

# ON THE PRESENCE OF SH IN THE SUNSPOT SPECTRUM

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**Abstract.** The expected equivalent widths of individual rotational lines of the most intense  $Q_2$  branch of the 0—0 band of the  $A^2\Sigma-X^2\Pi_i$  system of  $S^{32}H$  and  $S^{34}H$  have been calculated in the umbral spectrum for five disk positions using Zwaan's (1974) sunspot model. Percentage abundance of  $S^{34}$  in the terrestrial case has been considered valid in our calculations.

Strong lines of  $S^{32}H$  and  $S^{34}H$  of the A—X band system should be detectable in the sunspot spectrum. The molecule SH may play a possible role as a major opacity source in the ultraviolet spectrum of sunspots along with the molecule OH in the upper layers (up to  $\tau_{0.5\mu m} = 1.0$ ) wherefrom most of the continuum arises. Study of this molecule in the umbral spectrum may also provide the solar isotopic abundance ratio  $N(S^{32})/N(S^{34})$ .

## 1. Introduction

Efforts for predicting the ultraviolet spectrum of sunspots are still lacking in the literature. As a part of a program for predicting the sunspot molecular spectra in the ultraviolet region, we have considered the  $A^2\Sigma-X^2\Pi_i$  transition of the SH molecule in this communication. The reasons which prompted us to carry out this investigation are as enumerated below:

(i) Sinha *et al.* (1977) calculated the expected equivalent widths for a few lines of the strongest 0—0 band of the transition  $A^2\Sigma-X^2\Pi_i$  of the molecule  $S^{32}H$  for the photospheric case. On the basis of a comparison of abundances of SH and NO in sunspots, Sinha *et al.* (1977) have further suggested that a search for this molecule should be made in the infrared umbral spectrum as well.

(ii) The molecule  $S^{32}H$  seems to have a much larger abundance in well-developed sunspots as compared to the photosphere (Sinha *et al.*, 1977). Consequently, if the lines belonging to the 0—0 band of the  $A^2\Sigma-X^2\Pi_i$  transition of  $S^{32}H$  show large equivalent widths, then an effort for determining the isotopic ratio  $N(S^{32})/N(S^{34})$  may be made. We have discussed the expectations regarding the detection of the 0—0 band of the transition  $A^2\Sigma-X^2\Pi_i$  for the molecule  $S^{34}H$  in the umbral spectrum assuming that the terrestrial isotopic ratio is valid for the solar atmosphere too. At this stage, as the actual isotopic ratio  $N(S^{32})/N(S^{34})$  is not known such an assumption appears reasonable since the abundance of isotopes of Cl, C, O, Si, Ti, Ni and Mg (cf. Hall and Noyes, 1972; Hall, 1970; Lambert and Mallia, 1970, 1971, 1972; Sotirovski, 1971) are consistent with the terrestrial value.

Here, we report the results of the equivalent width calculations for some individual rotational lines of the most intense  $Q_2$  branch of the 0—0 band of the  $A^2\Sigma-X^2\Pi_i$  transition of SH molecule for the umbral model by Zwaan (1974), hereinafter abbreviated as ZSM-74. We also discuss here the possibility of detecting the isotopic

lines of the same transition of  $S^{34}H$ . At  $\tau_{0.5\mu m} = 0.01, 0.10, \text{ and } 1.00$  of the umbral atmosphere the opacity due to this molecule has also been computed and compared with the other sources of opacity.

## 2. Calculations

The method adopted by us for equivalent width calculations is the same as used by Krishna Swamy (1975) for the linear and flat portion of the curve of growth. For the variation of physical parameters with depth the umbral model ZSM-74 has been adopted since it is an improved version of the earlier continuum based sunspot models. Elemental abundances used by us for dissociation equilibrium calculations are according to Gingerich *et al.* (1971) with a terrestrial isotopic abundance ratio of  $N(S^{32})/N(S^{34}) = 22.565$ . Internal partition functions, dissociation constants and the molecular constants are from Glushko *et al.* (1962) and the rotational intensity factors were obtained from the formulation by Schadee (1964). The wavelength of the lines of the  $Q_2$  branch of the 0—0 band of the  $A-X$  system of  $S^{32}H$  were borrowed from Ramsay (1952) and the theoretical oscillator strength is adopted from Henneker and Popkie (1971). The reliability of the selected oscillator strength has already been discussed by Sinha *et al.* (1977), who conclude that a laboratory check of the oscillator strength is required.

The equivalent widths of the lines ranging from  $J'' = 3.5$  to 13.5 of the already mentioned transition have been calculated for five disk positions for the model ZSM-74. Depths of formation for these lines were derived according to Laborde (1961). The peak of the predicted equivalent width corresponds to a  $J'' = 10.5$  for which the lines should be most intense under the physical conditions prevailing in sunspots. The observed wavenumbers listed for the 0—0 band of the  $Q_2$  branch of the  $A-X$  system of  $S^{32}H$  by Ramsay (1952) cannot be reproduced with enough accuracy with the molecular constants given by Ramsay (1952), nor by the otherwise available molecular constants of Johns and Ramsay (1961). Because of the above uncertainty we did not calculate the wavenumbers of isotopic lines although the isotopic shifts could have been calculated even with crudely known molecular constants. Due to this limitation, we calculated equivalent widths for the isotopic lines of  $S^{34}H$  adopting the same wavelenths as are valid for the normal species  $S^{32}H$  since the isotopic shifts in the molecular electronic transitions are rather small. The equivalent widths for the lines of the isotopic species  $S^{34}H$  are also listed in Table I.

While calculating the continuous opacity due to various sources like  $H^-$ ,  $H$ , scattering due to  $H$ ,  $H_2$  and electrons following Tsuji (1966) and ultraviolet metal opacity according to the formulations by Travis and Matsushima (1968), we noticed that the molecule  $OH$  may dominate as a source of opacity in the considered spectral region. To calculate the opacity we have included the 0—0, 1—0, 2—0, 3—0, 4—0, 0—1, 1—1, 2—1, 0—2, 1—2, and 0—3 bands of the  $A-X$  transition of  $S^{32}H$  molecule and the 0—0, 1—0, 2—2, 1—1, 0—1, 2—1, 3—2, 3—3 and 1—2 bands of  $A-X$  transition of  $OH$  in the considered wavelength region. This opacity has been

TABLE I

Centre to limb variation of the equivalent widths of the lines of the  $Q_2$  branch of the 0—0 band of  $A^2\Sigma-X^2\Pi_i$  system of  $S^{32}H$  and  $S^{34}H$  in ZSM-74

$J'' \cos \theta$	$S^{32}H$ $W$ (mÅ)					$S^{34}H$ $W$ (mÅ)				
	1.00	0.75	0.70	0.50	0.30	1.00	0.75	0.70	0.50	0.30
3.5	129	143	148	175	201	31	35	35	43	47
4.5	132	147	152	180	206	39	43	44	54	61
5.5	135	149	154	183	209	46	51	52	65	72
6.5	137	152	156	185	212	53	59	59	73	83
7.5	138	153	158	187	214	59	65	66	82	92
8.5	139	154	159	189	216	64	71	72	89	100
9.5	140	155	160	189	217	58	75	76	94	106
10.5	140	156	161	190	218	70	78	79	97	109
11.5	140	156	161	190	217	70	78	79	97	109
12.5	140	155	160	190	217	68	75	77	94	106
13.5	139	155	160	189	217	66	73	74	92	103

accounted for using the ‘smeared line model’ formulation by Golden (1967). The Franck–Condon factors adopted for these bands of SH and OH are from Nicholls *et al.* (1960) and Suchard (1975), respectively.

We also realised that a straight application of Golden’s (1967) method to the  $A-X$  system of the OH molecule may not be appropriate. Golden (1967) has pointed out that the  $A-X$  system of OH corresponds to a transition with strong vibration rotation interaction and consequently one can not conclude a priori that the results obtained from his smeared line model will agree with those from the ‘line to line model’ as proposed by Johnson *et al.* (1972) although the cases of weak vibration rotation interaction (such as NO- $\gamma$ -system and CN red system) show such an agreement. However, Figure 1 shows that also in the case of OH the two models lead to comparable results. The investigations by Dieke and Crosswhite (1962) have been used for calculating the opacity due to the molecule OH according to Johnson *et al.* (1972) at  $\tau_{0.5\mu\text{m}} = 0.01$ . While using the method of Johnson *et al.* (1972) we calculated absorption cross-sections of the individual lines of all the main and satellite branches of all the considered bands. We then averaged out the absorption cross-section over a wavenumber difference of  $100 \text{ cm}^{-1}$ . It may be noted that it is cumbersome to calculate the absorption cross-section of the individual lines and then obtain an averaged cross-section over a certain wavenumber interval. In Figures 2, 3 and 4 we show the behaviour of the opacity as a function of the wavenumber for optical depths  $\tau_{0.5\mu\text{m}} = 0.01, 0.10, \text{ and } 1.00$  in ZSM-74.

### 3. Discussions

From Tables I and II we conclude that the molecule  $S^{32}H$  and  $S^{34}H$  should be observable in the umbral spectrum. If the isotopic abundance of  $S^{34}$  be reduced by a

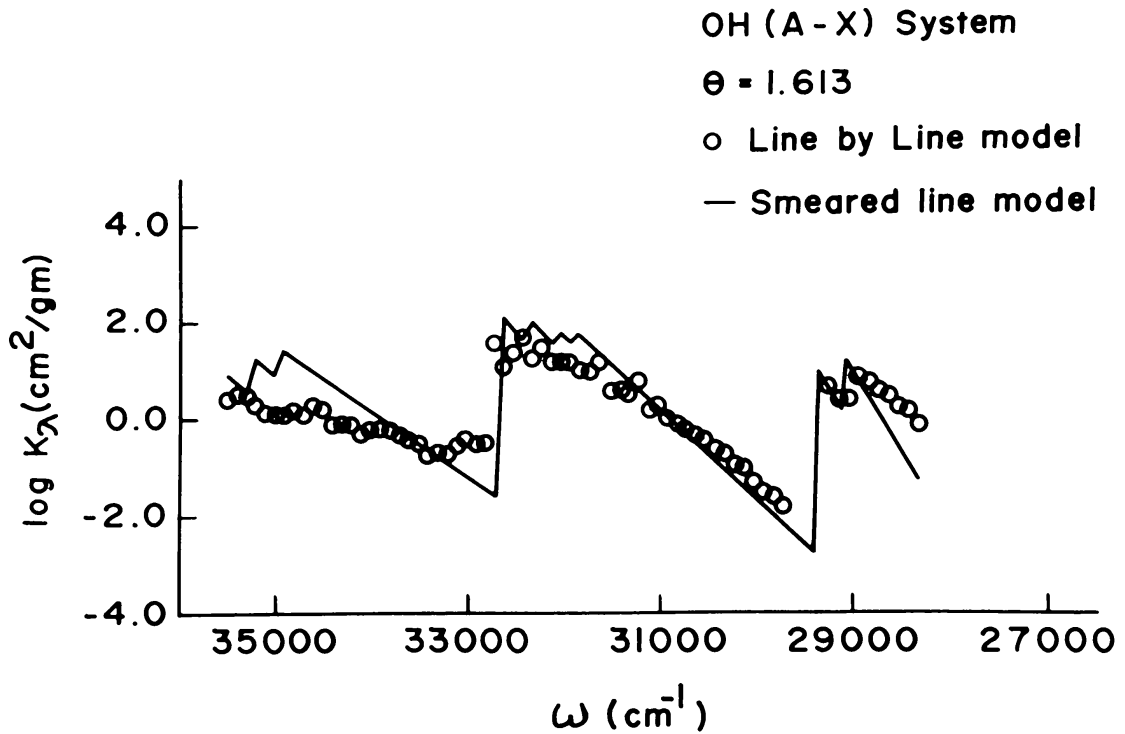


Fig. 1. Comparison of the results of smeared line model and line by line model calculations of bound-bound opacity due to the molecule OH for a typical sunspot condition ( $\tau_{0.5\mu\text{m}} = 0.01$ , ZSM-74).

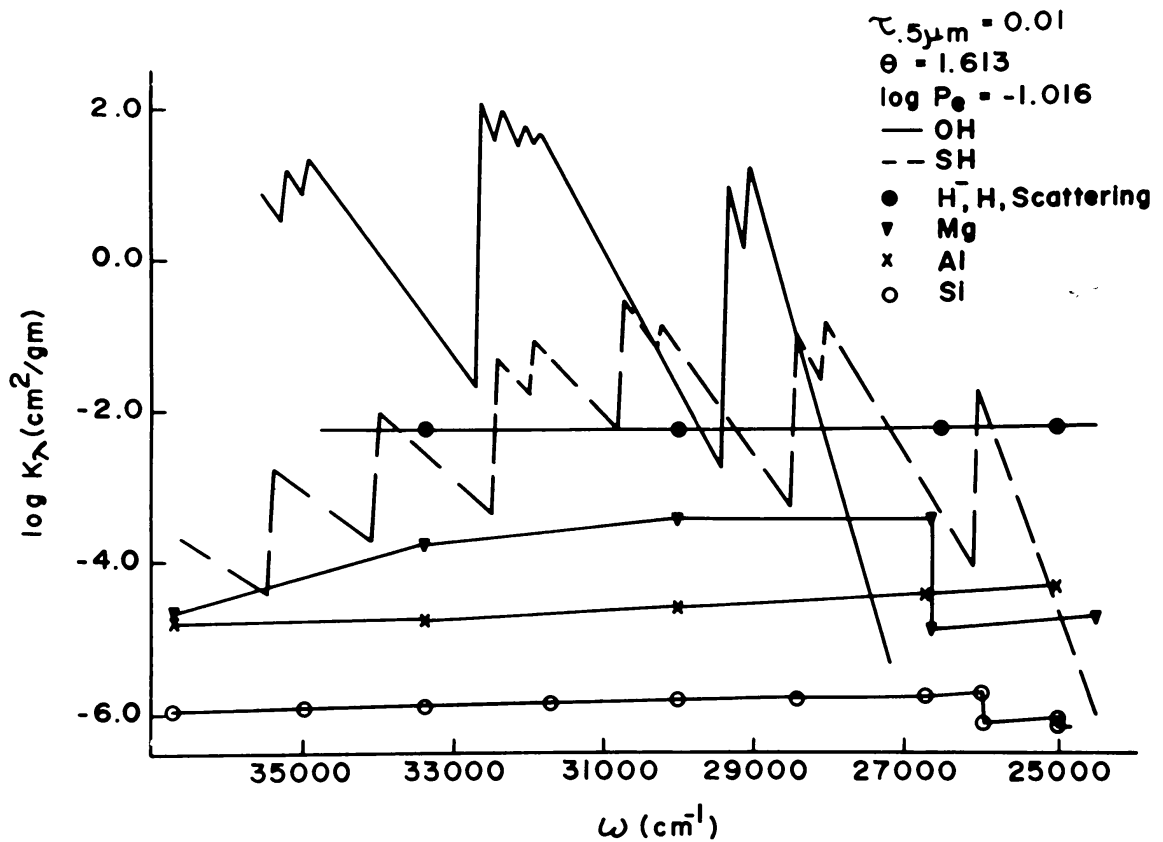


Fig. 2. Variation of mass absorption coefficient  $K_{\lambda}$  ( $\text{cm}^2 \text{g}^{-1}$ ) with wavenumber,  $\omega$  due to the molecules (bound-bound) OH and SH as compared with Al, Mg, Si,  $\text{H}^{-}$ , H and scattering due to  $\text{H}_2$  and electron in ZSM-74.

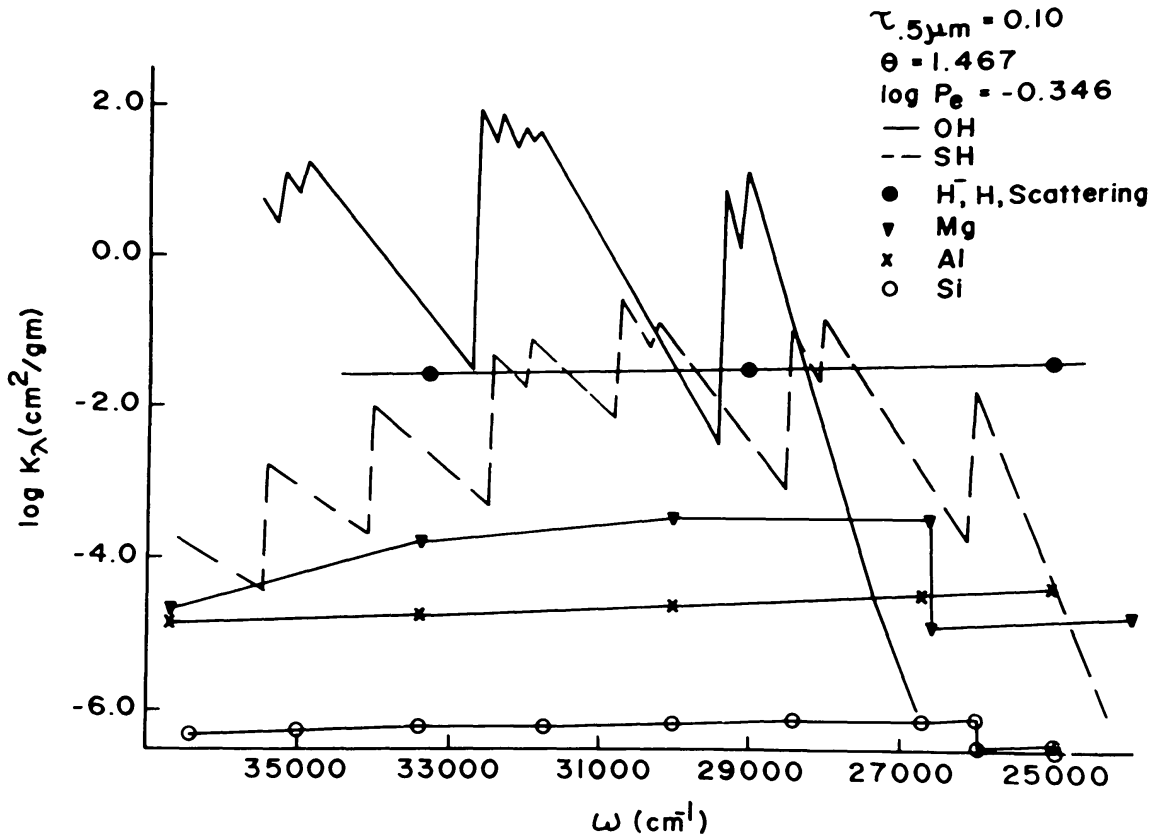
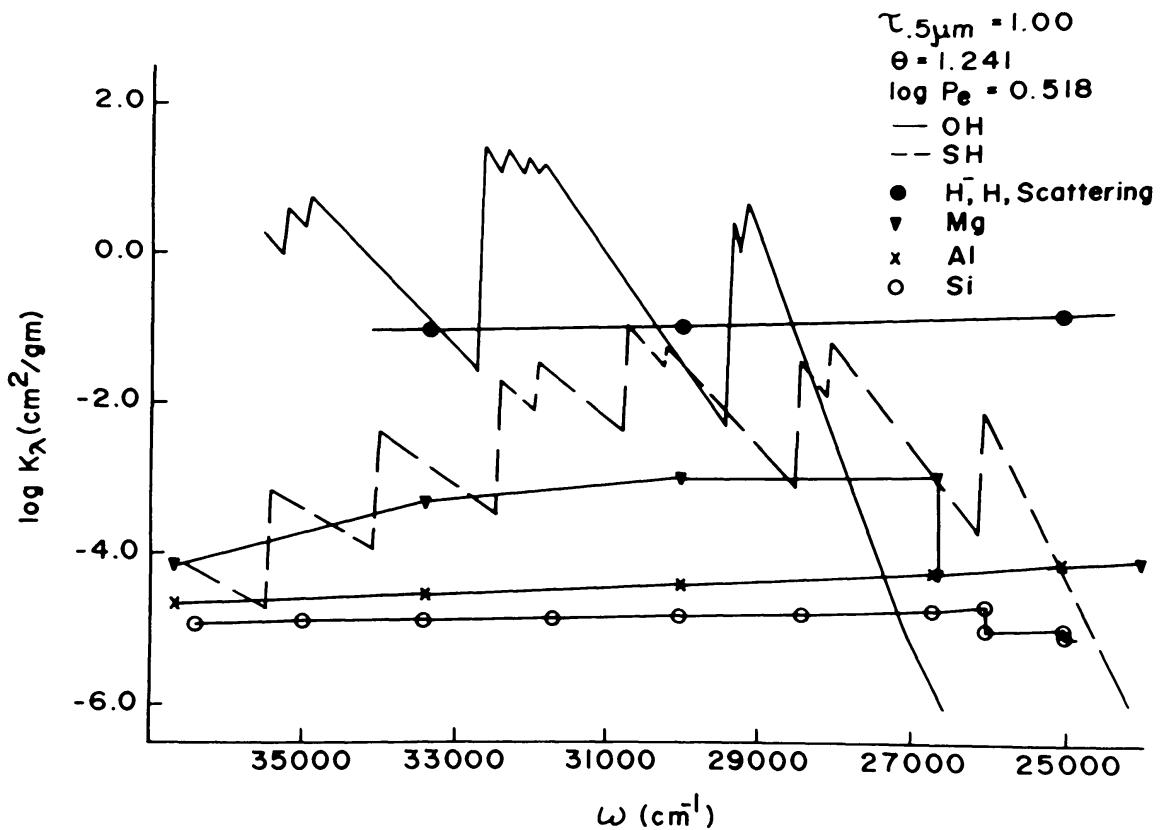
Fig. 3. Same as Figure 2, for different  $\tau$ ,  $\theta$ , and  $\log P_e$ .Fig. 4. Same as Figure 2, for different  $\tau$ ,  $\theta$ , and  $\log P_e$ .

TABLE II

Equivalent widths and depths of formation of most intense line ( $J'' = 10.5$ ) of the  $Q_2$  branch of the 0—0 band of  $A^2\Sigma-X^2\Pi_i$  system of  $S^{32}H$  and  $S^{34}H$  in ZSM-74

		$\cos \theta$	1.00	0.75	0.70	0.50	0.30
$W$ (mÅ)	$S^{32}H$		140	156	161	190	218
	$S^{34}H$		70	78	79	97	109
$\tau_{0.5\mu m}$	$S^{32}H$		0.12	0.10	0.08	0.07	0.04
	$S^{34}H$		0.15	0.13	0.10	0.09	0.05

factor of about 10, equivalent widths of about 10 mÅ are expected for the strongest lines which may be detectable in the umbral spectrum near the limb provided that the theoretical oscillator strength and the ZSM-74 model used by us are realistic.

The molecules OH and SH fall nearly in the same wavelength region of the spectrum but fortunately the lines of the strongest branch of the most intense 0—0 band of the  $A-X$  transition of SH fall in the region which is comparatively more free from the lines of the molecule OH as is clear from the opacity considerations of OH and SH. The synthetic spectrum in this wavelength region may help identify the lines of  $S^{32}H$  and  $S^{34}H$  and thus establish the isotopic ratio  $S^{32}/S^{34}$  in the solar atmosphere. To match the theoretical equivalent widths with the observations, the laboratory observations for the wavenumbers of the  $A^2\Sigma-X^2\Pi_i$  transition of the molecule  $S^{34}H$  are required. From the centre to limb variation of the average optical depth we infer that SH forms approximately in a thin layer since the temperature difference from centre to limb is nearly 300 K.

As is clear from the Figures 2, 3, and 4 in the considered spectral region the opacity due to the molecule SH is smaller than the opacity due to OH in ZSM-74 except between 25 000 and 28 000  $\text{cm}^{-1}$ . However, compared to the other known sources of opacity, the opacity due to SH is larger or comparable with the total opacity due to  $H^-$ , H, scattering due to H,  $H_2$  and electrons. It thus may be inferred from this circumstance that the bound-bound ultraviolet opacity due to SH molecule may become significant in late type stars.

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