which the fish and invertebrates were exposed is probably the major factor responsible for the uniformly negative results that were obtained in this testing program. The inertness and associated insolubility, discovered in chemical and physical tests, was clearly of major significance.

A physical difference was noted between the sterilized and unsterilized lunar samples when these materials were added to the aquatic environment. Unsterilized lunar material was easily wetted and sank immediately to the bottom of the container. The dry, heat-sterilized material was cohesive and hydrophobic and required considerable stirring to suspend it in the water. Earth soils similarly sterilized react in the same way.

The results of these tests provided no information that would indicate that the lunar samples returned by the Apollo 11 mission contained replicating agents hazardous to life on earth. The lunar rocks and fines were released from quarantine on 12 September 1969 for further investigation.

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Jupiter's Clouds: Structure and Composition

Abstract. *Recent infrared radiometric observations of Jupiter have disclosed local temperatures in the North Equatorial Belt far in excess of those at the level of the solid ammonia clouds, and visual observations reveal an orange-brown coloration within this belt. We suggest that, in a multilayer cloud model, solar ultraviolet photolysis of hydrogen sulfide in regions where ammonia clouds are sparse or absent should lead to the production of substantial quantities of inorganic chromophores.*

As a result of a study of the chemistry of Jupiter's atmosphere, Lewis (*1*) has suggested that distinct cloud layers other than the well-known solid NH_3 clouds should be found at lower altitudes. He particularly emphasized the importance of a layer of NH_4HS clouds with maximum density at the 229°K level, and clouds composed of aqueous NH_3 solution with maximum density near the 309°K level. Calculations of cloud masses and structures for a model of Jupiter characterized by a solar composition and wet adiabatic equilibrium suggested that the NH_3 cloud layer may be partially transparent.

Recently Jupiter's North Equatorial Belt (NEB) has changed color to a distinct orange-brown, and infrared emission measurements made by Gillett *et al.* (*2*) at 5 μ have disclosed a temperature of 225°K for this belt. Some local breaks in this uniform cloud layer have also been detected, within which, according to Westphal (*3*), emission measurements at 5 μ have disclosed brightness temperatures up to 310°K.

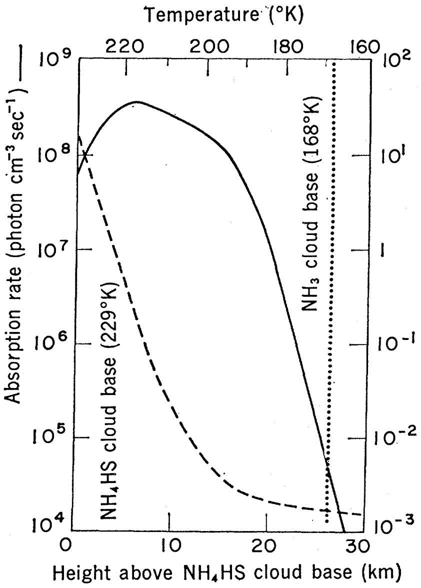

Fig. 1. Rate of solar ultraviolet photolysis of H_2S and H_2S lifetimes in the atmosphere of Jupiter. The solid curve gives the rate of photolysis as a function of height above the NH_4HS cloud layer for a model in which the H_2S vapor density is determined by the dissociation equilibrium of solid NH_4HS. The dashed curve gives the lifetime of this amount of H_2S in the presence of normally incident solar ultraviolet flux. The atmosphere must undergo convective overturn on a time scale shorter than this lifetime in order that significant amounts of H_2S may be present at a given altitude. For a convection time scale of ~1 year essentially no H_2S will be present above the 220°K level.

It has been suggested independently by Owen (*4*) and by Lewis that these NH_4HS clouds might contain the yellow-orange solid $(NH_4)_2S$, but the available thermodynamic data on $(NH_4)_2S$ are insufficient to permit one to decide whether or not it might be stable. Also, the yellow color of laboratory-synthesized $(NH_4)_2S$ is due entirely to the oxidation by atmospheric oxygen of sulfide to elemental sulfur; the colored product is in fact ammonium polysulfide, $(NH_4)_2S_x$. An appropriate chemical oxidizing agent is surely absent on Jupiter.

Wildt (*5*), however, pointed out long ago that gaseous H_2S will readily undergo photolysis by solar ultraviolet radiation to produce free sulfur. This photolytic oxidation obviates the necessity for free oxygen.

To investigate the feasibility of the solar ultraviolet photolysis of H_2S, we have carried out a calculation for the case where the NH_3 cloud cover is optically very thin or absent. We have used a scattering phase function

$$\Phi(Y) = 1 + a_1 \cos(Y)$$

as discussed by Chandrasekhar (*6*) and Sobolev (*7*), where a_1 is the forward-scattering parameter and Y is the scattering angle, to solve the equation of radiative transfer for a semi-infinite absorbing and scattering atmosphere composed of plane parallel layers, with normal incidence of solar radiation. We have obtained the total radiation intensity and hence the total absorption rate of the absorbing gases H_2, He, CH_4, NH_3, and H_2S as a function of depth in the atmosphere. Such calculations by Prinn (*8*) have shown that the solar flux shortward of 2200 Å is totally absorbed by H_2, He, CH_4, and NH_3 before it reaches the NH_3 cloud level. We have considered here only the radiation from 2200 to 2700 Å, the latter being the long-wavelength absorption limit for H_2S. In this spectral region H_2, He, and CH_4 do not absorb, NH_3 absorbs a little (*9*), and H_2S absorbs considerably (*10*). The Rayleigh scattering cross sections used were those of Dalgarno and Williams (*11*) for H_2 and those of Chan and Dalgarno (*12*) for He, since the scattering properties of the cloud-free atmosphere are well approximated by these two gases alone. The values of incident solar flux used were those tabulated by Schultz and Holland (*13*). We have used an atmospheric model based on Trafton's (*14*) radiative equilibrium calculations above the NH_3 cloud base and Lewis's (*1*) cloud model with a vertical lapse rate of 2.2°K km^{-1} from this level down to the NH_4HS cloud base at 229°K. At all levels the partial pressure of H_2S was determined from the dissociation equilibrium of solid NH_4HS. The ammonia pressure was determined from its saturation vapor pressure above the 168°K level and by a constant mixing ratio of 0.13 percent of the H_2 concentration below this level. The He concentration has been taken as 20 percent and the CH_4 concentration as 0.4 percent of the H_2 concentration at each level. The results obtained (Fig. 1) clearly indicate that there is considerable ultraviolet absorption by H_2S in the region of the NH_4HS clouds (210° to 229°K). Recombination of the HS and H produced by photolysis will lead to formation of the hydrogen polysulfides H_2S_x, elemental sulfur, and ammonium polysulfides $(NH_4)_2S_x$. All of these species are yellow, orange, or brown. Thus in areas where the NH_3 cloud layer is thin or absent we have a feasible mechanism for the rapid formation of colored polysulfides. Furthermore, this high rate of H_2S photolysis probably will greatly lower the H_2S abundance above the NH_4HS clouds, thus making H_2S difficult to detect spectroscopically. The above calculations do not preclude H_2S photolysis in areas covered with NH_3 clouds. Since the amount of ultraviolet absorption by solid NH_3 between 2200 and 2700 Å is small, some of this radiation may penetrate through a solid NH_3 cloud cover. In our calculations we have not considered scattering by NH_3 cloud particles, and therefore we are not able to draw conclusions for this case.

It is of interest to compare the calculated photolysis rate of H_2S with the total amount of H_2S available in a model characterized by adiabatic equilibrium and solar composition (*1*). At the NH_4HS cloud base the equilibrium H_2S vapor density is roughly 10^{16} molecule cm^{-3}. The local photolysis rate as given in Fig. 1 is of order of 10^8 cm^{-3} sec^{-1}, and hence some 10^8 seconds of exposure to normally incident solar ultraviolet radiation (or 10 years of average exposure) would be required to exhaust the available H_2S. Near the 200°K level the H_2S abundance is much less, and only a few days' exposure would be necessary for the photolysis of all the H_2S. We thus can suppose that, if the NEB clearing is on the order of 1 year old, and if convective overturn of the NH_4HS cloud region occurs on a time scale of a little less than 1 year, then H_2S will be present in observable amounts only within about 5 km of the NH_4HS cloud base. A steady-state solution would deviate from the results shown in Fig. 1 only in that much less H_2S photolysis would occur above the ~220°K level. The time scales required for destruction of H_2S at various altitudes are given in Fig. 1.

It is also informative to compare the production rate of sulfur-bearing chromophores with the total production rate of organic matter by ultraviolet photolysis given by Sagan (*15*). Sagan estimated a rate of about 1 kg cm^{-2} over 5×10^9 years, or about 10^{-5} mg cm^{-2} per week. The integrated production rate of sulfur-bearing chromophores should be of the order of 1 mg cm^{-2} per week. It seems that a few weeks' clearing of the NH_3 clouds would suffice to produce a distinctly visible coloration, whereas thousands of years would be required to accumulate a significant amount of organic matter, most of which is probably colorless. Meteorologists would not readily accept the notion that the visible clouds of Jupiter are stable against convective overturn for millenia, since drastic changes in the appearance of Jupiter frequently occur in a few weeks or months.

The principal features of our cloud model may be briefly summarized as follows:

1) The 225°K region seen at 5 μ is a distinct, stable, cloud layer composed mainly of NH_4HS or $(NH_4)_2S$, or both.

2) This cloud layer is in local equilibrium with gaseous NH_3 and H_2S, but rapid photolysis of H_2S above these clouds may render H_2S difficult to detect spectroscopically.

3) The coloring matter in this cloud layer is a mixture of hydrogen polysulfides, ammonium polysulfides, and sulfur produced by the photochemical oxidation of H_2S. The clouds are therefore yellow to brown in color.

4) In order to explain the observed coloration it is not necessary that complex organic matter be present. Indeed, the observed association of this intense coloration with a cloud band of very unusual temperature suggests a causal relation between bulk cloud composition and superficial color.

5) High-resolution spectroscopic searches for traces of gaseous H_2S may not be successful, but enhancement of the observed NH_3 and CH_4 abundances may indeed be found over the NEB.

6) A high-resolution spectroscopic examination of the hot (310°K) spots might possibly result in the detection of water vapor in the atmosphere of Jupiter. Although it is far from certain that atmospheric transparency at 5 μ is a sufficient condition for deep penetration at 1 to 3 μ, the experiment still seems worthy of attention.

7) In the design of Jupiter flyby and orbiter missions for the 1970's, the possibility of conducting related experiments in the immediate vicinity of the planet should be considered. Data on the atmospheric and cloud structure derived in this manner could greatly reduce present uncertainties in the design parameters of entry probes.

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