1.2 SCIENTIFIC SUMMARY

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This section is a brief overview of Chapter 2, which contains the presentations made at the Workshop, with the discussion and some supplementary material. A few of the principal literature references are included, but references to Chapter 2 are mostly implied.

Composition of the Atmosphere

Methane absorptions are prominent in the spectrum, but their interpretation is complicated by the possibility of pressure broadening by other gases; moreover, the true surface may be hidden by clouds. If such gases are not important, the methane abundance is 2 km-A (Trafton, 1972b). With 20 km-A of N_2 (as an example), the methane comes to 0.1 km-A, and the surface pressure is 350 mb. The methane atmosphere thus gives the smallest mass, and a surface pressure of 20 mb. A "possible detection" of H_2, in the amount of 5 km-A, was reported by Trafton (1972a), and subsequent work seems to confirm this difficult result. Although H_2 is common in the outer solar system, its prominence on a body as small as Titan is surprising: the loss by escape is large, and a correspondingly large source must be found, as discussed below.

For other possible gases we must turn to models of the formation and interior composition of Titan, since observational data are lacking. The work of Lewis (1971) makes use of the mean densities of the satellites, along with the hypothesis that such bodies are accreted from the condensed fraction of the solar nebula. About 60% of the mass should be a solution of NH_3 in H_2O, and a further 5% should be CH_4. The presence of the latter in the atmosphere fits this picture, which however suggests that there is far more methane remaining in the interior or on the surface. No H_2O, and very little NH_3, should be in the atmosphere at the prevailing temperatures. Photolysis of NH_3 and CH_4, and escape of H_2, could produce N_2, as well as a considerable range of other compounds, most of which should condense into aerosols or on the surface. Thus, the best candidate for a third atmospheric gas seems to be N_2. Noble gases might have been retained in small quantities. Although their rarity on Earth does not encourage this idea, Cess and Owen (1973) have developed a greenhouse model based on a mixture of H_2 and Ne.

Trafton (1973) has reported the presence of additional absorptions that do not seem to be due to CH_4, though many of them are also present in the spectrum of Uranus. One may speculate that some of the photolysis products are responsible, but such possibilities are limited because most compounds must condense at the low temperatures of Titan's atmosphere. The best candidates are therefore C_2H_6, C_2H_4, and C_2H_2, and perhaps methylamine CH_3NH_2 if ammonia photolysis occurs. Not enough is known about the spectra of any of these compounds for an identification or rejection; even the possibility of weak CH_4 bands remains.

In the absence of an atmosphere, Lewis (1971) would predict a surface of water ice containing CH_4 as a clathrate and NH_3 in solution. At a depth of a few tens of kilometers this medium should be melted. In the extreme case of a very deep atmosphere, it is conceivable that melting could extend all the way to the surface; the liquid CH_4 would then float on the H_2O-NH_3 solution. If the (p, T) relation passed through the critical point of methane, the atmosphere would merge into the ocean with no phase change, and could be regarded as having a surface pressure of some 1000 bars (cf. Lewis and Prinn, 1973).

A more likely situation is a cold surface covered with a layer of photolysis products and their polymers. Such mixtures are usually dark in color, as in Titan.

Cloud and Haze

Two kinds of aerosol are to be expected in Titan's atmosphere: clouds of solid CH_4, and a photochemical haze (or smog). Veverka (1973) and Zellner (1973) have published observations of Titan's polarization, which can be obtained only to a phase angle of 6°. Despite this limitation, it is clear that negative polarization is absent, in striking contrast to observations of the Moon, Mars, Mercury, and many terrestrial solid surfaces. Positive polarization is shown by glassy surfaces and by atmospheric scattering. However, pure Rayleigh scattering by a gas is ruled out by the low albedo and the absence of a wavelength dependence. An absorbing aerosol is therefore suggested, and Veverka further suggests that it should be optically thick to hide the negative polarization from the surface. However, it is not at all obvious that ordinary planetary surfaces are a good model for Titan. Indeed, this body could well be covered by a glassy or tarry layer of photolysis products, which would give a positive polarization. If such a possibility is accepted, the atmosphere could still be optically thin (see postscript, p. 57).

Another line of evidence is the low ultraviolet albedo of Titan, observed at 2600 Å by Caldwell (1973) and above 3000 Å by Barker and Trafton (1973). The model by Danielson *et al.* (1973) shows that an absorbing aerosol is required at stratospheric heights; otherwise the atmosphere would be too bright. One possibility is CH_4 ice, darkened by radiation; but a photochemical smog seems far more likely. Indeed, the stratosphere must be heated by the ultraviolet energy absorbed, and is probably too warm for methane condensation. The evidence for photochemical haze is almost beyond question; CH_4 ice may also be present at low altitudes, but does not seem to be required.

Thermal Structure

Much of the current wave of interest in Titan is due to the striking results obtained by several observers in the thermal infrared, summarized by Morrison *et al.* (1972). The recent data of Gillett *et al.* (1973) show that still more is to be expected when full spectral coverage of the 8-30 micron region has been attained. For some time there was a remarkable unanimity in seeking the explanation through a greenhouse effect. This complacency was rudely shattered by Danielson and Caldwell, who pointed out that the available data were equally well satisfied by a model based on radiation from a warm stratosphere. Indeed, the latest infrared data, those of Gillett *et al.*, are strongly in favor of a warm stratosphere, for they show a high brightness temperature at 8 μm, in the wing of the 7.7-micron band of CH_4. However, a significant greenhouse effect could still exist. Figure 1-1 shows two cartoons that compare and contrast the two types of models. The effective temperature

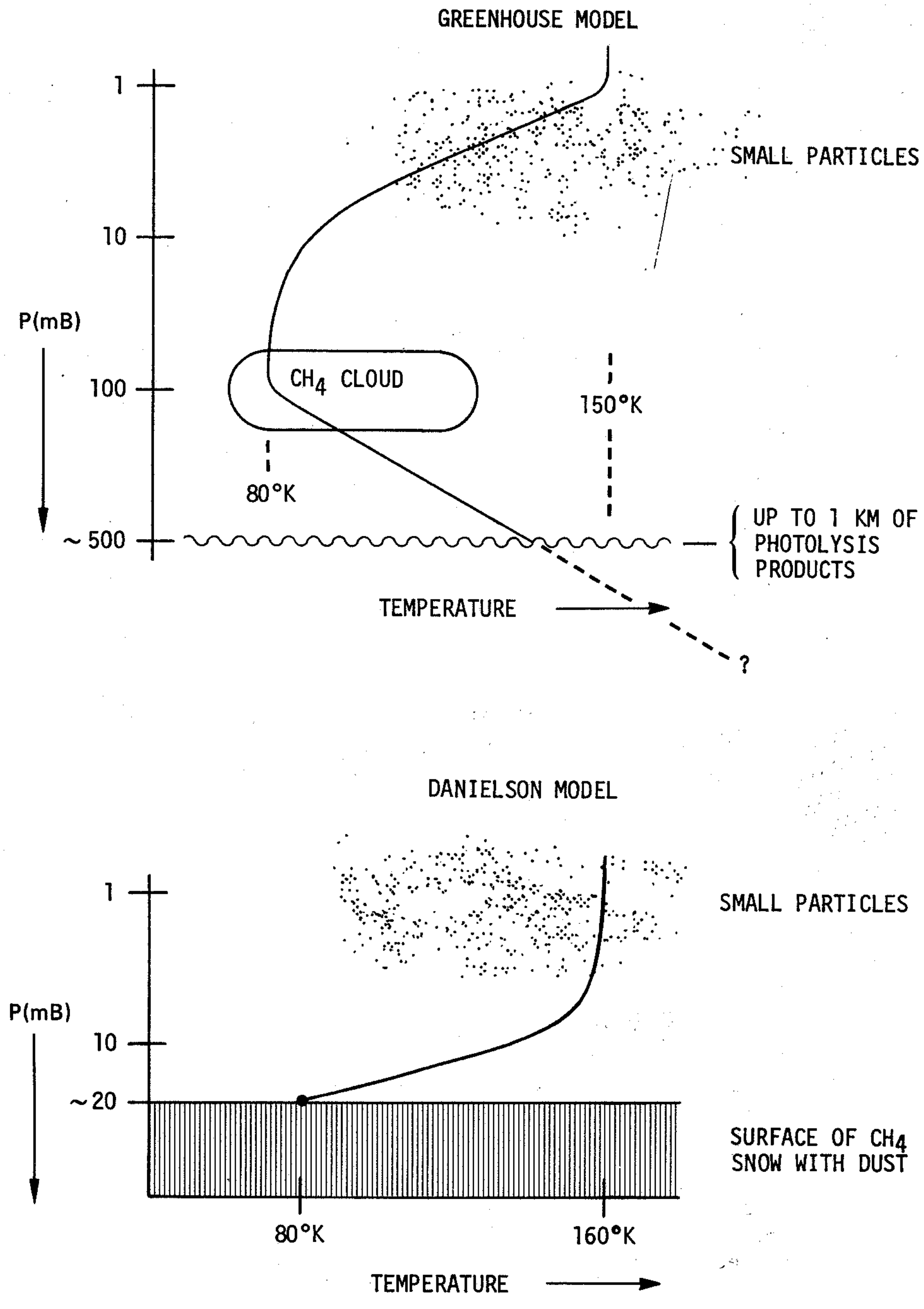

Figure 1-1. Contrasting Titan Atmospheric Models

of Titan should be close to 82°K, the value obtained for equilibrium with solar radiation when the energy is distributed over the globe by the atmosphere. Essentially this value is observed in the 20-micron region, close to the peak of the Planck curve. The question is whether the 82° temperature is that of the surface or of an elevated layer in an opaque atmosphere. The only known source of opacity above 15 μm in a cold atmosphere is pressure-induced absorption by H_2. The peak of this diffuse band is at 17 μm, and an optical depth of 2 will be produced by the observed 5 km-A of H_2 with some 15 km-A of N_2 or CH_4; the surface pressure is around 200 mb. A series of quantitative greenhouse models for H_2-CH_4 mixtures has been presented by Pollack (1973). The best agreement with the earlier broadband observations was obtained with equal abundance and a surface pressure of 440 mb. Mixtures including He were also considered, but are hard to accept because of the rapid escape of helium that must occur.

The suggestion of a warm stratosphere was based on the observed low ultraviolet albedo, which implies the deposition of the corresponding solar energy at high altitudes. Since the absorbing particles are probably too small to be efficient infrared radiators, they transfer the heat to the gas, which then radiates in any available vibration-rotation bands. The best candidates are the fundamentals of CH_4 (7.7 μm), C_2H_6 (12.2 μm), and C_2H_2 (13.7 μm). The first two are probably present (Gillett et al., 1973), and data are lacking for the third. A heuristic model by Danielson et al. (1973) puts the surface temperature at 80°K; but the cold radiating layer could probably be at some height in an atmosphere for a greenhouse model.

The presence or absence of a greenhouse due to H_2 can be decided by the shape of the spectrum around 17 μm: a negative temperature gradient implies a minimum at the center of the band. Confirmation and extension of the band structure at shorter infrared wavelengths will also be highly revealing. All these measurements appear to be technically feasible today, and many questions should be answered within a year.

Atmospheric Escape and Recycling

Several authors have touched on the problem of retention of H_2 by such a small body as Titan, and a detailed discussion has been given by Hunten (1973a). An atmosphere of pure H_2 is simply unbound, and would fly away in a few hours. If a heavier gas is present, it retards this loss, and a situation of "limiting flux" is closely approached. The composition is independent of height, except in an outer corona of H_2 that matches the limiting flux to the escape level. The flux depends only on the mixing ratio; it is about 2×10^{11} cm^{-2} sec^{-1} for 10% H_2, and 10^{12} cm^{-2} sec^{-1} for equal parts of H_2 with CH_4 or N_2. The 1/e time constant for H_2 escape is increased to around a million years. Thus, even though transient stability is assured, a source equal to the escape flux is required. A source of even 10^{11} molecules cm^{-2} sec^{-1} is difficult to find, and no really credible one has been suggested. Photolysis of NH_3 could suffice if the surface were as warm as 145°K, and if ultraviolet radiation could penetrate deep enough. The low ultraviolet albedo does not encourage this idea. Sources in the interior remain entirely speculative.

The same principles apply to helium, with only a slight change in the numerical coefficient. Radioactive decay would be expected to produce a source of around 10^5 cm^{-2} sec^{-1}, by comparison with Earth. The corresponding mixing ratio, with whatever heavy gas may be present, is about 10^{-7}.

McDonough and Brice (1973a, b) have pointed out that gas molecules lost from Titan do not escape completely, but go into orbit around Saturn. Depending on the rate of loss from the resulting toroid of H_2, there could be a significant recycling back to Titan, and a significant reduction in the net loss rate. Titan's first response to recycling would be to build up the coronal density to retain the same net loss rate as before. Thus, rather large densities may be required for the toroid; one rough estimate by Hunten gives 10^{10} cm^{-3}. If such densities are permitted, recycling would greatly ease the problem of finding an adequate source for H_2 for Titan's atmosphere. The toroid is a fascinating object in itself, and will doubtless be discussed in detail in the next few years.

Chemistry

The photochemistry of the atmosphere has many ramifications, some of which have been touched on above. Generally speaking, irradiation of CH_4 is sure to produce more complicated organic compounds and free H_2. If NH_3 is present as well, the possibilities are even greater. It is not clear that H_2 is produced fast enough by such processes to explain its probable large abundance, but some production is a certainty. At least a small production of N_2 is likely as well. Sagan and Khare have reported the production of a brown polymer in laboratory irradiations.

On Titan, most compounds with more than 2 carbon atoms will condense, many of them permanently on the surface. (Or they may dissolve in an ocean of liquid methane, if that unlikely medium is present.) The observed presence of a fine, dark aerosol to high altitudes agrees well with this expectation. It can hardly be said that life should be expected under such circumstances; but "prebiotic molecules", which are almost as interesting, should be abundant.

An interior dominated by hot ammonium hydroxide solution should also be kept in mind as a possible medium for chemistry. Radiolysis could be a source of gases, especially H_2 and N_2, that could reach the atmosphere.