

ON THE INFRARED OPACITY OF SUNSPOTS

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Abstract. In the umbral atmosphere the depth dependence of the opacity due to the vibration rotation bands of various abundant molecules in the wavelength region $1\ \mu\text{m}$ to $10\ \mu\text{m}$ has been calculated. In the higher layers of the umbral atmosphere, the molecular opacity seems to dominate the opacity due to the negative hydrogen ion.

1. Introduction

One of the differences between the cool and hot stellar atmospheres is the extent to which the formation of molecules occurs in the former case. In constructing model atmospheres this characteristic of the cool stellar atmospheres should be borne in mind since it may alter the structure of such atmospheres radically.

Analogous to the case of the cool stars, sunspots radiate a substantial fraction of the energy in the infrared ($\lambda_{\text{max}} \approx 0.7\ \mu\text{m}$ for $T_{\text{eff}} = 4000\ \text{K}$) and as such the infrared opacity, specially due to molecules, may have a large effect on the atmospheric structure of sunspots. The concentration of H^- ion, a major source of opacity in the solar atmosphere, is decidedly less in sunspots because the decreased ionization of metals depletes the supply of free electrons. The bound-free absorption coefficient of H^- is greatest near $0.85\ \mu\text{m}$ and falls to zero at $1.64\ \mu\text{m}$. The free-free (H^-) absorption occurs throughout the infrared and its cross-section increases towards longer wavelengths.

To emphasize the role played by molecules in the case of the solar photosphere, one may mention investigations made by Holweger (1970) and Tarafdar and Vardya (1972, 1975) who have estimated line haze opacity, considering various abundant molecules, to explain the disparity between the observed and predicted emergent fluxes. Zwaan (1974) in sunspots has introduced an additional source of opacity in the wavelength region $\lambda < 0.8\ \mu\text{m}$, which in the first approximation, may be attributed to the bound-bound opacity due to molecules (cf. Gaur *et al.*, 1979).

The present investigation has been made to assess the role played by molecules towards the continuous opacity in the wavelength region $1\ \mu\text{m}$ to $10\ \mu\text{m}$.

2. Calculations

The molecules considered by us are H_2O , CO , OH , HCl , HF , NO , SiO and H_2 . The concentrations at various optical depths for each of these molecules in Zwaan's sunspot model (Zwaan, 1974) were found according to Gaur *et al.* (1973). The

sources for band origins and oscillator strengths for different molecules are given in Table I. Elemental abundances are according to Engvöld (1977). The opacities at three different depths of the model were calculated according to the just overlapping

TABLE I
Sources for band origins and oscillator strengths

Molecule	Band origin	Oscillator strength
SiO	Singh (1975)	Hedelund and Lambert (1972)
NO	Carpenter and Franzosa (1965)	Carpenter and Franzosa (1965)
HF	Guelachvili (1976)	Pande and Gaur (1974)
HCl	Rank <i>et al.</i> (1965)	Penner (1959)
H ₂ O	Tsuji (1966)	Tsuji (1966)
CO	Tsuji (1966)	Tsuji (1976)
OH	Tsuji (1966)	Tsuji (1976)
H ₂	Tsuji (1969)	Tsuji (1969)

line approximation (cf. Tsuji, 1966). For comparison the opacity due to negative hydrogen ion is also given in Figures 1, 2, and 3 along with the molecular (vibration-rotation) opacity.

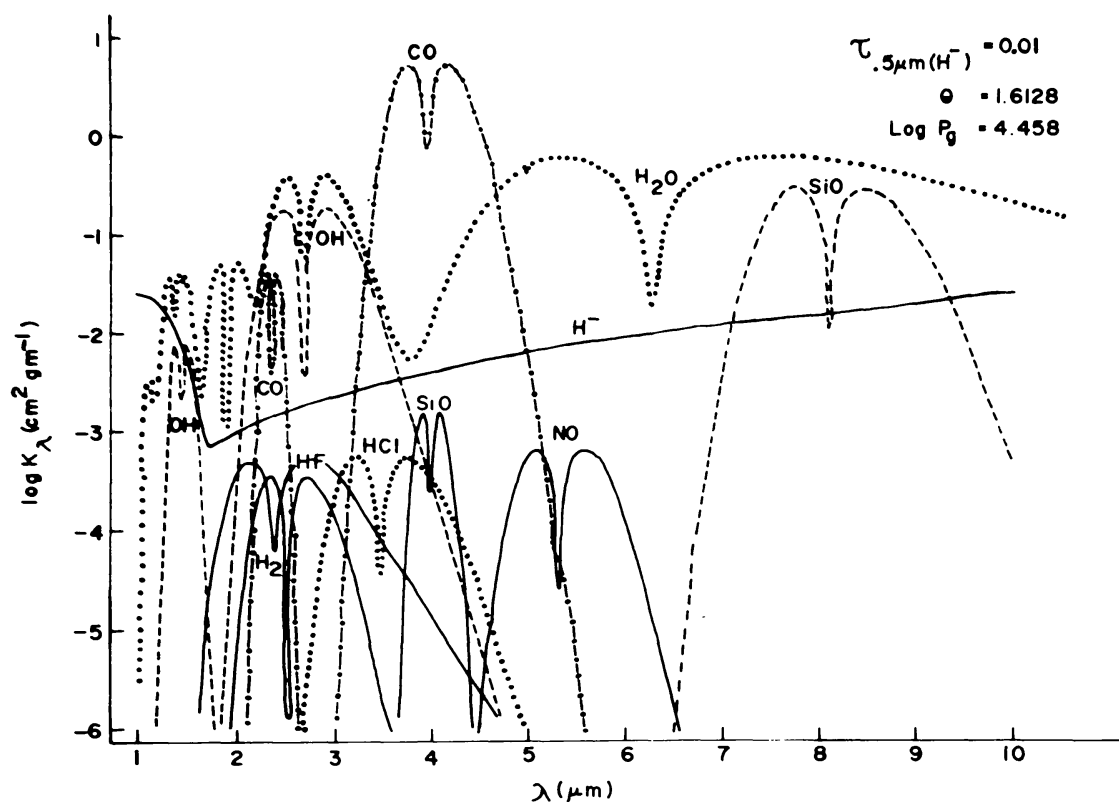


Fig. 1. Variation of mass absorption coefficient, K_λ ($\text{cm}^2 \text{g}^{-1}$) due to the vibration rotation bands of various abundant umbral molecules with wavelength λ (μm) as compared with H^- absorption at $\tau_{0.5 \mu\text{m}}(\text{H}^-) = 0.01$.

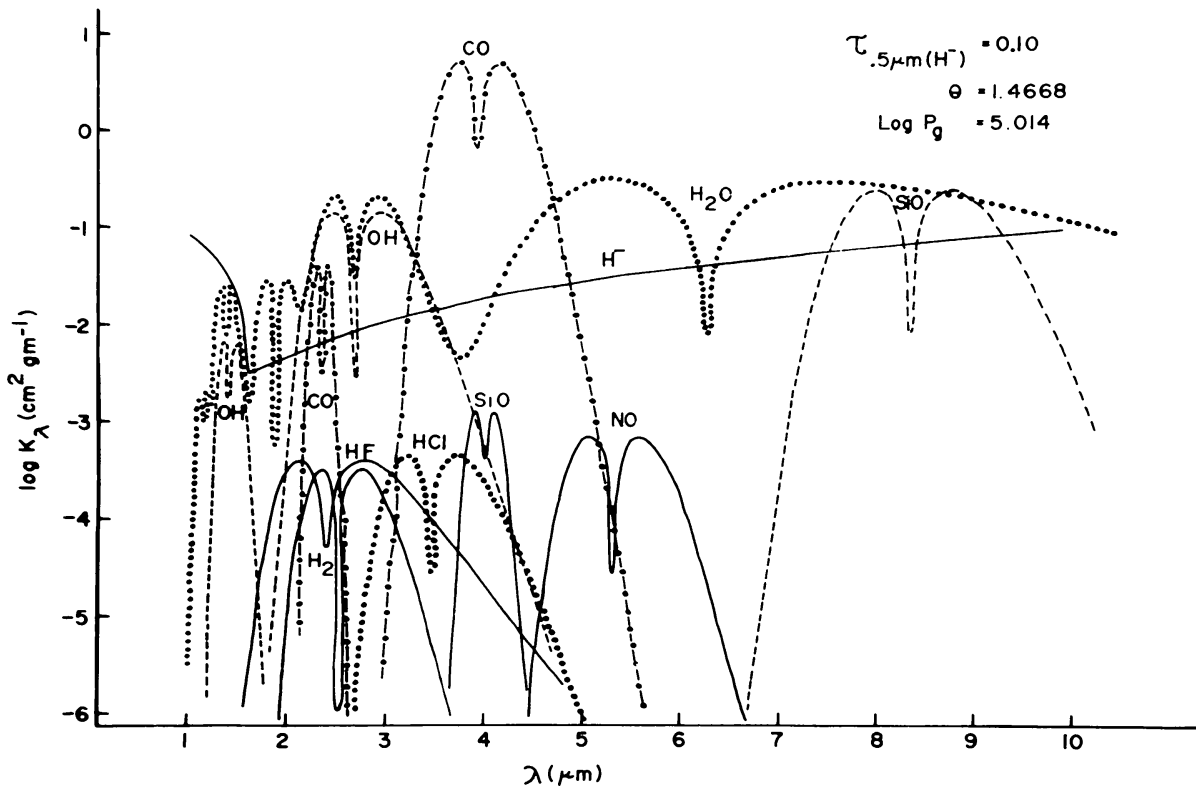


Fig. 2. Same as in Figure 1, for $\tau_{0.5 \mu\text{m}(\text{H}^-)} = 0.10$.

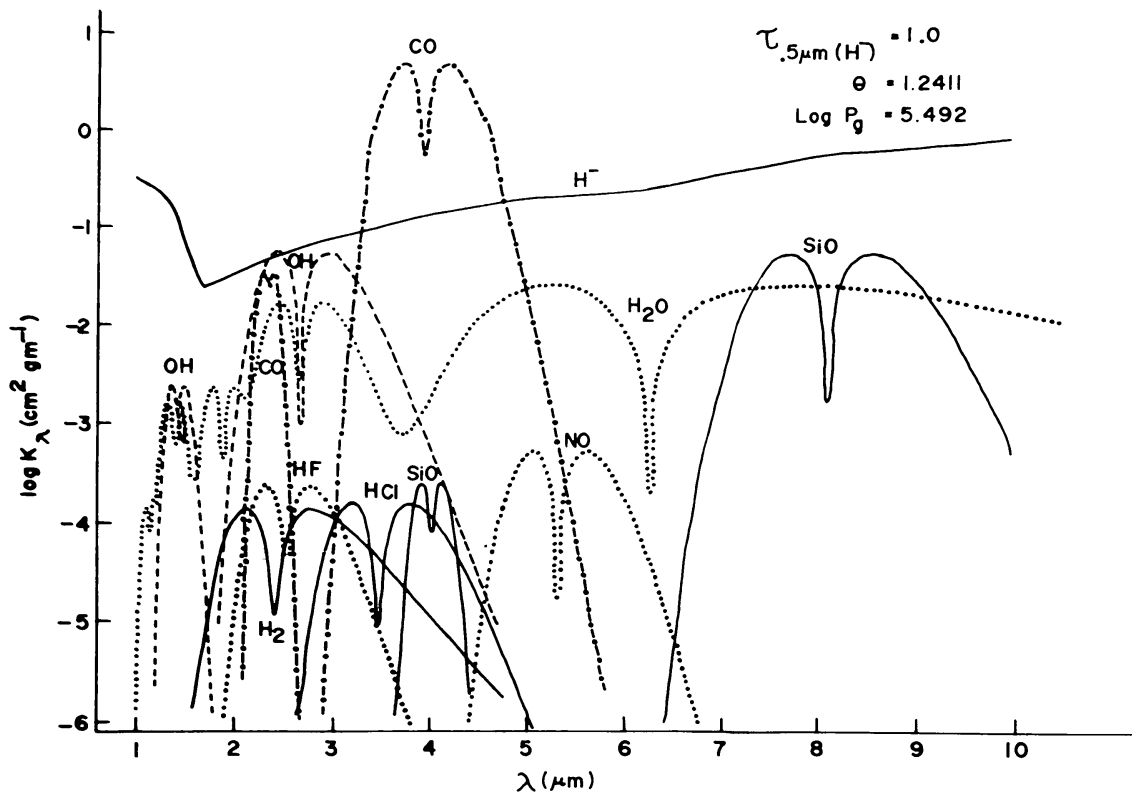


Fig. 3. Same as in Figure 1, for $\tau_{0.5 \mu\text{m}(\text{H}^-)} = 1.00$.

3. Discussions

Table II by Gaur *et al.* (1973) suggests that H_2O , HCl , H_2 , SiO , OH , SH , N_2 , HF , NO , MgH , CO , SiH , NH , CN , and CH are the most abundant molecules in well developed sunspots. Out of these, H_2 and N_2 have zero permanent dipole moment. However, collision induced dipole transitions of H_2 may be important near $2.4 \mu\text{m}$ because of high pressure of H_2 in sunspots. As regards N_2 , the collision induced transitions may not be important in sunspots because N_2 is less abundant than H_2 by a factor of 10^4 . A comparison of the concentration versus optical depth curves of molecules CH and CN in the sunspot and the photosphere shows larger concentration of these molecules in the photosphere. This is due to the depletion of carbon atoms owing to the formation of CO molecules. No vibration rotation lines of SiH , MgH , and SH have so far been observed or predicted. About NH Lambert and Beer (1972) conclude that the vibration rotation lines of NH should be detectable in sunspots provided if the oscillator strength of NH is comparable to that of OH . It may be mentioned here that the concentration of OH is larger than that of NH by a factor of about 100.

Simplified opacity calculations, based on the just overlapping line approximation (cf. Tsuji, 1966) which in the case of H_2O give the same result as that obtained from line by line calculations for the Rosseland mean opacity (cf. Tsuji, 1971), were made. Since the line density decreases at low temperatures, the assumption of just overlapping line approximation may be oversimplified but at temperatures above 2800 K the assumption of complete smearing out of the rotational fine structure is valid as is clear from Figure 2 of Tsuji (1971). Further, Figure 5 in the paper by Tsuji (1976) demonstrates the effect of different approximations in the treatment of line opacity. Except for the depressions at 2.3 and $4.6 \mu\text{m}$ the just overlapping line approximation may reasonably well describe the variation with wavelength and temperature of the infrared molecular opacity in sunspots.

An inspection of Figures 1, 2, and 3 shows that:

- (i) The opacities due to H_2O , CO , OH , and SiO are comparable and are consistently greater than the opacities due to HF , HCl , NO , SiO (first overtone), and H_2 (collision induced) at all depths;
- (ii) in the wavelength region $3.4 \mu\text{m}$ to $4.7 \mu\text{m}$, the opacity due to CO dominates over all the other opacities throughout the umbral atmosphere;
- (iii) in higher layers H_2O opacity dominates all known sources except in the region $3.4 \mu\text{m}$ to $4.7 \mu\text{m}$ (cf. Figure 1);
- (iv) the H^- opacity becomes comparable to the molecular opacity at $\tau_{0.5 \mu\text{m}} = 0.10$ (cf. Figure 2);
- (v) in the deeper layers, H^- opacity dominates over the molecular opacity excepting the opacity due to CO (cf. Figure 3).

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