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SATURN: TROPOSPHERIC AMMONIA AND NITROGEN

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Abstract. Photochemical calculations based on recent data on the Saturn temperature structure and Lyman alpha albedo indicate that detectable amounts of gaseous ammonia may exist between 20 and 35 km above the cloud tops. An instrument that might be able to observe this gas is the spectrometer on board the International Ultraviolet Explorer satellite. The calculations also yield a maximum nitrogen mixing ratio at the cloud tops between 1.8×10^{-10} and 6×10^{-8} by volume, depending upon the degree of supersaturation of ammonia and hydrazine. Even the lower limit could produce intense emissions if electrical discharges such as those observed on Jupiter by Voyager are also present on Saturn, or if high energy particles penetrate to the Saturnian troposphere.

Gaseous Ammonia has been detected on Saturn by several observers (Encrenaz, et al., 1974; Woodman, et al., 1977; and references cited in review by Newburn and Gulkis, 1973). All these observations, however, were carried out at the visible, infrared and microwave wavelengths which are capable of probing the region below the cloud tops provided that the clouds are relatively tenuous. The interpretation of the only ultraviolet observations of Saturn near 2100Å on OAO-2 is quite ambiguous (Caldwell, 1977). Since the cloud top temperature of Saturn is much lower than that of Jupiter, it has been generally assumed that ammonia could not be observed above this cold trap, particularly if the observations were carried out in the ultraviolet part of the spectrum. The recent Pioneer observations of Saturn by the radio science technique (Kliore, et al., 1980), and infrared radiometer (Ingersoll, et al., 1980) have provided the much needed critical data to model the problem of ammonia on Saturn.

Ingersoll's measured temperature profile is consistent with Kliore's in the region where the infrared and radioscience data overlap. The infrared analysis places the level of the ammonia cloud tops at 0.7 to 0.6 bars where the temperature is 120K. The temperature then decreases more or less monotonically to a value of 82K at ~70 mbar. The analysis of the Pioneer/Saturn IR data by Ingersoll (personal communication, 1980) reveals that there are presumably clear or broken cloud regions in the atmosphere, and substantial horizontal variability in the clouds. It is important to emphasize that even if unity optical depth for 'aerosols' reaches at ~300 mbar level as is revealed by the revised calculations of the Pioneer/Saturn polarimetry group, it is only the saturation vapor pressure of NH_3 as a function of temperature which enters the calculations presented here. The gaseous ammonia will exist alongside ammonia crystals which will not appreciably prevent penetration of the solar UV photons responsible for ammonia photolysis. The clouds are at best in the haze form in the pressure regime of our calculations, and the presence of clear regions further removes the complications due to clouds. The interpretation of the Pioneer/Saturn IR data does not place strong constraints on the validity of our calculations.

We present in this paper a discussion of a calculation of the distribution of NH_3 and N_2 above the cloud tops of Saturn that might be expected on the basis of these results.

Ammonia photolysis on Saturn is highly sensitive to the cloud top temperature as well as the lapse rate above the clouds since the saturation vapor pressure depends strongly on temperature. The calculations are also somewhat sensitive to the choice of eddy mixing coefficient in the troposphere.

Rocket measurements yield a value of 0.7kR for the disc average Lyman α albedo of Saturn (Weiser, et al., 1977), recent IUE observations result in a value on the order of 1kR (Clarke, 1980), and OAO-Copernicus measurements (Barker, et al., 1980) give 1.4 ± 0.45kR. The exospheric plasma temperature appears to be on the order of 800K from the Pioneer Saturn radio occultation data (Kliore, et al., 1980). It is reasonable to assume that the neutral temperature is quite similar to the plasma temperature (Henry and McElroy, 1969; Atreya and Donahue, 1976). According to a theory developed by Hunten (1969), the eddy diffusion coefficient at the homopause, K_h has a functional dependence on $N(H)^{-1}$, the inverse of the atomic hydrogen column abundance above the methane absorption layer; the albedo on the other hand grows as $\sqrt{N(H)}$. Although the theory was developed for cold exospheric temperatures, one can estimate K_h to be within a factor of two to three for warmer exospheres (Atreya, et al., 1980; Festou, et al., 1980). Once the value of the eddy coefficient at the homopause is determined we can assume that in the region where our calculations are to be carried out K varies inversely with M or $\sqrt{M}$, where M is the atmospheric number density (Lindzen, 1971). Although there is no a priori reason for such variations of K on Saturn, there is a strong indication of $K \propto M^{-1/2}$ variation on Jupiter (Atreya, et al., 1980). As we shall see later, our results are more sensitive to factors other than the eddy diffusion such as supersaturation or supercooling. The value of the eddy coefficient, K_h, deduced from the Lyman alpha albedo, is of the order of 5×10^6 - 5×10^7 cm^2 s^{-1} and the resultant range for K_o at the cloud tops then lies between 10^3 and 10^4 cm^2 s^{-1}.

The temperature (120K) at the cloud tops gives a vapor pressure of ammonia of 2.6×10^{-4} mbar which corresponds to a mixing ratio at the cloud tops of 4×10^{-7} provided that no supersaturation

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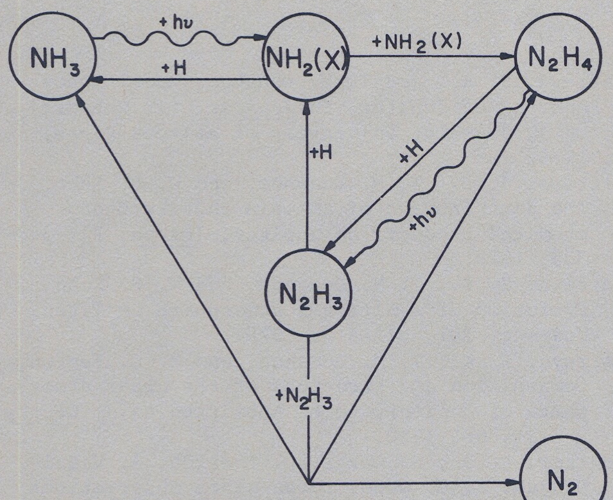

Fig. 1. Photochemistry of ammonia on Saturn (Atreya, et al., 1978, reprinted by permission of the American Association for the Advancement of Science, Copyright 1978). In the absence of supersaturation and supercooling of NH_3 and N_2H_4 only a small quantity of N_2 would be produced.

exists. Ammonia photolysis calculations are carried out along the same lines as they were previously for Jupiter and Titan (Atreya, et al., 1977, 1978). The chemical pathway leading to the production of nitrogen is shown schematically in Figure 1. The reader is referred to the abovementioned earlier papers of the authors for details of chemical kinetics and rate constants. Photoabsorption in the 160-230 nm range leads to the production of atomic hydrogen and the amidogen radical NH_2 in the ground state. Although a portion of NH_2 is used to recycle some of the NH_3, most of it reacts with itself to produce the intermediate product hydrazine N_2H_4. The photochemical scheme can either terminate with the production of N_2H_4 or proceed further to produce the hydrazyl radical N_2H_3 by photolysis of N_2H_4 or by a reaction of N_2H_4 with H. The final product will be nitrogen, the recycling of NH_3 by the self-reaction of N_2H_3 is quite inefficient. The abundance of N_2 will depend on supersaturation of NH_3, and supercooling and supersaturation of hydrazine, N_2H_4. It is in this respect that the Saturn calculations differ from those of Jupiter; the latter were most sensitive to the degree of supersaturation and supercooling of N_2H_4. It is interesting that the Saturn calculations are similar to those applicable to Titan for a relatively large cloud top pressure (Atreya, et al., 1978). We show in Figure 2 results of the Saturn ammonia photolysis calculations for several models.

There are three curves for the ammonia mixing ratio: one for $K_o = 2x10^3$ cm^2 s^{-1} at the cloud top, and varying as $1/\sqrt{M}$; another for $K_o = 10^4$ cm^2 s^{-1} and constant with altitude; and a third for a saturation mixing ratio of NH_3 appropriate to the measured temperature profile which is independent of the eddy diffusion coefficient. The first two NH_3 distributions are sensitive to the choice of boundary value determined by the saturation vapor pressure at the cloud tops. Above the boundary, however, the distribution is determined primarily by the photochemical scheme shown in Figure 1. Rayleigh scattering was taken into consideration, with an assumed polarizability for a 10% mixture of He in a He-H_2 atmosphere. The resulting H, NH_2 and N_2 distributions for $K_o = 2x10^3$ cm^2 s^{-1} are shown by the broken line curves and yield a

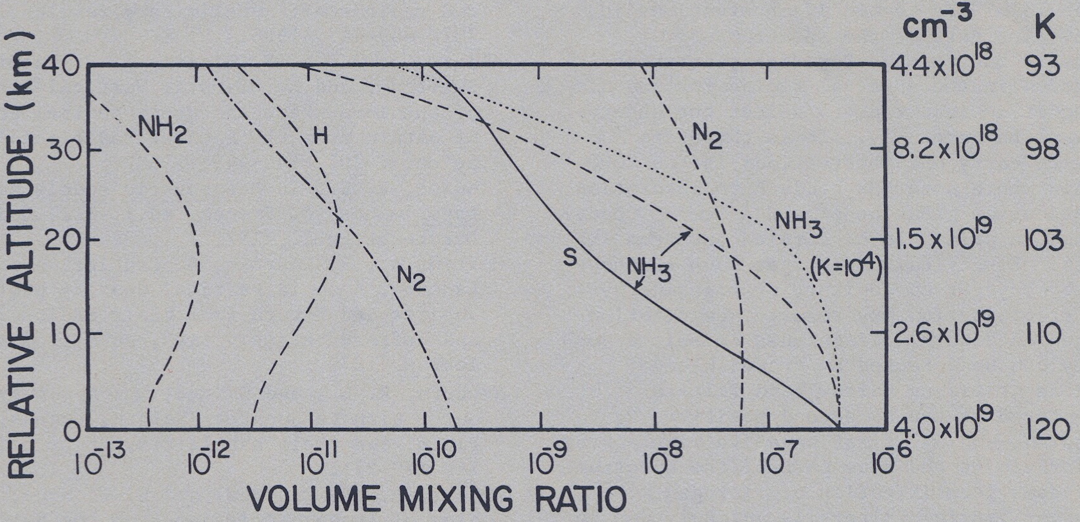

Fig. 2. Distribution of NH_3, NH_2, and N_2 above the cloud tops on Saturn. The NH_3 curve marked 'S' refers to the saturation mixing ratio, and represents the minimum NH_3 mixing ratio profile. A small degree of supersaturation is allowed in the broken line curve ($K_o = 2x10^3$ cm^2 s^{-1} and $K \propto 1/\sqrt{M}$) and the dotted curve ($K_o = 10^4$ cm^2 s^{-1} and constant). N_2H_4 mixing ratios are smaller than 1.3×10^{-9}. Rayleigh scattering has been taken into consideration. Optical depth of NH_3 is sufficient between 20 and 30 km for all these distributions for a detection of NH_3. The two limiting cases of N_2 refer to: no supersaturation of NH_3 and N_2H_4 (dot-dashed curve), and small degree of supersaturation (broken line curve). The right ordinate gives densities and temperatures corresponding to altitude above the cloud tops (left scale), and are deduced from Ingersoll's Pioneer Saturn infrared data (Science, 207, 441, 1980).

maximum N_2 mixing ratio of $6x10^{-8}$ v/v at the cloud tops. Since both the $K_o = 2x10^3$ cm^2 s^{-1}, and $K_o = 10^4$ cm^2 s^{-1} cases are possible only if there is some degree of supersaturation allowed in the NH_3 vapor pressure, we have also carried out the calculations for the case where no such supersaturation in either NH_3 or N_2H_4 is permitted. The resulting N_2 distribution is given by the dot-dashed curve and produces a maximum N_2 mixing ratio of ~$1.8x10^{-10}$ at the cloud tops. Since some supersaturation could possibly exist in clear atmospheric regions as is the case in the earth's atmosphere, it is likely that the N_2 mixing ratio at the cloud tops will lie somewhere between $1.8x10^{-10}$ and $6x10^{-8}$, weighted heavily toward the lower value. The nitrogen mixing ratio at the cloud tops may extend well below this pressure region due to transport.

The average mixing ratio in the 20-30 km height range is such that a vertical optical depth near unity is approached in some bands of NH_3 in the vicinity of 2000Å where the absorption cross section is ~10^{-17} cm^2. If the atmosphere contains a slightly greater amount of He, say 15-20%, it would even be possible to penetrate at 2000Å deeper than 20 km. However, for all practical purposes, Rayleigh scattering in the altitude range below about 22 km is quite dominant at 2000Å. If a small degree of supersaturation should exist detection up to 35 km would be possible.

The NH_3 mixing ratios inferred from the recent microwave and infrared emissivities (Marten, et al., 1979) lie between $3x10^{-8}$ and $2x10^{-11}$ at 20 km. Our calculations give NH_3 mixing ratios of $1.5x10^{-7}$ ($K_o = 10^4$ cm^2 s^{-1}), $3x10^{-8}$ ($K_o = 2x10^3$ cm^2 s^{-1}), and $2x10^{-9}$ (saturation).

The presence of gaseous ammonia and its degree of supersaturation above cloud tops on Saturn can likely be tested if observations in the ultraviolet part of the spectrum are carried out. Due to high Rayleigh scattering cross section in the spectral region for ammonia absorption it is important to select the observing wavelengths carefully. It is therefore desirable to carry out observations in the 2000-2100Å range where some NH_3 bands have absorption cross sections as great as $1.5x10^{-17}$ cm^2. Observations can in principle be carried out from IUE spacecraft. Electrical discharges such as those observed by Voyager on Jupiter, or high energy particle precipitation may result in excitation of nitrogen on Saturn. If intense emissions do occur they can be detected by ground based observations utilizing narrow band filters (≤10Å) centered at the N_2 second positive, N_2 Vegard-Kaplan, and N_2^+ first negative wavelengths in the ultraviolet and blue part of the spectrum. An unambiguous identification of nitrogen using Voyager Imaging filters is unlikely due to relatively broad widths (~500Å) of the ultraviolet and blue filters.

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