(A—X) SYSTEM OF SiO IN SUNSPOTS

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Abstract. The calculated equivalent widths of some lines of SiO in the umbral spectrum suggest that strong lines of $Si^{28}O^{16}$, $Si^{29}O^{16}$ and $Si^{30}O^{16}$ may be present in the sunspot ultraviolet spectrum. We also find that between 37 000 and 47 000 cm^{-1} the quasi-continuous absorption of SiO dominates all other absorptions.

1. Introduction

Though SiO is one of the abundant species in the solar photosphere and sunspots, only the following investigations have been made regarding its detectability in the solar atmosphere:

(1) SiO (A—X) system would show hardly detectable features <10 mÅ around 228 nm in the photospheric spectrum (cf. Krishna Swamy, 1976).

(2) Gaur *et al.* (1978) have predicted that the vibration rotation bands of SiO may be detectable in the infrared umbral spectrum.

(3) Pande and Joshi (1978) have made investigations about the $Si^{29}O^{16}$ and $Si^{30}O^{16}$ vibration rotation band in the infrared umbral spectrum.

(4) Tarafdar and Vardya (1972) have shown that SiO could be one of the molecules that could explain the unknown source of opacity in the ultraviolet spectrum of the solar photosphere.

Among the transitions originating from the ground level namely A—X, E—X, F—X, G—X, H—X and I—X, it is only the A—X transition that would be observed in absorption, for it lies redward of 2074 Å, shortward of which the opacity due to Al starts playing a dominant role. While considering the case of the γ system of NO, Joshi *et al.* (1978) have shown that sunspots may provide more favourable conditions for the detection of the resonance systems of abundant molecules. As SiO is fairly abundant in the umbral atmosphere we calculated the intensity of the lines of the (A—X) system of SiO in sunspot ultraviolet spectrum both for the $Si^{28}O^{16}$ and its isotopic species $Si^{29}O^{16}$ and $Si^{30}O^{16}$. The wavenumbers for the isotopic species have been calculated by us. Also the role of the $Si^{28}O^{16}$ (A—X) system bound–bound transition in the ultraviolet umbral opacity has been considered in the following.

2. Calculations

2.1. Calculation of the isotopic shift

The method for calculating the isotopic shifts is the same as used by Lambert and Mallia (1970) for the (A—X) system of SiH. Molecular constants and the requisite

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expressions for term values have been taken from Saper (1932). The various constants entering the expressions for term values have been modified for the isotopic case as by Lambert and Mallia (1970). The isotopic shifts for the SiO(0–1) band, $\Delta\lambda$ (mÅ) $= \lambda[Si^{28}O^{16}] - \lambda[Si^{29}O^{16}]$ and $\Delta\lambda$ (mÅ) $= \lambda[Si^{28}O^{16}] - \lambda[Si^{30}O^{16}]$ have been calculated. These are approximated by second degree polynomials $a + bJ + cJ^2$, whose coefficients are given in Table I. The shifts in wavelengths attributable to Λ-splitting and electronic shift have not been included. These will contribute only $\Delta\lambda < 10$ mÅ (cf. Lambert and Mallia, 1970). The isotopic shifts calculated by us are thus uncertain to that extent.

TABLE I

The values of the coefficients (a), (b), and (c) used in the polynomial for isotopic shift calculations

Shift for	Branch	(a)	(b)	(c)
$Si^{29}O^{16}$–$Si^{28}O^{16}$	*P*	5.2305 E−1	3.5655 E−4	8.0005 E−5
	Q	5.2233 E−1	−5.4959 E−4	7.9590 E−5
	R	5.2110 E−1	−1.4749 E−3	7.9466 E−5
$Si^{30}O^{16}$–$Si^{28}O^{16}$	*P*	1.0146	7.0863 E−4	1.5438 E−4
	Q	1.0142	−1.0825 E−3	1.5394 E−4
	R	1.0121	−2.8912 E−3	1.5394 E−4

2.2. Equivalent width calculations

We have selected the 0—1 band for equivalent width calculations for the following two reasons:

The Franck–Condon factor for the 0—1 band is the largest, and the vibrational isotopic shift will be greater for the case of the 0—1 band as compared to the 0—0 band. Our shifts are larger by a factor of 4 to 8 as compared to that of $\Delta\lambda$ (mÅ) = $Si^{28}H^1 - {}^iSiH^1$ for the 0—0 band of the (A—X) system (Lambert and Mallia, 1970).

The equivalent widths of some subsequent lines of the *P*-branch of the 0—1 band of the (A—X) system have been calculated for five disc positions for Zwaan's sunspot model (abbreviated as ZSM–1975) using the method given by Krishna Swamy (1976).

The following, lists the various sources of constants used by us: (1) Elemental abundances; Engvöld (1977). (2) Isotopic abundance ratio: Lambert and Mallia (1970) and Greenstein (1966). (3) Internal partition functions and dissociation constants; Glushko *et al.* (1962). The dissociation energy of SiO has been discussed by Pande and Joshi (1978). (4) Molecular constants: Suchard (1975). (5) Franck–Condon factors: Liszt and Smith (1972). (6) Rotational intensity factors: Schadee (1964).

The band oscillator strengths $f_{v'v''}$ have been calculated with the help of the electronic transition moment as determined by Park and Arnold (1978) using the

relationship $\sum |R_e|^2 = 3.295 \times 10^{-3} f_{v'v''} \times \lambda_{v'v''}/q_{v'v''}$. The values of the calculated equivalent widths for normal as well as the isotopic species have been tabulated in Table II.

2.3. Opacity calculations

The following sources of opacity included to calculate the continuous opacity in the region where the selected lines are situated: (1) H, H^- and the scattering due to H, H_2 and electrons (Tsuji, 1966) and (2) ultraviolet opacity due to the metals Al, Mg, and Si (Travis and Matsushima, 1968).

To illustrate how the molecular opacity due to the SiO (A—X) system and the NO—γ-system behave in the sunspots, we have made opacity calculations for these molecules using Golden's (1967) method at three optical depths ($\tau_{0.5\mu m} = 0.01$, 0.10, and 1.00) in ZSM-75. We have included 20 bands of the SiO (A—X) system

TABLE II

Centre to limb variation of equivalent widths of some lines of the P branch of the 0 – 1 band of SiO and ^{i}SiO in ZSM-1975*

cos θ	J	$Si^{28}O^{16}$	LM $Si^{29}O^{16}$	G $Si^{29}O^{16}$	LM $Si^{30}O^{16}$	G $Si^{30}O^{16}$
1.0	31	198.3	179.8	159.7	174.6	154.3
0.75		211.5	190.8	170.0	185.1	164.2
0.70		215.9	194.5	173.7	188.7	167.5
0.50		245.6	220.1	197.4	213.7	190.0
0.30		318.7	283.7	255.6	275.6	245.3
1.0	41	200.3	182.0	161.6	176.6	156.3
0.75		213.5	192.7	172.2	187.1	166.1
0.70		218.0	196.5	175.7	190.6	169.6
0.50		247.5	222.2	199.5	215.8	192.1
0.30		320.5	285.6	257.7	277.8	247.4
1.0	57	195.0	170.2	151.7	165.0	146.2
0.75		208.4	188.5	168.6	182.8	162.2
0.70		212.9	193.4	173.1	187.6	166.5
0.50		242.8	220.3	197.9	214.0	189.9
0.30		315.6	280.1	252.8	272.6	241.5
1.0	63	192.9	168.1	149.3	163.2	144.1
0.75		206.3	184.4	165.6	178.9	158.9
0.70		210.8	188.1	169.1	182.6	162.2
0.50		240.6	213.4	192.6	207.6	184.1
0.30		313.0	275.7	249.6	268.9	237.5
1.0	73	188.5	166.9	150.6	162.4	144.3
0.75		201.9	177.8	160.6	173.3	153.2
0.70		206.3	181.5	164.0	177.0	156.3
0.50		235.8	206.5	186.6	201.7	177.0
0.30		306.8	267.6	241.4	261.8	227.5

*Isotopic abundance ratio, LM: Lambert and Mallia (1970); G: Greenstein (1966).

and 19 bands of the NO-γ-system. For the NO-γ-system the molecular constants, dissociation constants, internal partition functions, Franck–Condon factors and the electronic oscillator strengths have been taken respectively from Suchard (1975), Glushko *et al.* (1962) and Farmer *et al.* (1972).

Figures 1, 2, and 3 respectively show the behaviour of the molecular opacities at three selected optical depths. For comparison we have also shown all other known opacity sources.

3. Discussions

It is clear from Table II that the sunspot spectrum may show strong lines of not only the normal species of $Si^{28}O^{16}$ but also of the isotopes $Si^{29}O^{16}$ and $Si^{30}O^{16}$, as against the weak (<10 mÅ) features of the SiO (A—X) system in the case of the solar photosphere (cf., Krishna Swamy, 1976). Further, it is apparent from the Krishna Swamy's Figures 1 and 5 that with moderate dispersion the lines of SiO would be separated distinctly from the lines of CO, and not clamped together as stated by him. Both factors, namely the larger intensity and larger isotopic shift as compared to the 0—0 band of the (A—X) system of SiH investigated by Lambert and Mallia (1970) would make the isotopic abundance fixation for Si^{28} and Si^{29} and Si^{30} easier.

As regards the contribution of SiO towards continuous opacity in the considered spectral region, it dominates all the other known sources of opacity in sunspots. It

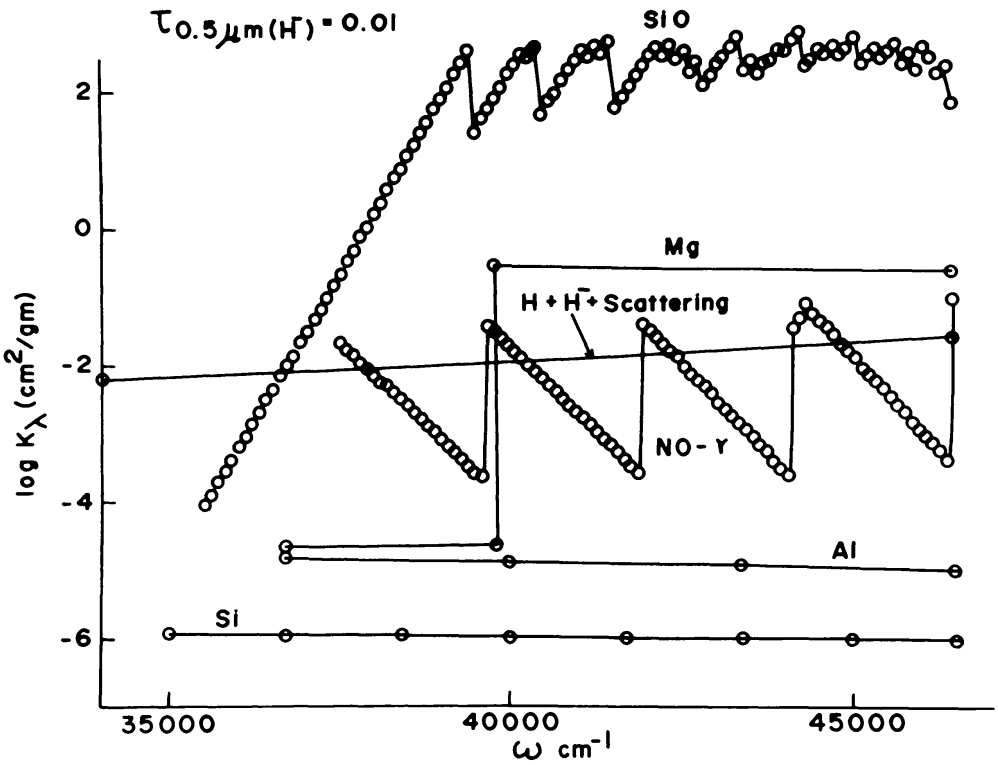

Fig. 1. Variation of mass absorption coefficient, K_λ ($cm^2\ g^{-1}$) with wave number, ω due to the molecules SiO and NO as compared with Al, Mg, Si, $H+H^-$ + scattering at $\tau_{0.5\mu m}(H^-) = 0.01$ in ZSM-1975.

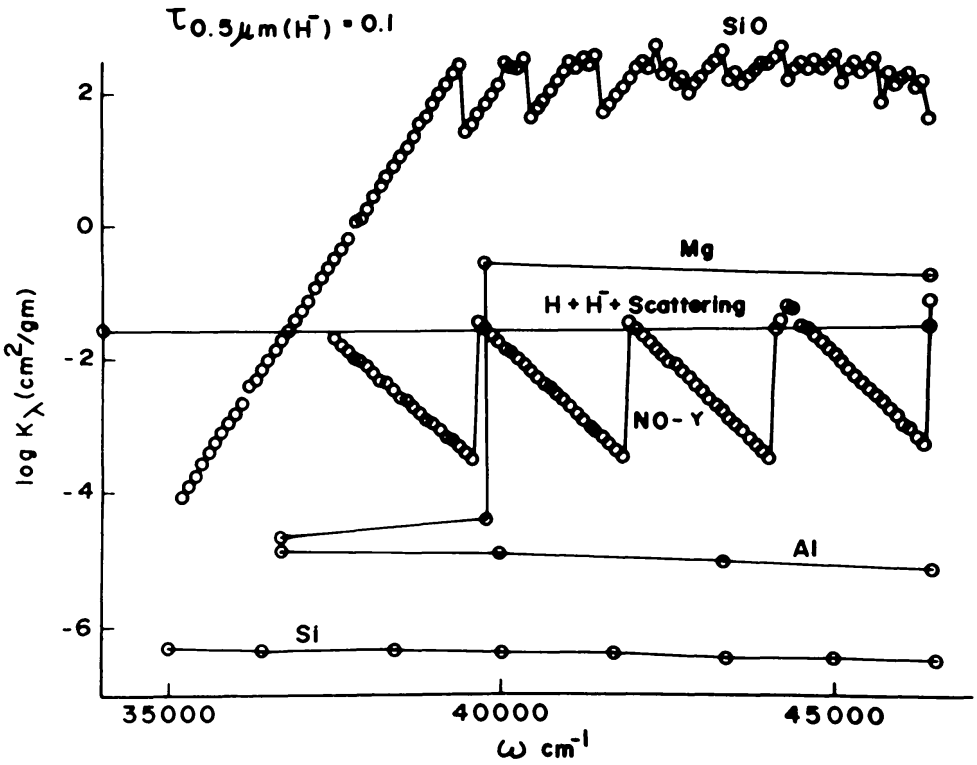

Fig. 2. Same as Figure 1 for $\tau_{0.5\mu m}(H^-) = 0.10$.

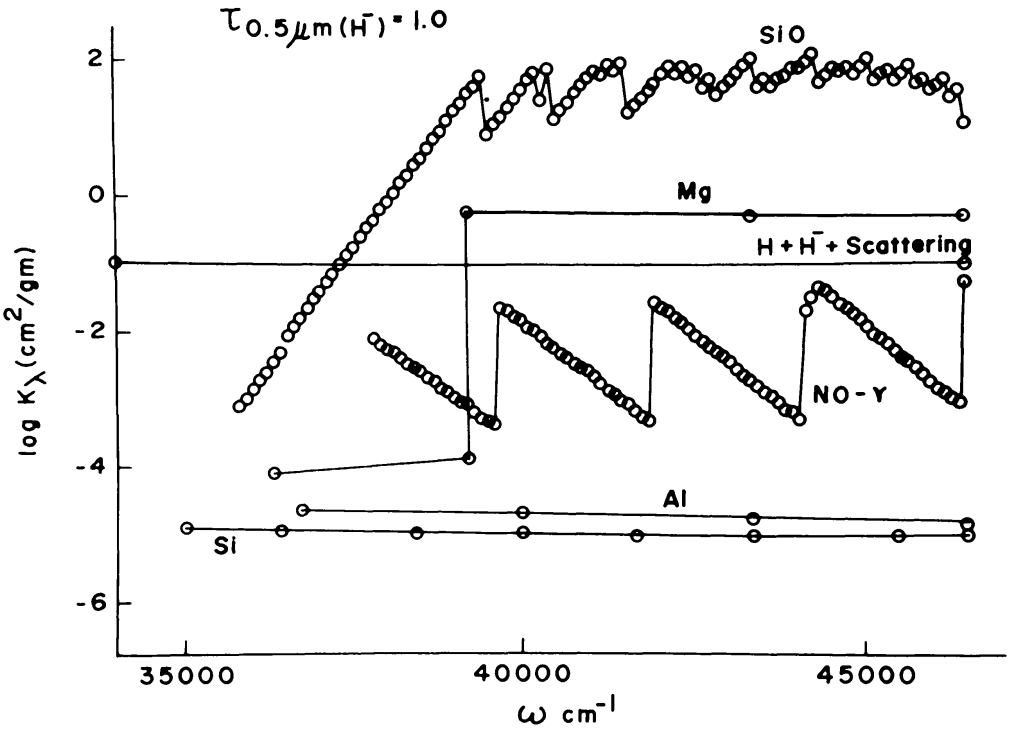

Fig. 3. Same as Figure 1 for $\tau_{0.5\mu m}(H^-) = 1.00$.

may be noted that the oscillator strength used by Tarafdar and Vardya (1972), while calculating the opacity in the solar photosphere for the (A—X) system of SiO is larger by a factor of 3 compared to the recent and a more refined value adopted by us.

Consequently, the role of the (A—X) system of SiO in the photospheric case will be much diminished.

Observations for elements like C, O, Ti, and Mg, show that the solar and terrestrial isotopic abundance ratios are nearly identical (cf. Hall, 1970; Sotirovski, 1971; Lambert and Mallia, 1972). Therefore, the upper abundance limits for the Si isotropic ratios by Lambert and Mallia (1970) may not be relevent.

The Zwaan (1974) model has been able to explain the observed rotational temperature of TiO (Sinha, 1977). The Zwaan (1965) model is somewhat hotter than the Zwaan (1974) model and to assess the model effect a comparison made by us of calculated molecular abundances in the two models shows that the overall SiO abundance decreases by a factor of 1.5 in the hotter model. Consequently, the selective opacity due to SiO will decrease if hotter models turnout to be more representative.

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