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Technical Memorandum 33-672

Titan Atmosphere Models (1973)

Neil Divine

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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PREFACE

The work described in this report was performed by the Project Engineering Division of the Jet Propulsion Laboratory.

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CONTENTS

ABSTRACT

Current state-of-the-art knowledge of the composition and structure of the atmosphere of Titan, based on theory and on spectroscopic and infrared data, is reviewed for the development of numerical engineering models. LIGHT, NOMINAL, and HEAVY atmospheres are described and tabulated, and their profiles of radius, temperature, pressure and density are illustrated. Corresponding descriptions of atmospheric dynamics, condensates and surfaces are outlined.

1. INTRODUCTION

Titan is the only satellite in the solar system known to have an atmosphere. For probe or lander spacecraft to investigate Titan effectively, potential interactions of this atmosphere with the trajectory, with the thermal control, radio frequency communications, and other subsystems, and with planetary quarantine considerations require that mission and spacecraft design and performance criteria be based on thorough descriptions of Titan's atmospheric environment. Thus the following sections describe the background of our knowledge of Titan's atmosphere and present a set of detailed engineering models for this atmosphere, including gaseous constituents, condensates, and candidate surfaces.

The major scientific questions raised by observations of Titan's atmosphere formed the bases for wide-ranging discussions by noted investigators at the Titan Atmosphere Workshop held at the Ames Research Center, Moffett Field, CA, on 25-27 July 1973. Appendix A briefly describes the Workshop. Many of the points raised at the Workshop have been incorporated in the models developed below.

2. STATE OF THE ART

2.1 Physical Data

Titan is the largest satellite of Saturn, sharing Saturn's heliocentric distance and year, but having a radius comparable to that of Mercury. Its rotation is considered to be synchronous with its revolution about Saturn, with its pole perpendicular to its orbit (in Saturn's equatorial plane); thus its "day" is 16d, its "seasons" result from an inclination of 27° (comparable to the Earth's), and its "year", 30 yr. long, has 675 "days". Its structure, comparable to that of the other large satellites of the outer planets (J I through IV, and Triton), is described by Lewis (1971), and includes a rocky, muddy core, a liquid (H_2O solution) mantle (most of the volume), possibly an ice crust, and an atmosphere. The last of these items may be unique to Titan, on both theoretical and observational grounds.

Values for several physical parameters, many from standard references with some updated to reflect the working consensus from the Workshop (Appendix A), are specified in table IV (sec. 3.1).

2.2 Atmosphere and Models

Those considerations which establish the presence and properties of Titan's atmosphere are sketched in the following paragraphs.

2.2.1 Theory

The relatively large mass, modest radius, and low effective temperature of Titan permit retention of candidate atmospheric gases for times comparable to the age of the solar system (Kuiper, 1952). Light gases ($u \lesssim 6$ g/mole, namely hydrogen and helium) cannot be retained in substantial quantities (McGovern 1971) unless they are mixed with heavier gases and replenished as they escape (Hunten, 1972 and 1973), a low exospheric temperature ($\lesssim 100$ K) being required in this case. Thus the prime candidates are CH_4, NH_3, H_2O, N_2, the noble gases other than He, and some others, based on abundance considerations. Adequate sources of these and some other volatiles exist in the bulk material comprising Titan (Lewis 1971), providing suitable release and/or synthesis processes apply. However, some candidate gases (notably H_2O and NH_3) condense at temperatures high enough that they would not be found in substantial quantities in the observable atmosphere.

2.2.2 Visual and UV Photometry and Polarimetry

The wavelength dependence of Titan's reflectivity exhibits similarities to Saturn, Saturn's Rings, and Uranus in diverse regards (McCord *et al.*, 1971; Barker and Trafton, 1973). This dependence, the low albedo (Younkin, 1973, and others), and the positive polarization *vs.* phase angle (Veverka, 1973; Zellner, 1973) suggest that a thin Rayleigh scattering atmosphere overlying a dark, opaque cloud or surface is most nearly consistent with these observations. Methane gas and ice are inferred from their known presence in some of the comparison objects, but a dark aerosol or surface ("dust") is needed to reduce the albedo. Further the absence of reflectivity variation with rotation (Harris, 1961; McCord *et al.*, 1971) is more characteristic of a thick and/or cloudy atmosphere (e.g., Venus) than of a thin atmosphere and/or surface (e.g., Mars).

2.2.3 Near Infrared Spectroscopy

Absorption lines in several bands identified conclusively as methane (CH_4) in Titan's atmosphere have been reported, analysed, and re-evaluated (Kuiper, 1944; Kuiper, 1952; Trafton, 1972b) on the basis of photographic and direct photometric spectroscopy. Estimates of the abundance of CH_4 over the effective reflecting level are based on the equivalent widths of lines near 0.89 μm wavelength and on the width-abundance product for the $3\nu_3$ band of CH_4 near 1.1 μm wavelength. Their interpretation requires not only plentiful CH_4 but probably another major gas constituent as well (Trafton, 1972b). Two other lines tentatively identified as pressure-induced dipole transitions in H_2 near 0.82 μm wavelength (Trafton, 1972a) lead to an abundance estimate of 5000 m-atm H_2 above the same level; if this amount of H_2 is responsible for the broadening of the CH_4 lines as well, the appropriate CH_4 abundance is 1400 m-atm. The uncertainty in these abundance estimates is considerable because plausible (rather than confirmed) values have been used for some of the related unknowns, notably temperatures. Several unidentified absorption lines also appear in Titan spectra (Trafton, 1973) and their future identification and analysis is expected to lead to additional gas constituents and/or abundance values.

2.2.4 Thermal Infrared Spectrophotometry

Both broad-band and narrow-band measurements of Titan's infrared flux or brightness temperature have been made with cooled infrared detectors. The results are summarized in table I. Those entries which include brightness temperatures well in excess of the effective temperature ($T_e \sim 82$ K, with an expected emission peak near 35 μm wavelength) indicate the presence of an atmosphere which at some levels is warmer than T_e. At short wavelengths ($\lesssim 8$ μm) the extra energy is radiated from an inversion layer (Danielson *et al.*, 1973; Gillett *et al.*, 1973), whereas at longer wavelengths (8 to 14 μm) an inversion and/or a greenhouse effect (Cess and Owen, 1973; Pollack, 1973; Sagan, 1973) are responsible.

TABLE I. INFRARED PHOTOMETRY OF TITAN

	EFFECTIVE WAVELENGTH (μm)	BRIGHTNESS TEMPERATURE (K)	REFERENCE
NARROW-BAND	8.0	158 ± 4	Gillett *et al.* (1973)
	9.0	130 ± 6	Gillett *et al.* (1973)
	10.0	124 ± 3	Gillett *et al.* (1973)
	11.0	123 ± 3	Gillett *et al.* (1973)
	12.0	139 ± 2	Gillett *et al.* (1973)
	12.5	129 ± 2	Gillett *et al.* (1973)
	13.0	128 ± 2	Gillett *et al.* (1973)
BROADBAND	4.9 ± 0.4	< 190	Joyce *et al.* (1973)
	8.4 ± 0.4	146 ± 5	Gillett *et al.* (1973)
	10.0 ± 2.5	132 ± 5	Low (1965)
	11.0 ± 1	134 ± 2	Gillett *et al.* (1973)
	12.0 ± 1	132 ± 1	Gillett *et al.* (1973)
	12.4 ± 2	125 ± 2	Allen & Murdock (1971)
	20 ± 3.5	93 ± 2	Morrison *et al.* (1972)

TABLE II. PARAMETERS OF MODEL ATMOSPHERES OF TITAN

REFERENCE	GAS & ABUNDANCE* (ratio or km-atm)	PRESSURE, (N/m^2)	TEMPERATURE (K)	REMARKS
Cess & Owen 1973	$[H_2]$ = 340	1.4×10^4	103	Tropopause
		4.5×10^4	155	Surface greenhouse
	$[H_2]$ = 40, $[Ne]$ = 200	1.1×10^5	111	Tropopause
		2.7×10^5	155	Surface greenhouse
	$[H_2]$ = 28, $[Ne]$ = 280	1.7×10^5	112	Tropopause
		3.7×10^5	155	Surface greenhouse
Danielson *et al.*, 1973	$[H_2]$ = 0 to 5, $[CH_4]$ = 2	$\sim 10^3$	160	Base of isothermal inversion
		2×10^3	80	Surface
Hunten, 1972 Hunten, 1973	$[H_2]$, $[N_2]$, $[CH_4]$ present			Discussion of concepts and parameter values; no model proposed;
			~ 100	Upper atmosphere
Lewis & Prinn 1973	$[CH_4]$ large	9×10^3	91	CH_4 triple point
	hydrocarbons minor	$>(T/10)^4$	$T>145$	Surface
McGovern, 1971	$\frac{[H_2]}{[CH_4]} < 10^{-6\pm1}$, $\frac{[He]}{[CH_4]} < 10^{-3.5\pm0.5}$		120-150	Exosphere
Pollack, 1973	$\frac{[CH_4]}{[H_2]} = 1\times3^{\pm1}$	5.6×10^3	76.3	Base of CH_4 saturation
		10^4	94	Adiabatic lapse rate
		$>4\times10^4$	>146	Surface greenhouse
Sagan, 1973	$[H_2]$ large, $[CH_4]$ modest	$(3-5)\times10^3$	130	Several models, all with surface greenhouse
		$(5-45)\times10^3$	150-210	

* Constituent gases not listed are present if at all in only minor amounts.

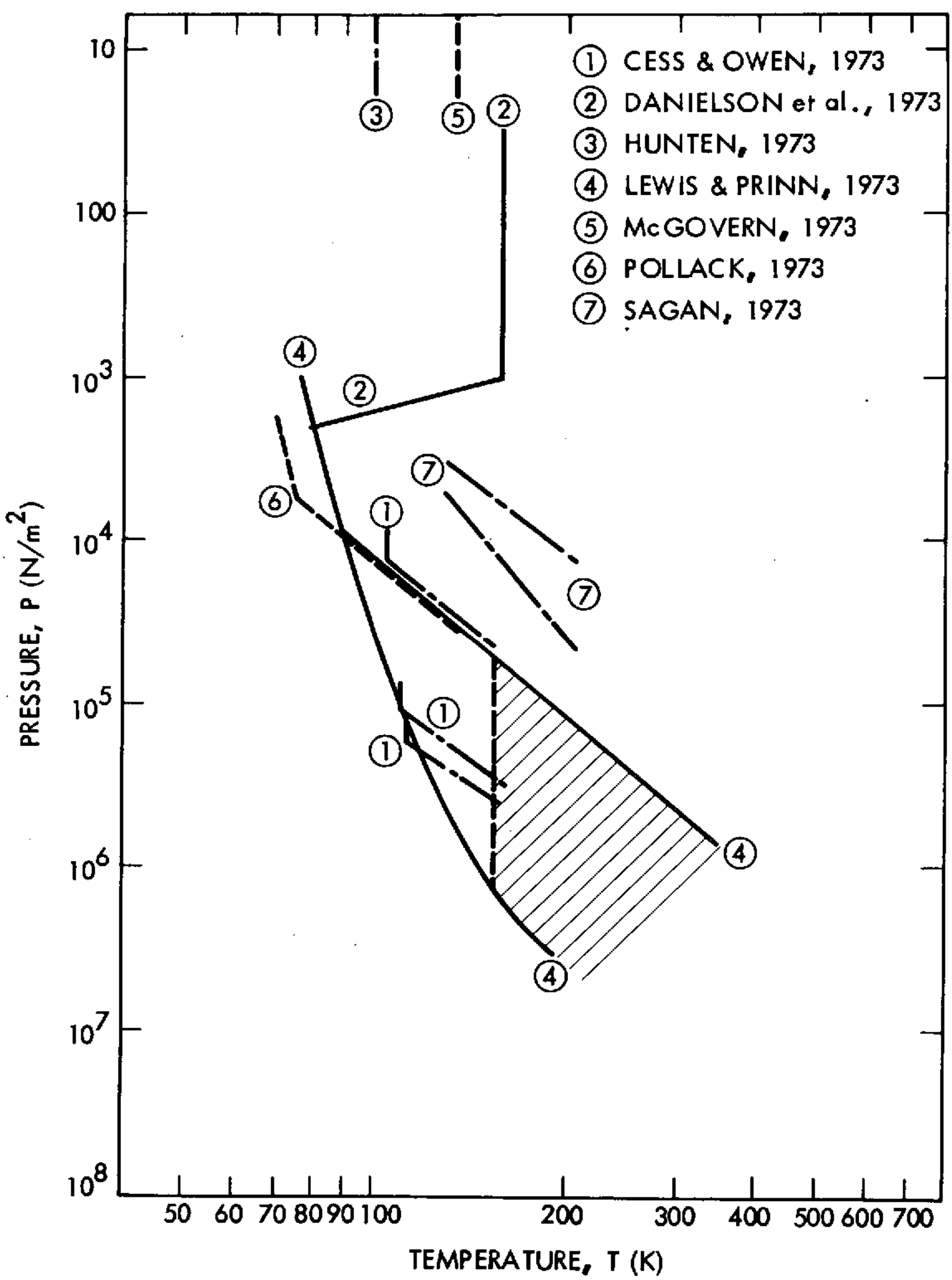

Figure 1. Pressure-temperature profiles of several model atmospheres of Titan from the literature.

2.2.5 Atmospheric Models in the Literature and Workshop

Several numerical models of various aspects of Titan's atmosphere have been prepared in the last three years. They are summarized in table II, and the available pressure-temperature points or profiles are shown in fig. 1. The variety of compositions is apparent and will be emphasized below.

Also shown in fig. 1 (but not in table II) are the pressure-temperature profiles of two models discussed in depth at the Workshop, and illustrating contrasting interpretations of the pressure-temperature structure. Both contain an inversion layer ($T \sim 160$ K near $P \sim 10^2$ N/m^2), but in one case this inversion extends throughout most of the atmosphere, being responsible for the observed infrared radiation and control of the atmospheric energy balance, with a low surface temperature ($T \sim T_e \sim 80$ K at $P \gtrsim 2 \times 10^3$ N/m^2); in the other case the inversion is a minor phenomenon, the infrared temperature being ascribed to a strong greenhouse effect which results in high surface temperatures ($T \gtrsim 150$ K at $P \gtrsim 4 \times 10^4$ N/m^2). This controversy received more emphasis when the Workshop participants attempted to derive consensus values for atmospheric parameters.

Thus the Workshop proposed several candidate parameter sets, for both a level at a pressure near 10^2 N/m^2 (1 mb, near peak deceleration and heating for an entry probe) and for a surface. These candidate sets are summarized in table III. No specific, new, Workshop model of the atmosphere of Titan was generated.

TABLE III. CANDIDATE PARAMETER SETS FROM TITAN ATMOSPHERE WORKSHOP

<table>
<tr><td>ATMOSPHERIC COMPOSITION</td><td>2 km-atm CH_4
5 km-atm H_2
(u ~ 6)</td><td>*
pure CH_4
(u ~ 16)</td><td colspan="2">*
some H_2
some CH_4
some N_2
(u ~ 16)</td><td>some CH_4
much N_2
(u ~ 26)</td><td colspan="2">some CH_4
some noble gas
(u ~ 16 to 40)</td></tr>
<tr><td>ATMOSPHERIC DECELERATION LEVEL</td><td colspan="3">*
$P \sim 10^2$ N/m^2
$T \sim 160$ K</td><td colspan="4">$P \sim 10^2$ N/m^2
$T \sim 70$ to 150 K</td></tr>
<tr><td>ATMOSPHERE NEAR SURFACE</td><td>*
$P \sim 2 \times 10^3$ N/m^2
$T \sim 80$ K</td><td colspan="2">*
$P \sim 5 \times 10^4$ N/m^2
$T \sim 150$ to 200 K</td><td colspan="4">$P \sim 10^8$ N/m^2
$T \sim 150$ to 800 K</td></tr>
<tr><td>SURFACE</td><td>CH_4 solid with dark dust
(T<91K)</td><td colspan="2">Red-brown polymer and/or solid H_2O, $NH_3 \cdot H_2O$ and CH_4 clathrate hydrate
(T<173K)</td><td>Liquid
CH_4
(91<T<191K)</td><td colspan="2">Liquid H_2O with NH_3 in solution, plus CH_4 clathrate hydrate
(173<T<547K)</td><td>No
Surface
(T>547K)</td></tr>
</table>

* These boxes are included in the NOMINAL model atmosphere

2.2.6 Engineering Models of Titan's Atmosphere

In the construction of a set of model atmospheres of Titan, the foregoing discussion suggests that the various compositions (table III) yield an uncertainty in the mean molecular weight which dwarfs the uncertainties in the physical parameters (table IV) and in the pressure-temperature profile (fig. 1). Thus it is appropriate to generate nominal, heavy and light numerical models of the atmosphere corresponding to values of the mean molecular weight $u = 16 \pm 10$, respectively. For all three models the nominal values of the physical parameters specified in table IV are adopted.

As a starting point, for the NOMINAL atmosphere, a composition of pure CH_4, in which case $u = 16$, is appropriate. If an observed abundance of 2 km-atm CH_4 is adopted and a CH_4 solid cloud represents the effective reflecting level, then the pressure is about 2000 N/m^2 and the corresponding temperature for CH_4 saturation is 82 K (fortuitously close to the effective temperature). Such a level could correspond to the atmosphere just above one of the candidate surfaces (table III). Above this level we adopt an isothermal stratosphere for about one scale height, an inversion layer which includes $P \sim 10^{-2}$ N/m^2 and $T \sim 160$ K, and a somewhat cooler upper atmosphere (representative $T \sim 100$ K). Below the cloud top we include about one scale height of CH_4 at saturation (to provide plenty of opacity in the cloud) and below that (taken for convenience at the triple point of CH_4, $P \sim 8000$ N/m^2, $T \sim 91$ K) we adopt an adiabatic lapse rate corresponding to a greenhouse model, extending indefinitely downwards (but capable of interruption by a surface at any level for which $T \gtrsim 150$ K). This model profile is shown in fig. 2, and includes the boxes starred in table III. The molecular weight $u = 16$ is appropriate either for pure CH_4 or for nearly equal fractions of H_2, CH_4, and N_2.

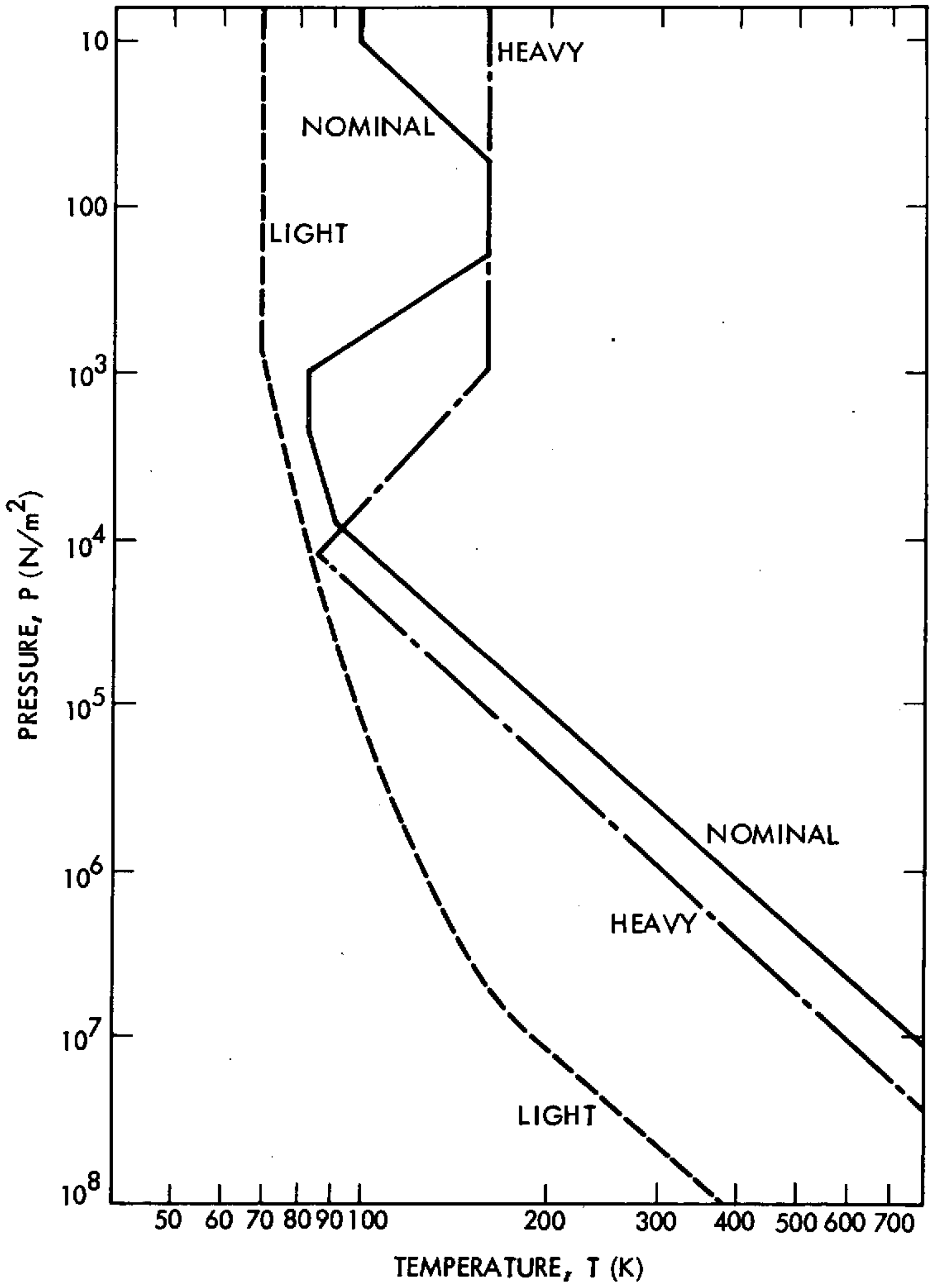

Figure 2. Pressure-temperature profiles of engineering models of Titan's atmosphere.

An isothermal upper atmosphere near $T \sim 160$ above the inversion cannot easily retain as much hydrogen as represented by the extreme $u = 6$ composition, so for the LIGHT model an upper atmosphere temperature of $T \sim (0.5)^{1/4}\, T_e \sim 70$ K, (the radiative boundary temperature) is adopted, down to that level at which CH_4 saturation pressure is met. Below this level ($P \sim 750$ N/m^2, $P(CH_4) \sim 215$ N/m^2, $T \sim 70$ K) the atmosphere would freeze out unless the temperature rises, so we follow the shape of the methane saturation curve. The abundance 2 km-atm CH_4 (and 5 km-atm H_2) is reached one scale height below, at $P \sim 3000$ N/m^2, $P(CH_4) \sim 810$ N/m^2, corresponding to CH_4 saturation at $T \sim 77$ K, which represents the coolest surface consistent with the spectroscopic data; to reach the effective temperature $T \sim 82$ K, a pressure $P \sim 7500$ N/m^2 is needed for this profile. The saturation shaped profile can extend downward until interrupted by a surface or until the critical point of CH_4 is reached ($P \sim 1.2 \times 10^7$ N/m^2, $T \sim 191$ K). Below this level an adiabatic profile is adopted.

Taking a somewhat warmer pressure-temperature profile for the HEAVY model ($u = 26$) we take $T \sim 160$ K in the upper atmosphere, down to an inversion base near $P \sim 10^3$ N/m^2. To provide a cloud or saturated surface in this model adopt a tropopause at $P \sim 1.1 \times 10^4$ N/m^2, $P(CH_4) \sim 3.3 \times 10^3$ N/m^2, and $T \sim 85$. Below this level an adiabatic lapse rate provides the warmest likely profile.

The pressure-temperature profiles of these three new models are shown in fig. 2. They bracket the profiles described in the literature and at the Workshop (sec. 2.2.5 and fig. 1) and correspond also to most of the composition and pressure-temperature boxes in table III.

2.3 Non-Gaseous Constituents

Condensation processes are expected in those regions of the lower atmosphere within which the temperature increases with increasing pressure ($dT/dP>0$) and with decreasing altitude ($dT/dZ<0$). There cloud formation is likely if fP exceeds the saturation vapor pressure of the potential condensate at the local temperature (fP is the partial pressure of the gas with mixing ratio f). Thus for CH_4, for which $f \leq 1$, solid methane ice clouds may form in the region indicated on fig. 4 within ($70 < T < 91$ K), and liquid methane droplet clouds may form in the region shown ($91 < T < 191$ K). These clouds probably constitute the primary reflecting or scattering medium for (visible) sunlight.

The NH_3 and H_2O will be effectively completely frozen out of the atmosphere unless the surface temperature exceeds about 240 K and 430 K respectively (assuming approximately solar ratios of [N]/[C] and [O]/[C] in the nominal atmosphere). Liquid droplet clouds of these materials could occur in the regions shown in fig. 4 (bounded by $240 < T < 406$ for NH_3 and $430 < T < 547$ for H_2O). Any water clouds present will form in regions with comparable pressures of H_2O and NH_3, and will thus include NH_3 in solution at concentrations between about 0.01 and 0.1 (Lewis, 1969), corresponding to a range of pH values between 10 and 11.

Two circumstances suggest additional solid condensates (aerosols, dust, or comparable material). One is the evidence for the formation of hydrocarbons in methane-rich environments subjected to (solar) UV or to electrical discharge (Sagan 1973). The other is the low albedo of Titan in the visible and UV (Barker and Trafton, 1973; Caldwell *et al.*, 1973; and others), indicating the presence of an absorbing substance with reflectivity much smaller than would be expected from a pure cloud or icy surface at the effective reflecting level. These circumstances are consistent with contamination of clouds or surfaces with dust or tar, and with suspension of fine dust particles within the cloud-free portions of the atmosphere. Such meteoritic dust could form nuclei of cloud droplets; thus weather, including precipitation, lightning, thunder, and related phenomena, is to be anticipated if the atmosphere extends to pressures of the order of 10^5 N/m^2 or greater. However, the slow rotation and low solar illumination would yield more subdued weather than for the Earth.

2.4 Surfaces

The radius of Titan which appears in table IV refers to an effective reflecting or absorbing level which could be either in the atmosphere or a liquid or solid surface. These three possibilities appear in order of decreasing probability, first because a visible solid surface would be expected to display albedo variations (contrary to observations, sec. 2.2.2), and second because the narrow range of physical conditions needed for a completely liquid surface is not likely to be met at the low pressures and temperatures indicated for this level (sec. 2.2.3). If a surface exists, then, the atmospheric pressure and temperature there exceed about 2000 N/m^2 (from the CH_4 abundance) and 82 K (the effective temperature), respectively.

For potential surface locations below such levels, several candidate surfaces are consistent with the physical chemistry appropriate to the local conditions. In particular, the atmospheric pressure must exceed the vapor pressure of the surface material at the local temperature, and that temperature must be within the stability field of the surface material. Clearly the candidate materials are those consistent with the likely bulk composition of Titan and its atmosphere (Lewis, 1971; Trafton, 1972b). They appear in the last row of table III, and the atmospheric pressure-temperature domains within which they can persist are shown in fig. 5 (sec. 3.4).

Surface deposits of less volatile materials are likely to exist (if the surface is solid) considering two potential sources, namely meteorite infall and hydrocarbon production (sec. 2.3). Thus a surface at least partly covered with dust or tar is probable.

Lastly, surface activity is to be expected. If the surface is liquid interactions with atmospheric weather systems and dynamics (sec. 2.5) may occur, although the slow rotation should make this activity more subdued than for the Earth. If the surface is that of a solid ice crust, thermal and tidal stresses within the underlying liquid mantle may produce the analogs of geological activity, such as volcanism, seepages, and icequakes involving water, steam, ammonia, etc.

2.5 Titanographic and Diurnal Variations, and Dynamics

These effects are probably very subdued on Titan. One reason is that substantial energy transport and deposition can be readily achieved with modest atmospheric circulation and temperature gradients using the large latent heat involved in the condensation and vaporization of a major atmospheric constituent, methane (Danielson *et al.*, 1973). Another reason is that a weak symmetric circulation regime is anticipated in view of the relations among the rotation rate and the characteristic times for thermal transport and relaxation (Leovy and Pollack, 1973). Thus the surface or atmosphere temperature horizontal contrast (even between the subsolar point and the current winter pole) is small, say less than tens of degrees Kelvin, and polar caps of CH_4 ice (if any) are not expected to undergo major seasonal adjustment. Horizontal wind speeds are probably less than or of the order of the surface rotational speed ~ 10 m/s, and vertical wind speeds are at most comparable.

3. CRITERIA

3.1 Physical Data

Values and uncertainties for several physical properties of Titan are specified in table IV.

3.2 Model Atmospheres

Table V specifies compositions, molecular weights, and other parameters for three model atmospheres, labelled LIGHT, NOMINAL, and HEAVY. Their profiles of pressure P, temperature T, density ρ, pressure scale height H, geopotential altitude Z, distance r from Titan's center, and molecular number density n are presented in tables VI, VII, and VIII and in fig. 3. In each model the zero of Z, the radius of Titan 2500 km, and the CH_4 saturation level corresponding to an abundance of 2000 m-atm of CH_4 are coincident.

3.3 Non-Gaseous Constituents

Meteoric dust and various hydrocarbons, both dark absorbers, may exist in the atmosphere as fine particulates. Clouds are also present in the pressure-temperature domains indicated in fig. 4; precipitation is possible. The uppermost clouds (solid or liquid CH_4) form the visual reflecting layer, and the lowermost clouds (liquid water with NH_3 in solution, at concentrations between 0.01 and 0.1) range in pH between 10 and 11.

TABLE IV. PHYSICAL PARAMETERS FOR TITAN

Radius*	a = 2500 ±250 km
Mass*	M = (1.37 ±0.02)×10^{23} kg
Mean density*	$\bar{\rho}$ = 2.1 ±0.6 g/cm^3
Surface acceleration of gravity	g_o = 1.5 m/s^2
Escape speed	V_e = 2.7 km/s
Visual geometric albedo*	p_v = 0.20 ±0.04
Bolometric Bond albedo*	A_{bol} = 0.26 ±0.08
Effective temperature*	T_e = 82 ±2 K
Rotation rate	ω = 4.56x10^{-6} s^{-1}
Period of rotation ("day")	15.945 d
Inclination of equator to (solar) orbit	26°7
Period of revolution about Sun ("year")	29.46 yr
Distance from Sun	9.0 to 10.1 AU

* Workshop consensus value

TABLE V. COMPOSITIONS AND PARAMETERS FOR MODEL ATMOSPHERES OF TITAN

	LIGHT	NOMINAL	HEAVY
Composition (number fraction)	H_2 0.714 CH_4 0.286	CH_4 1.0 or H_2 0.3 CH_4 0.4 N_2 0.3	CH_4 0.3 N_2 0.7
Mean molecular weight, u	6	16	26
Ratio, um_H/k $\left(\frac{g}{cm^3}\ \frac{K}{N/m^2}\right)$	7.261×10^{-7}	1.936×10^{-6}	3.146×10^{-6}
Ratio, $k/um_H g_o$ (km/K)	0.9182	0.3443	0.2119

TABLE VI. HEAVY MODEL ATMOSPHERE OF TITAN

P (N/m^2)	T (K)	ρ (g/cm^3)	H (km)	Z (km)	r (km)	n (cm^{-3})
0.0001	160	1.97(-12)	59	604	3297	4.5(+10)
0.0003	160	5.90(-12)	57	567	3233	1.4(+11)
0.001	160	1.97(-11)	54	526	3166	4.5(+11)
0.003	160	5.90(-11)	52	489	3108	1.4(+12)
0.01	160	1.97(-10)	50	448	3046	4.5(+12)
0.03	160	5.90(-10)	49	411	2992	1.4(+13)
0.1	160	1.97(-9)	47	370	2934	4.5(+13)
0.3	160	5.90(-9)	45	333	2884	1.4(+14)
1.0	160	1.97(-8)	44	292	2831	4.5(+14)
3.0	160	5.90(-8)	42	255	2784	1.4(+15)
10	160	1.97(-7)	41	214	2734	4.5(+15)
30	160	5.90(-7)	39	177	2690	1.4(+16)
100	160	1.97(-6)	38	136	2644	4.5(+16)
300	160	5.90(-6)	37	99	2603	1.4(+17)
1000	160	1.97(-5)	36	58	2559	4.5(+17)
2000	132	4.76(-5)	29	37	2537	1.1(+18)
5000	103	1.53(-4)	22	+14	2514	3.5(+18)
0.1(+5)	85	3.70(-4)	18	0	2500	8.5(+18)
0.2(+5)	105	6.01(-4)	22	-14	2486	1.4(+19)
0.5(+5)	138	1.14(-3)	28	-37	2463	2.6(+19)
1.0(+5)	170	1.86(-3)	34	-60	2442	4.3(+19)
2.0(+5)	209	3.01(-3)	41	-87	2416	6.9(+19)
5.0(+5)	275	5.72(-3)	53	-134	2373	1.3(+20)
10(+5)	338	9.30(-3)	62	-179	2333	2.1(+20)
20(+5)	417	0.0151	74	-234	2286	3.5(+20)
50(+5)	548	0.0287	91	-327	2211	6.6(+20)
100(+5)	675	0.0466	105	-417	2143	1.1(+21)

TABLE VII. NOMINAL MODEL ATMOSPHERE OF TITAN

P (N/m²)	T (K)	ρ (g/cm³)	H (km)	Z (km)	r (km)	n (cm⁻³)
0.0001	100	1.94(-12)	61	628	3338	7.2(+10)
0.0003	100	5.81(-12)	59	590	3272	2.2(+11)
0.001	100	1.94(-11)	57	548	3203	7.2(+11)
0.003	100	5.81(-11)	54	511	3142	2.2(+12)
0.01	100	1.94(-10)	52	469	3078	7.2(+12)
0.03	100	5.81(-10)	50	431	3021	2.2(+13)
0.1	100	1.94(-9)	48	390	2962	7.2(+13)
0.3	100	5.81(-9)	47	352	2910	2.2(+14)
1.0	100	1.94(-8)	45	311	2855	7.2(+14)
3.0	100	5.81(-8)	43	273	2806	2.2(+15)
10	100	1.94(-7)	42	231	2755	7.2(+15)
20	122	3.16(-7)	50	205	2723	1.2(+16)
50	160	6.05(-7)	63	161	2672	2.3(+16)
100	160	1.21(-6)	61	122	2629	4.5(+16)
200	160	2.42(-6)	59	84	2587	9.1(+16)
500	109	8.85(-6)	39	42	2543	3.3(+17)
1000	82	2.36(-5)	29	+20	2520	8.8(+17)
2000	82	4.12(-5)	28	0	2500	1.8(+18)
4000	86	8.96(-5)	29	-20	2480	3.4(+18)
8000	91	1.70(-4)	30	-41	2459	6.4(+18)
0.1(+5)	98	1.98(-4)	32	-49	2452	7.4(+18)
0.2(+5)	120	3.22(-4)	39	-75	2428	1.2(+19)
0.5(+5)	158	6.12(-4)	50	-118	2387	2.3(+19)
1.0(+5)	195	9.94(-4)	59	-160	2350	3.7(+19)
2.0(+5)	240	1.61(-3)	70	-212	2305	6.0(+19)
5.0(+5)	316	3.07(-3)	87	-299	2233	1.1(+20)
10(+5)	389	4.98(-3)	101	-383	2168	1.9(+20)
20(55)	479	8.09(-3)	116	-486	2093	3.0(+20)
50(+5)	630	0.0154	136	-660	1978	5.8(+20)
100(+5)	776	0.0250	151	-827	1879	9.3(+20)

TABLE VIII. LIGHT MODEL ATMOSPHERE OF TITAN

P (N/m^2)	T (K)	ρ (g/cm^3)	H (km)	Z (km)	r (km)	n (cm^{-3})
0.0001	70	1.04(-12)	208	1111	4500	1.0(+11)
0.0003	70	3.11(-12)	189	1041	4282	3.1(+11)
0.001	70	1.04(-11)	170	963	4067	1.0(+12)
0.003	70	3.11(-11)	155	893	3888	3.1(+12)
0.01	70	1.04(-10)	142	815	3709	1.0(+13)
0.03	70	3.11(-10)	130	745	3560	3.1(+13)
0.1	70	1.04(-9)	120	667	3410	1.0(+14)
0.3	70	3.11(-9)	111	597	3283	3.1(+14)
1.0	70	1.04(-8)	102	519	3155	1.0(+15)
3.0	70	3.11(-8)	95	449	3047	3.1(+15)
10	70	1.04(-7)	89	371	2936	1.0(+16)
30	70	3.11(-7)	83	301	2842	3.1(+16)
100	70	1.04(-6)	78	223	2745	1.0(+17)
300	70	3.11(-6)	73	153	2662	3.1(+17)
750	70	7.78(-6)	69	94	2597	7.8(+17)
1000	71	1.02(-5)	70	75	2577	1.0(+18)
2000	75	1.94(-5)	70	+28	2529	1.9(+18)
3000	77	2.84(-5)	71	0	2500	2.8(+18)
6000	81	5.38(-5)	71	-50	2451	5.4(+18)
0.1(+5)	84	8.64(-5)	72	-89	2414	8.6(+18)
0.2(+5)	89	1.64(-4)	73	-144	2364	1.6(+19)
0.5(+5)	96	3.80(-4)	74	-221	2297	3.8(+19)
1.0(+5)	102	7.18(-4)	75	-285	2245	7.2(+19)
2.0(+5)	108	1.34(-3)	77	-351	2192	1.3(+20)
5.0(+5)	119	3.07(-3)	79	-447	2121	3.1(+20)
10(+5)	129	5.67(-3)	81	-525	2066	5.7(+20)
20(+5)	140	0.0104	83	-611	2009	1.0(+21)
50(+5)	161	0.0227	88	-737	1931	2.3(+21)
100(+5)	184	0.0399	94	-846	1868	4.0(+21)
120(+5)	191	0.0454	96	-876	1851	4.5(+21)
200(+5)	223	0.0652	106	-973	1799	6.5(+21)
500(+5)	293	0.124	124	-1189	1694	1.2(+22)
1000(+5)	361	0.201	137	-1397	1604	2.0(+22)

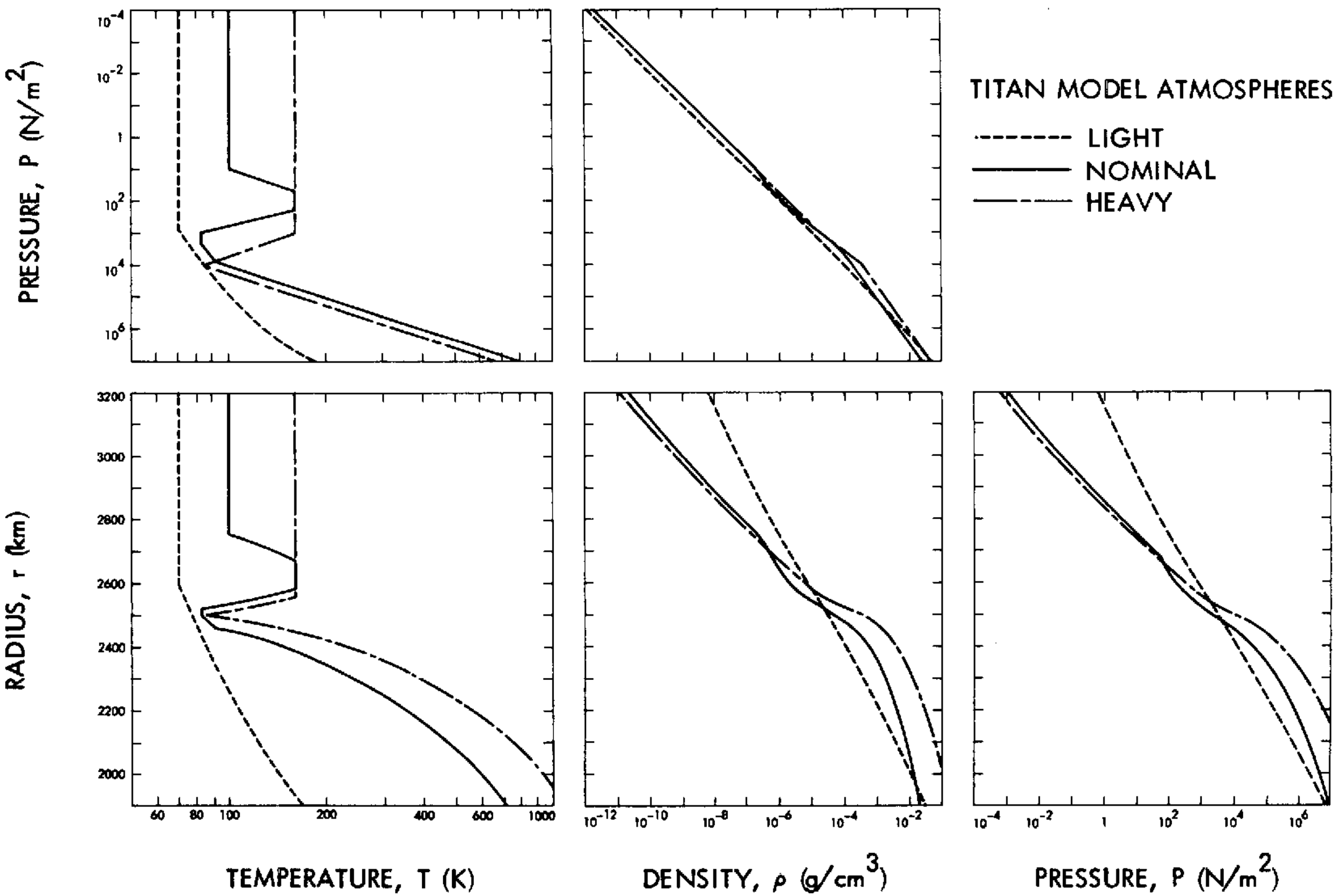

Figure 3. Profiles of radius, temperature, pressure and density for engineering models of Titan's atmosphere.

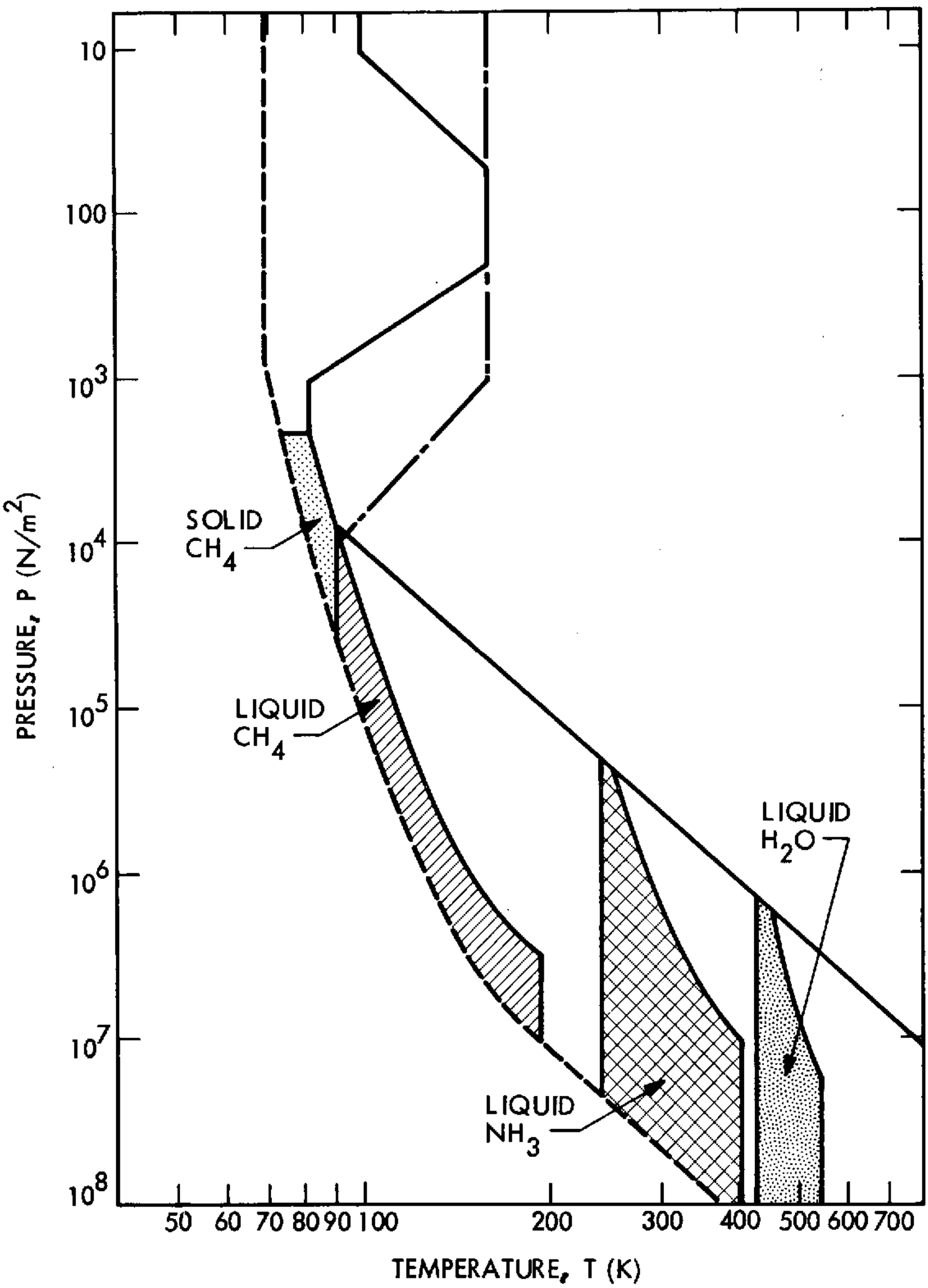

Figure 4. Pressure-temperature domains for various potential condensates in Titan's atmosphere. Portions of the engineering model profiles are reproduced from fig. 2.

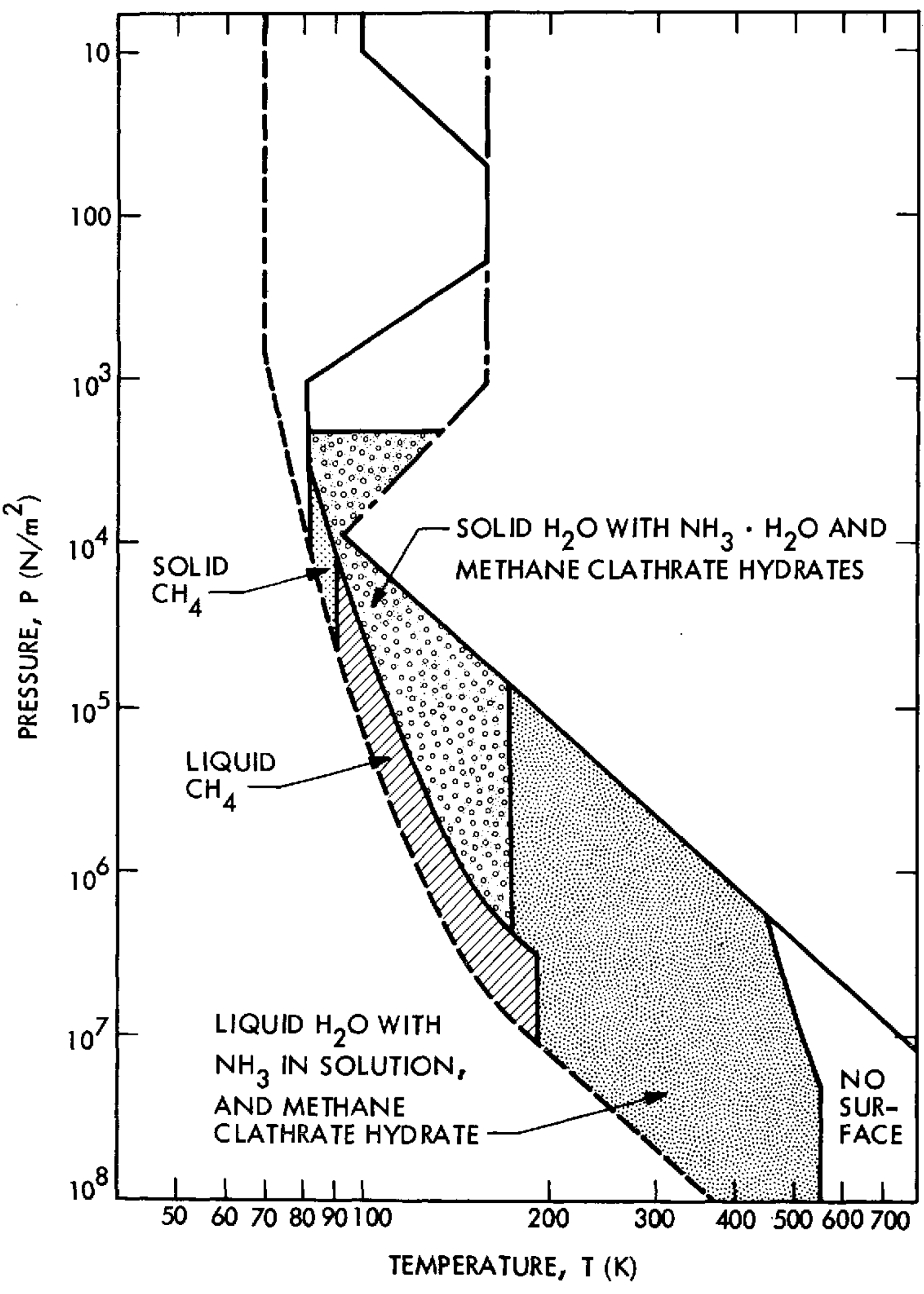

Figure 5. Candidate surface materials corresponding to pressure-temperature regions at the bottom of Titan's atmosphere. Portions of the engineering model profiles are reproduced from fig. 2.

3.4 Surfaces

Any one of several candidate surfaces is likely, its nature depending on the pressure ($P \gtrsim 2\times10^3$ N/m^2) and temperature ($T \gtrsim 80$ K) at the bottom of the atmosphere. The surface material corresponds to that of the region within which the atmospheric profile terminates, as indicated in fig. 5. The most likely candidate is solid water ice, plus $NH_3 \cdot H_2O$ hydrate and CH_4 clathrate hydrate corresponding to the large region near $P \sim 10^5$ N/m^2 (1.0 atm) and $T \sim 150$ K at the bottom of the atmosphere. Any surface may be strongly contaminated with meteoric dust and/or hydrocarbon (tar) deposits. If the liquid water surface pertains, it will contain NH_3 in solution at concentrations in the range 0.1 to 0.5, corresponding to pH values between 11 and 12.5. The analogs of geological activity, including ice-water-steam dominated volcanism, seepages, and icequakes may occur.

3.5 Dynamics

Temperature variations in the atmosphere and at the surface do not exceed a few tens of degrees Kelvin, with the warmest region corresponding to the subsolar point and the coolest to the winter pole. A symmetric regime dominates atmospheric circulation, but wind speeds are less than 10 m/s, either horizontally or vertically. Weather, including precipitation, electrical discharge, etc., is possible but would be more subdued and/or less frequent than for the Earth.

APPENDIX A. The Titan Atmosphere Workshop

NASA sponsored a Workshop on the atmosphere of Titan at Ames Research Center, Moffett Field, CA on 25, 26, and 27 July 1973. The chairman, participants, observers, and other personnel involved are listed in table IX. The presentation of papers and the discussion were limited to the participants, and most of the prepared talks dealt with material available as publications or preprints (see REFERENCES).

In addition to discussions of the technical aspects of Titan's atmosphere, the Workshop adopted working values for several physical parameters (table IV, sec. 3.1), developed several candidate parameter sets for composition, pressure-temperature levels, and surfaces (table III, sec. 2.2.5), and made numerous recommendations both for earth-based observation and analysis and for space program strategies involving Titan. These conclusions will be published in a Workshop proceedings.

TABLE IX. WORKSHOP PERSONNEL

Chairman	Donald M. Hunten, KPNO, Tucson, AZ
Participants	Jacques Blamont, CNES, Paris Lyle Broadfoot, KPNO, Tucson, AZ John Caldwell, Princeton, NJ Robert Danielson, Princeton, NJ John Lewis, MIT, Cambridge, MA Thomas McDonough, Cornell, Ithaca, NY David Morrison, U. of Hawaii, Honolulu, HI James Pollack, ARC, Moffett Field, CA Carl Sagan, Cornell, Ithaca, NY Darrell Strobel, KPNO, Tucson, AZ Nicole Tabarié, CNRS, France Laurence Trafton, U. Texas, Austin, TX Joseph Veverka, Cornell, Ithaca, NY
NASA Representatives	Dan Herman, Code SL Dan Kerrisk, Code SL S. I. Rasool, Code SL
Local Coordinators Hostess Proceedings Editor	Wm. Jackson, Code PD, ARC Ben Padrick, Code PS, ARC Louise Boyce, Code PS, ARC John Niehoff, Sci. Appl., Schiller Park, IL
Observers	T. Croft, SRL, Stanford, CA Neil Divine, JPL, Pasadena, CA Wm. Dixon, TRW, Redondo Beach, CA Tom Ledbetter, Martin-Marietta, Denver, CO Several others

APPENDIX B. Atmospheric Structure Relations

In terms of the symbols defined in Appendix C, the models are governed, within each atmospheric region, by the equations which represent

(1) hydrostatic equilibrium $$\frac{dP}{dr} = -\rho g_o (a/r)^2 \tag{B1}$$

(2) the perfect gas law $$\rho = um_H P/kT \tag{B2}$$

and (3) a temperature gradient $$\frac{d\ell ogT}{d\ell ogP} = \beta \ . \tag{B3}$$

Substitution of the geopotential altitude, given by $Z=a-(a^2/r)$, in eq. B1 yields solutions of the form

$$T = T_A (P/P_A)^{\beta} \tag{B4}$$

and $$Z = Z_A - k(T-T_A)/um_H g_o \beta \tag{B5}$$

for constant $\beta \neq 0$ in a region within which the values Z_A, P_A and T_A describe a common level. If $\beta=0$ eq. B5 is replaced by

$$Z = Z_A - (kT_A/um_H g_o) \ell n(P/P_A) \tag{B6}$$

In the LIGHT atmosphere model the expression for the temperature gradient (eq. B3) in the form $\beta = (0.0664)(140+T)/(280-T)$ permits the pressure-temperature profile to approximate a multiple of the methane saturation curve for $70 \leq T \leq 191$ K. In this case the appropriate solutions of eq. B1 through B3 are given by

$$\left(\frac{P}{P_A}\right)^{0.0664} = \left(\frac{T}{T_A}\right)^2 \left(\frac{T_A + 140}{T + 140}\right)^3 \tag{B7}$$

and

$$Z = Z_A + \frac{k}{um_H g_o}\left[(140)\ell n\,\frac{P}{P_A} + \frac{1}{0.0664}\left(T - T_A - 280\ell n\,\frac{T}{T_A}\right)\right] \,. \tag{B8}$$

The auxiliary quantities pressure scale height, molecular number density and mean molecular weight are given by

$$H = (kT/um_H g_o)(r/a)^2 \tag{B9}$$

$$n = P/kT \tag{B10}$$

and

$$u = \sum_i f_i\, m_i/m_H \quad . \tag{B11}$$

Here m_i is the mass of a molecule whose mixing ratio (fraction by number or volume) f_i is proportional to its abundance.

APPENDIX C. Symbols*

a	radius of Titan (2500 ±250 km)
A_{bol}	bolometric Bond albedo of Titan (0.26 ±0.08)
f	mixing ratio = fraction by number or volume
g_o	acceleration of gravity at $r=a$ (1.5 m/s^2)
H	pressure **scale height** (km)
k	Boltzmann's constant (1.38×10^{-23} J/K)
m_H	mass of Hydrogen atom (1.67×10^{-27}kg)
M	mass of Titan ([1.37 ±0.02]×10^{23} kg)
n	number molecules per unit volume (cm^{-3})
p_v	visual geometric albedo of Titan (0.20 ±0.04)
P	local pressure of atmospheric gas (N/m^2)
P_A	P evaluated at the level A (N/m^2)
$P(CH_4)$	partial pressure of methane (N/m^2)
r	distance from center of Titan (km)
T	local temperature of atmospheric gas (K)
T_e	effective temperature of Titan (K)
T_A	T evaluated at the level A (K)
u	mean molecular weight of atmospheric gas
V_e	escape speed from Titan (2.7 km/s)
Z	**geopotential altitude** (km)
Z_A	Z evaluated at the level A (km)
β	logarithmic pressure-temperature gradient
ρ	local mass density of atmospheric gas (g/cm^3)
$\bar{\rho}$	mean density of Titan (2.1 ±0.6 g/cm^3)
ω	rotation rate of Titan (4.56×10^{-6} s^{-1})

* Expressions in **bold face** are defined in the Glossary (Appendix D).

APPENDIX D. Glossary

abundance	The quantity of gas traversed by electromagnetic radiation. In an atmosphere it is commonly described in units of length times atm or Amagat, each of which represents a density (not a pressure) at standard temperature and pressure (STP). At STP Avogadro's number N_o of molecules (1 mole) occupies a volume V_o such that 1 m-atm = 1 m-Amagat is equivalent to (1 m)(N_o/V_o) = 2.69×10^{25} molecules/m^2.
geopotential altitude (Z)	The integral of the relative acceleration of gravity g along a radius r, defined by $Z = \int_a^r (g/g_o)dr$. If departures from spherical symmetry and the mass external to a sphere of radius r both contribute negligibly to g, then $Z = a-(a^2/r)$. For $\lvert Z\rvert \ll a$, the geopotential altitude Z is equivalent to the geometric altitude $(r-a)$.
scale height (H)	A measure of the vertical gradient of an atmospheric quantity x (e.g., pressure P), such that if $H = -x(dx/dr)^{-1}$ is constant with radial distance r, the quantity x changes by a factor e in the interval $(\Delta r) = H$.

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