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The Jupiter Greenhouse

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A step function nongray approximation to infrared absorption by H_2, NH_3, and CH_4 on Jupiter implies a temperature at the lower clouds of 270 to 340°K. Such clouds are conjectured to be aqueous. No contradiction is implied by reported lower rotational temperatures.

Present estimates of the composition of the atmosphere of Jupiter, as well as the other Jovian planets, give molecular hydrogen as the primary constituent with $\sim 10^{-3}$ methane and ammonia. From the estimated near-infrared H_2 abundances, as well as the pressure broadening of individual rotational lines, effective pressures $\sim$ several bars have been calculated (see, e.g., McElroy, 1969; Farmer, 1969). Even with the presence of substantial quantities of chromophores in the Jovian atmosphere and Rayleigh scattering, a significant fraction of incident sunlight should arrive at this pressure level. However, permitted dipole transitions of methane and ammonia, as well as permitted quadrupole and pressure-induced dipole transitions of H_2, should provide a very substantial infrared opacity above this level. We are interested in calculating the resulting greenhouse effect, above the level at temperature T_s which, in the simple reflecting layer formalism, characterizes the infrared abundances. By analogy with Venus (Sagan and Pollack, 1969), we believe this formalism to be adequate for the problem.

We use a simple two-layer emission model with square-wave absorption bands. The condition of energy balance is

$$\tfrac{1}{4}S(1-\bar{A}) = \sum_i B_{\lambda i}(T_s)\,\Delta\lambda_i + \sum_j B_{\lambda j}(2^{-1/4}\,T_e)\,\Delta\lambda_j, \quad (1)$$

where S is the solar constant at Jupiter, $\bar{A}$ is the Jovian bolometric Russell–Bond albedo, the B_λ (T) are the Planck specific intensities in wavelength space, the $\Delta\lambda$ are the selected wavelength intervals, and T_e is the effective planetary temperature. We have used the Eddington approximation for the planetary skin temperature, and have assumed that emission to space in strong absorption features occurs at the skin temperature, and in windows occurs at the bottom of the absorbing layer. Equation (1) is solved iteratively for the temperature at the bottom. A similar protocol for the Earth (Sagan and Mullen, 1971) gives quite satisfactory global temperatures. Small variations in the precise step function assignments are found to have little effect on the derived temperatures. The assumed step function absorption for the gases in question are shown in Fig. 1, derived from laboratory absorption spectra kindly obtained with a Perkin-Elmer Model 621 double beam spectrophotometer for us by Dr. B. N. Khare; and calculated spectra kindly provided by Dr. L. D. G. Young. Jupiter's $\bar{A}$ is imperfectly known, in part because the phase integral cannot be evaluated properly until spacecraft fly by the planet. All published estimates, however, appear to lie in the range 0.4 to 0.6, corresponding to a range of effective temperature from 98 to 108°K. The resulting calculations for various combinations of the foregoing gases are displayed in Fig. 2. Methane, ammonia, and hydrogen together provide an atmosphere which is almost entirely opaque

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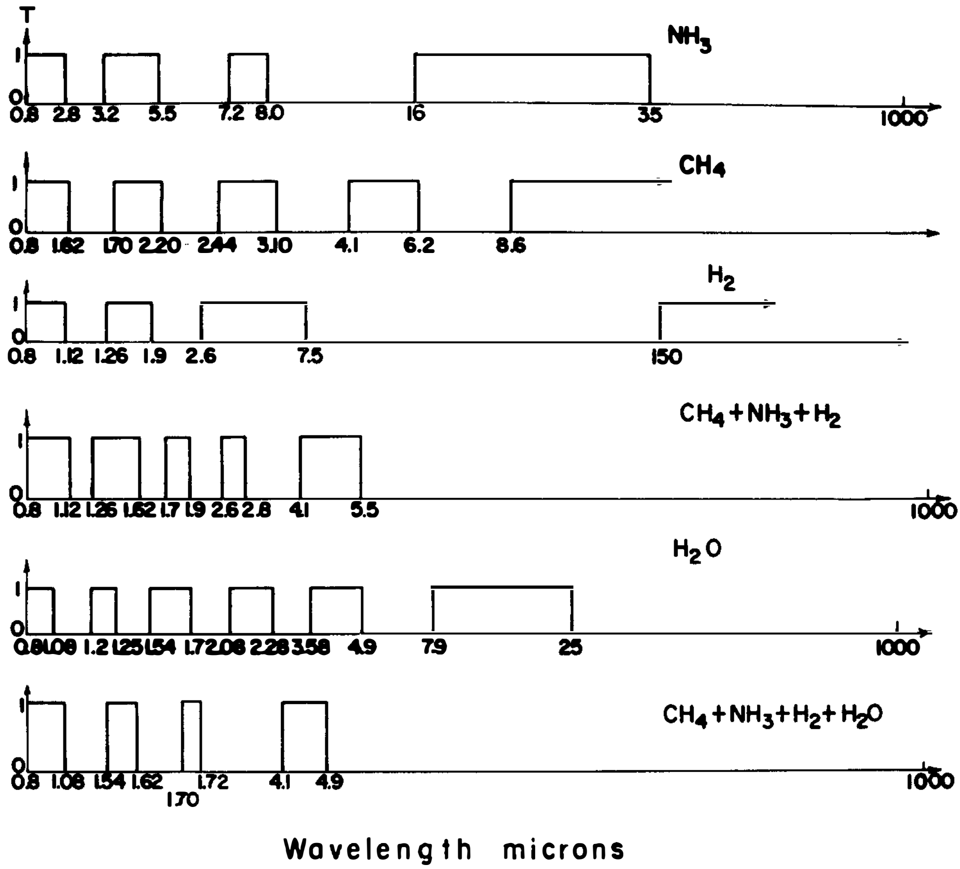

FIG. 1. Step function approximation to the transmission spectra of CH_4, NH_3, H_2O, and H_2, based on laboratory spectra (courtesy of Dr. B. N. Khare) and theoretical calculations (courtesy of Dr. L. D. G. Young) for paths and pressure broadening appropriate for Jupiter. Various combined spectra are also shown. T is the transmissivity.

longward of 5.5μ. The resulting temperature at the "effective reflecting level" is calculated to be $270 \pm 5°K$, depending upon the bolometric albedo (Fig. 2). If Jupiter emits 2.7 times its absorbed solar flux to space, due to internal energy sources (Aumann, *et al.*, 1969), the derived value of T_s is increased by a factor $<(2.7)^{1/4}$. Thus, we estimate $270°K < T_s < 340°K$.

Temperatures $\gtrsim 300°K$ are reported by Westphal (1969) for the North Equatorial Belt in the 5μ window, the longest wavelength window in which, according to these calculations, it is possible to look to the effective reflecting level in the near infrared (cf. Hogan *et al.*, 1969). The question of what is the 300°K reflector arises, and an answer equally naturally suggests itself: water, its compounds, and solutions are the only plausible cosmically abundant material to provide a 300°K cloud deck on Jupiter. This result confirms a previous conclusion that the opacity of NH_3, CH_4, and H_2 on Jupiter is too great for the effective reflecting level to be NH_3; water clouds were also suggested then (Sagan, 1966). Because of ammonia in the Jovian atmosphere, this water is likely to be present in the form of ammonium hydroxide (Lewis, 1969). Laboratory simulations (e.g. Sagan and Khare, 1971), suggest that there is substantial organic chemistry occurring in the vicinity of these aqueous clouds.

Our result has interesting implications for rotational temperatures determined

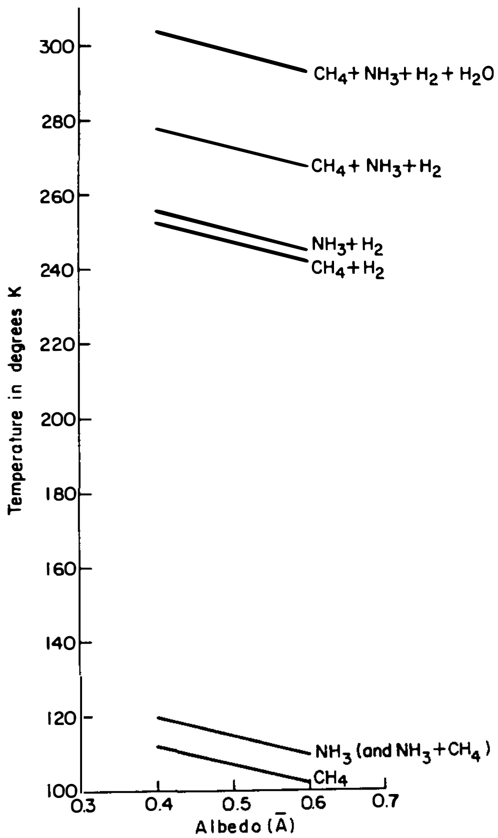

FIG. 2. Calculated temperature at bottom of "effective reflecting layer" for greenhouse effects due to various combinations of Jovian gases. The effect of adding comparable quantities of H_2S is negligible, For the mixtures of known gases, temperatures ~270°K, or larger if H_2O is included, are derived.

from the infrared rotation-vibration spectra. Young and Young (1972) have shown that the convolution of the Boltzmann rotational line distributions of two cloud layers—one high altitude and scattered, and the other low altitude and unbroken—will not be detectably bimodal unless the cloud temperature ratio is $\geqslant 9$; instead, it will appear as a unimodal Boltzmann distribution, characterized by an intermediate temperature. The Jovian rotational temperatures of about 200°K found, e.g., by Margolis and Fox (1969) are intermediate between those of a broken ammonia cirrus at 120°K and a dense water cumulus at 270 to 340°K.

If the clouds are aqueous there will be an equilibrium vapor pressure of water above them. The assumed absorption spectrum for this water vapor is shown in Fig. 1 and the resulting 26° greenhouse increment is shown in Fig. 2.

Because of band saturation, very considerable increases in the amounts of constituent gases will not alter these conclusions in a major way. Similar conclusions apply to the other Jovian planets. Preliminary arguments from microwave spectra for dense aqueous clouds on Jupiter and Saturn will be discussed elsewhere.

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