

# MOLECULAR LINE HAZE OPACITY IN SUNSPOTS

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(Received 4 September; in revised form 18 December, 1978)

**Abstract.** It has been shown that bound-bound opacity due to electronic transitions of molecules CN, CaH, MgH, and TiO explains, in a first approximation, the line haze opacity postulated by Zwaan (1974) for the region  $0.5 \mu\text{m}$  to  $0.9 \mu\text{m}$  of the umbral spectrum.

## 1. Introduction

While presenting his sunspot model, based on the measured relative umbral intensities in the continuum over a wavelength span  $0.5 \leq \lambda \leq 4 \mu\text{m}$ , Zwaan (1974) postulated the presence of an additional continuous opacity to explain the relative umbral intensities in the spectral region  $\lambda \leq 0.8 \mu\text{m}$ . The opacity enhancement factor i.e., the ratio of additional opacity to  $\text{H}^-$  ion opacity, is independent of depth and decreases towards longer wavelengths. Zwaan (1974) has also suggested that this additional opacity may be due to unresolved atomic and molecular lines. Furthermore, the presence of this source of opacity has twofold implications. Firstly, a neglect of this source may lead to an overestimation of the temperature gradient in empirical models. Secondly, it will also affect the interpretation of the umbral line profiles. However, Zwaan (1974) has not specified the nature of the absorbers responsible for this additional line haze opacity.

Realizing the significance of the above situation we decided to investigate the possibility of explaining the additional opacity to be primarily of molecular origin. The results of such an investigation are reported here.

## 2. Calculations of the Molecular Line Haze Opacity

The molecules CN, CaH, MgH, and TiO show electronic transitions in the region where additional opacity has been postulated by Zwaan (1974). Also, these molecules are amongst abundant molecules in the umbral atmosphere (Gaur *et al.*, 1973). For these reasons we selected these molecules for opacity calculations.

The abundances of these molecules as a function of optical depth in Zwaan's (1974) sunspot model, ZSM-74, were calculated adopting the same elemental abundances and calculational procedure as given by Gaur *et al.* (1973).

The bound-bound opacities due to molecules CN and TiO in the model ZSM-74 were obtained from the investigations of Johnson *et al.* (1972) and Collins and Fay (1974) respectively. For CaH and MgH, the molecular opacities at all depths in ZSM-74 were calculated using the formulations by Golden (1967) (cf. also Kipper, 1973). The molecular data used by us is summarised in Table I.

TABLE I  
Molecular data used in the present work

Molecule	Transition	Considered bands	References for	Oscillator strength	Franck Condon factors	Partition functions and dissociation constants
CN	$A^2\Pi_1 - X^2\Sigma^+$	$-3 \leq \Delta v \leq 12$	Fay <i>et al.</i> (1971)	$f_\infty = 3.2 \times 10^{-3}$ Johnson <i>et al.</i> (1972)	Spindler (1965)	Tatum (1966)
CaH	$A^2\Pi - X^2\Sigma$	(0, 0)	Rosen (1970)	$f_\infty = 0.64$ Webber (1971)	—	Tsuji (1964)
	$B^2\Sigma - X^2\Sigma$	(0, 0), (0, 1), (1, 0), (1, 1)	Rosen (1970)	$f_\infty = 0.24$ (assumed value)	Bell <i>et al.</i> (1976)	Tsuji (1964)
MgH	$A^2\Pi - X^2\Sigma$	(0, 0), (0, 1), (1, 0), (1, 1), (1, 2), (2, 1), (2, 2), (2, 3), (3, 2), (3, 3), (3, 4), (4, 3), (4, 4)	Balfour and Cartwright	$f_{e1} = 0.25$ Henneker and Popkie (1971)	Ortenberg and Glasko (1963)	Based on the data by Balfour and Cartwright (1976) and Balfour and Lindgren (1978). Tatum (1966)
TiO	$C^3\Delta - X^3\Delta$	$0 \leq \Delta v \leq 10$	Phillips (1973)	$f_{e1} = 0.18$ Price <i>et al.</i> (1974)	Collins and Fay (1974)	Tatum (1966)
	$A^3\phi - X^3\Delta$	$0 \leq \Delta v \leq 10$	Phillips (1973)	$f_{e1} = 0.49$ Price <i>et al.</i> (1974)	Collins and Fay (1974)	Tatum (1966)

For each band of a considered transition the bound-bound opacity was calculated as a function of wavenumber at intervals of  $200 \text{ cm}^{-1}$  for all optical depths in ZSM-74. At each depth the total molecular opacity,  $K_{\text{mol}}$  in  $\text{cm}^2 \text{ g}^{-1}$  was then easily obtained as a function of wavenumber by summing up the individual contributions of various bands of the considered transitions. The opacity due to  $\text{H}^-$  ion,  $K_{\text{H}^-}$ , was also calculated in the region  $0.5$  to  $0.9 \mu\text{m}$  with the help of Tsuji's (1966) absorption cross-section formulae. The ratio  $(K_{\text{mol}}/K_{\text{H}^-})$  has been plotted against wavelength for three typical depths of ZSM-74 in Figure 1. Using the continuous opacity  $K_{\text{mol}} + K_{\text{H}^-}$ , the umbral intensities in ZSM-74 were calculated for the centre of the disk. The wavelengths selected for these calculations are  $5089.06$ ,  $5420.05$ ,  $6006.00$ ,  $6079.03$ ,  $6644.52$ ,  $7117.44$ ,  $7905.14$ , and  $8888.89 \text{ \AA}$  which closely correspond to the windows chosen by various authors for relative continuum umbral intensities. For photospheric intensities we have utilised the measured intensities as tabulated by Vernazza *et al.*(1976). In Figure 2 the observed and computed relative umbral intensities in the region  $0.5$  to  $0.9 \mu\text{m}$  have been compared.

### 3. Results and Discussions

At all wavelengths the ratio  $K_{\text{mol}}/K_{\text{H}^-}$  shows a depth variation (cf. Figure 1). The fact that Zwaan (1974) could explain the measured continuum relative umbral

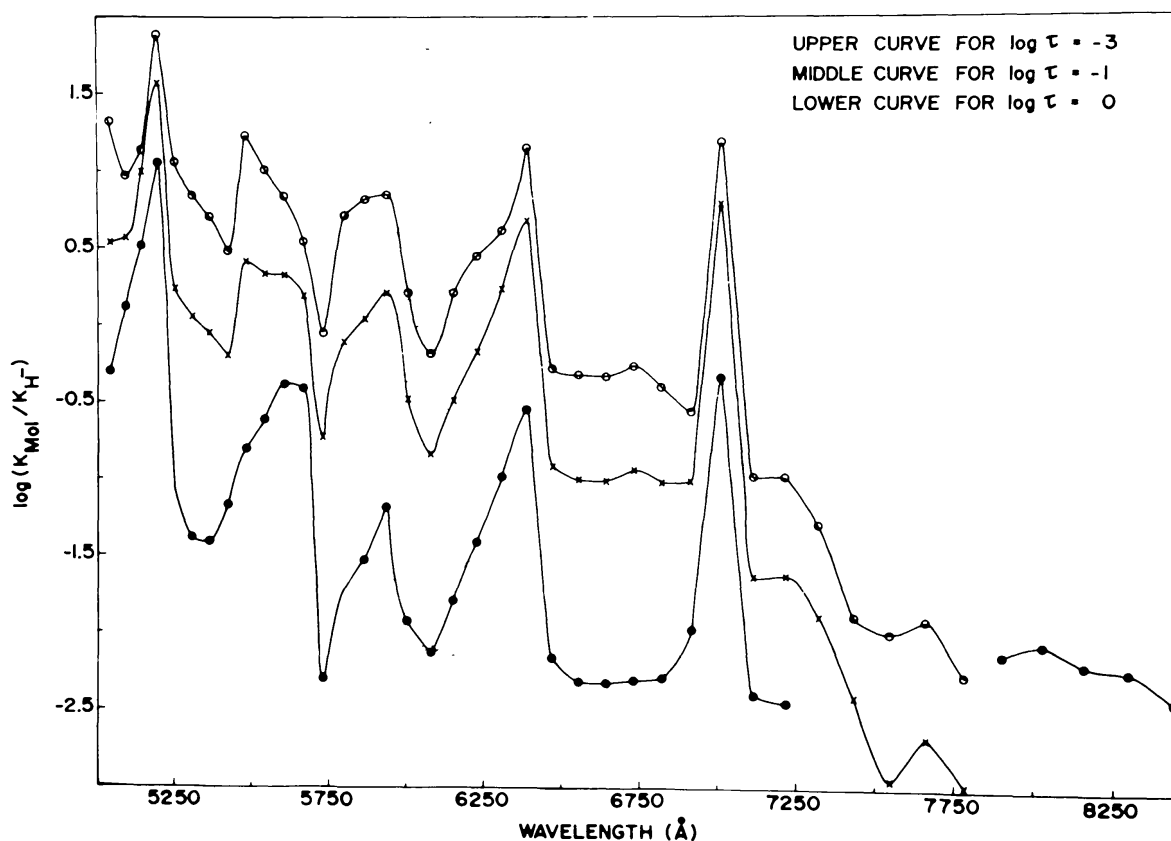


Fig. 1. The ratio of total molecular opacity  $K_{\text{mol}}$ , to  $\text{H}^-$  ion opacity,  $K_{\text{H}^-}$ , as a function of wavelength at three different optical depths.

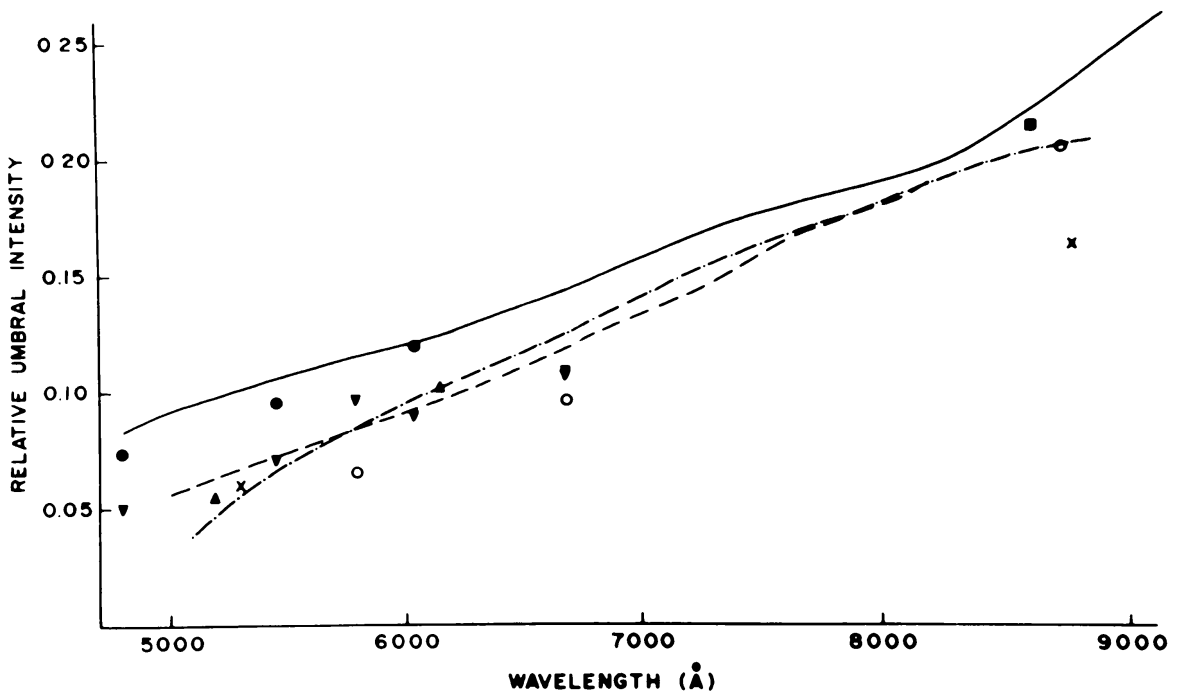


Fig. 2. Observed and computed relative umbral intensities near the centre of the disk as a function of wavelength. The computed intensities are denoted by lines: Solid line for  $H^-$  opacity, dashed line for Zwaan's enhanced and  $H^-$  opacity; dot-dash line for molecular plus  $H^-$  opacity. Narrow band photometry measurements are indicated by filled symbols: ■ Hénoux (1968), ● Hénoux (1969), ▼ Maltby (1970) and Engvold (1973), ▲ Mattig (1971); broad band photometry measurements: × Staveland (1970), ○ Maltby and Staveland (1971).

intensities with a depth independent opacity enhancement factor can be explained by the confinement of molecules basically to the higher layers. We also suggest that the wavelengths at which the molecular opacities are least would provide relatively cleaner regions for continuum measurements, provided if they do not overlap with strong atomic lines.

Figure 2 shows that the relative umbral intensities as obtained by us agree fairly well with those obtained by Zwaan (1974) for an additional continuous opacity. Consequently, we infer that, in the first approximation, the considered transitions largely explain the additional opacity. Also, the broad band photometric measurements give consistently lower relative umbral intensities which should obviously be so since the peak absorptions of the molecular opacity will get included in the wide band photometry. Hénoux's (1968, 1969) measurements which give higher relative umbral intensities, have already been criticized by Ekmann and Maltby (1974).

Summing up, it seems that the considered electronic transitions of CN, CaH, MgH, and TiO largely explain the line haze opacity suggested by Zwaan (1974). It may be mentioned that Zwaan (1975) has modified his earlier model ZSM-74 in the region  $\tau_{0.5}(H^-) > 1$ . However, this modification would not affect our conclusions since the molecular layer is essentially confined to regions  $\tau_{0.5}(H^-) \leq 1$ .

Bearing in mind the uncertainties in measured relative umbral intensities our assumption regarding the frequency independence of the adopted oscillator

strengths for the considered molecular bands does not seem to be unrealistic. However, relative umbral intensity measurements should be improved in future investigations and a synthetic model generated spectrum would be required in the neighbourhood of selected windows, to judge the spectral purity of relative umbral intensity measurements.

### Acknowledgements

The authors express their gratitude to Mr G. C. Joshi for extending assistance in computations and to Mr K. Sinha for valuable comments.

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