{const} - 0.6247\, J''\,(J'' + 1)\, B_{v''}/T_{\mu(\text{rot})}.$$

Here W_μ = equivalent width on the disc at $\mu = \cos\theta$; S_J = rotational intensity factor; $T_{\mu(\text{rot})}$ = rotational temperature on the disc at $\mu = \cos\theta$.

The calculated centre-to-limb variation of rotational temperature in different sunspot models is given in figure 1 and table 1.

3. Discussion

We have calculated the rotational temperatures at $\mu = 1.0, 0.7, 0.5, 0.3$ and 0.1. The temperature difference between the models M_1 and M_4 (extreme cases) is 400 K at the centre and 500 K near the limb. In M_1 the temperature decreases towards limb up to $\mu = 0.3$ and afterwards becomes almost constant. All other models have a monotonic temperature decrease towards the limb. This is so because M_1 has smaller temperature gradient than the other models in the line formation region. It may also be noted that T_{rot} at $\mu = 0.3$ for all the models except M_1 corresponds to $\tau_{0.5\mu m} = 0.015$ to 0.03 whereas for M_1 it corresponds to $\tau_{0.5\mu m} \simeq 0.10$. This so because the molecular opacity (Joshi *et al.* 1979) is less for M_1 (hottest model) which causes the lines to be formed in deeper layers as compared with the remaining cooler models, in which large molecular opacity shifts the line formation region to cooler parts. The centre-to-limb variation of the temperature in all the models is 150 to 400 K. The temperature gradient in M_6 is very steep. So of all the models considered here, M_6 shows the maximum centre-to-limb variation.

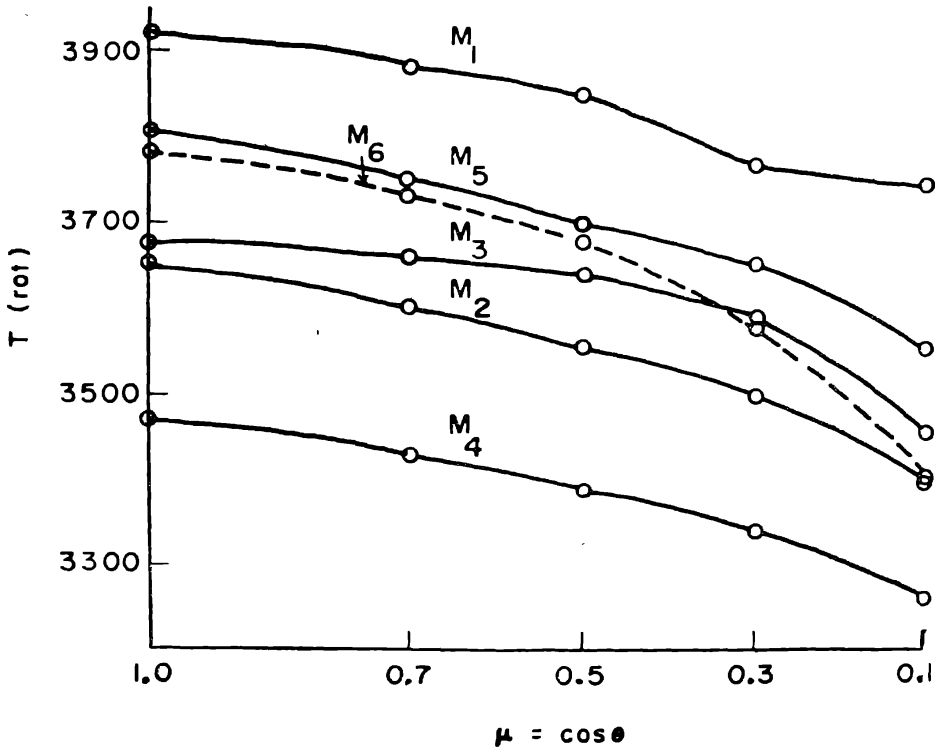

Figure 1. Centre-to-limb variation of rotational temperature of SiO in different umbral models.

Table 1. Centre-to-limb variation of rotational temperature of SiO in different models.

Model	$\mu = \cos\theta$				
	1.0	0.7	0.5	0.3	0.1
M_1	3918 ± 5	3876 ± 4	3848 ± 5	3770 ± 4	3751 ± 4
M_2	3648 ± 4	3598 ± 4	3555 ± 3	3498 ± 3	3399 ± 4
M_3	3675 ± 4	3657 ± 4	3640 ± 4	3594 ± 4	3455 ± 4
M_4	3468 ± 4	3426 ± 3	3389 ± 3	3337 ± 3	3262 ± 3
M_5	3807 ± 6	3748 ± 6	3704 ± 5	3656 ± 5	3555 ± 4
M_6	3780 ± 6	3731 ± 4	3682 ± 3	3583 ± 4	3404 ± 3

The ratio of two equivalent widths is expressed by $R(J_1, J_2) \equiv W(J_1)/W(J_2)$, which gives $\Delta \log R = -0.45\,[J_1(J_1+1) - J_2(J_2+1)]\,(\Delta T/T^2)$. For $J_1 = 25$ and $J_2 = 50$, $\Delta R/R$ is of the order of $(\Delta T/T^2) \times 10^3$, requiring accuracy of about 1% in the measurement of the equivalent widths, if only two lines are taken to define the rotational temperature. But as the number of lines n used to define the slope increases, the r.m.s. error that can be tolerated in each individual line measurement increases by a factor of $\sqrt{n}$. Tsuji (1977) has determined the rotational temperature of CO molecule in the solar photosphere by using a large number of first overtone lines of CO in the wavelength region 2.3 to 2.5 μm, with an accuracy of $\pm$40 K. The equivalent widths of these lines are in the range of 10 mÅ to 50 mÅ and their error of measurements is 10 to 20%. So by using a reasonable number of lines of the vibration-rotation bands of SiO, an appropriate model can be chosen with confidence.

Spectral region from 8 to 14 μm lies in the atmospheric transmission window. Recently spectral scans in the wavelength region from 8 to 10 μm have been made for the detection of NH_3 vibration-rotation line profiles in the Jovian spectrum using superheterodyne techique with a resolution of 10^7 (Kostiuk *et al.* 1980). Using the superheterodyne technique (Glenar *et al.* 1982) Glenar *et al.* (1983) have observed the rotational lines of the 0–1 and 2–1 vibration-rotation bands in sunspots with sub-Doppler ($\simeq 10^6$) resolution. They have found that the SiO lines are formed high up in the atmosphere where temperature distributions are very diverse in the models M1, M2 and M4 considered by them. The SiO lines are very sensitive to the temperature structure of the higher layers because of dissociation equilibrium considerations and provide a temperature sensitivity criterion of ± 100 K on the basis of log (W/ν) values.

There is considerable diversity between the rotational temperatures and their centre-to-limb variation which may allow one to pick up the representative model on the basis of observed rotational temperature of SiO.

References

Boyer, R. (1980) *Astr. Ap. Suppl.* **40**, 277.

Gaur, V. P., Pande, M. C. & Tripathi, B. M. (1978) *Solar Phys.* **56**, 67.

Glenar, D. A., Deming, D., Jennings, D. E., Kostiuk, T. & Mumma, M. J. (1982, 1983) *Appl. Opt.* **21**, 253; *Ap. J.* **269**, 309.

Henoux, J. C. (1969) *Astr. Ap.* **2**, 288.

Herzberg, G. (1950) *Molecular Spectra and Molecular Structure. 1, Spectra of Diatomic Molecules*, Van Nostrand.

Joshi, G. C., Punetha, L. M., & Pande, M. C. (1979) *Solar Phys.* **64**, 255.

Kneer, K. (1972) *Astr. Ap.* **18**, 39.

Kollatschy, W., Stellmacher, G., Wiehr, E. & Falipou, M. A. (1980) *Astr. Ap.* **86**, 245.

Kostiuk, T. *et al.* (1980) *Infrared Phys.* **17**, 431.

Pande, M. C. & Joshi, G. C. (1978) *Solar Phys.* **59**, 353.

Stellmacher, G. & Wiehr, E. (1970, 1975) *Astr. Ap.* **7**, 432; **45**, 69.

Tsuji, T. (1977) *Publ. Astr. Soc. Japan*, **29**, 497.

Zwaan, C. (1965) *Rech. Astr. Obs. Utrecht* **17**, No. 4.

Zwaan, C. (1974, 1975) *Solar Phys.* **37**, 99; **45**, 115.