periments are indicated, although even a limited mission might be able to use the spacecraft radio to detect surface conditions by directing transmissions toward Titan and receiving the scattered energy at Earth.

VON R. ESHLEMAN
Space, Telecommunications, and Radioscience Laboratory, Stanford University, Stanford, California 94305

GUNNAR F. LINDAL
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91109

G. LEONARD TYLER
Space, Telecommunications, and Radioscience Laboratory, Stanford University

References and Notes

1. G. L. Tyler, V. R. Eshleman, J. D. Anderson, G. S. Levy, G. F. Lindal, G. E. Wood, T. A. Croft, *Science* **212**, 201 (1981).
2. R. Hanel *et al.*, *ibid.*, p. 192.
3. A. L. Broadfoot *et al.*, *ibid.*, p. 206; S. K. Atreya, T. M. Donahue, W. R. Kuhn, *ibid.* **201**, 611 (1978).
4. D. M. Hunten, in *The Saturn System*, D. M. Hunten and D. Morrison, Eds. (Conference Publication 2068, National Aeronautics and Space Administration, Washington, D.C., 1978), p. 127.
5. G. P. Kuiper, *Astrophys. J.* **100**, 378 (1944); H. C. Urey, *The Planets: Their Origin and Development* (Yale Univ. Press, New Haven, Conn., 1952); D. M. Hunten, *NASA Spec. Publ. 340* (1974); T. Owen, *Sci. Am.* **246**, 98 (February 1982); J. B. Pollack, in *The New Solar System*, J. K. Beatty, B. O'Leary, A. Chaikin, Eds. (Cambridge Univ. Press, New York, 1981), p. 161; C. Sagan and S. F. Dermott, *Nature (London)* **300**, 731 (1982).
6. One of us (V.R.E.) discussed this possibility at the Voyager press conference at the Jet Propulsion Laboratory on 13 November 1980.
7. G. F. Lindal *et al.*, *Icarus* **53**, 348 (1983). Fundamental characteristics of Titan determined from the Voyager radio science experiment include the following: diameter, 5150 km (40 percent of Earth's); density, 1.88 g cm^{-3} (34 percent); surface gravity, 1.354 m sec^{-2} (14 percent); and a nitrogen atmosphere with surface pressure, density, and absolute temperature 1.5, 4.5, and 0.33 times that of Earth's average atmosphere, respectively.
8. See (*5*) plus the special issues of *Science* [**212**, 159 (1981) and **215**, 499 (1982)] and *Nature (London)* [**292**, 675 (1981)] on the Voyager mission, particularly the papers dealing with the aerosol.
9. R. E. Samuelson, R. A. Hanel, V. G. Kunde, W. C. Maguire, *Nature (London)* **292**, 688 (1981).
10. F. M. Flaser, R. E. Samuelson, B. J. Conrath, *ibid.*, p. 693.
11. B. M. Lasker, *Astrophys. J.* **138**, 709 (1963).
12. F. M. Flasar, *Bull. Am. Astron. Soc.* **14**, 713 (Abstr.) (1982); *Science* **221**, 55 (1983).
13. This differs from the situation on Earth, where a dry adiabat generally is found over the tropical ocean five to ten times this height, up to the base of the cumulus cloud layer.
14. Numerous authors [G. Fjeldbo, A. J. Kliore, V. R. Eshleman, *Astron. J.* **76**, 123 (1971); B. Lipa and G. L. Tyler, *Icarus* **39**, 192 (1979); V. R. Eshleman, D. O. Muhleman, P. D. Nicholson, P. G. Steffes, *ibid.* **44**, 793 (1980); P. G. Steffes and V. R. Eshleman, *ibid.* **46**, 127 (1981); and A. Seiff *et al.*, *J. Geophys. Res.* **85**, 7903 (1980)] have discussed the slope discontinuity in terms of a dry-to-wet adiabat transition involving carbon dioxide and sulfuric acid. On the other hand, J. B. Pollack, O. B. Toon, and R. Boese (*ibid.*, p. 8223) reproduced it with a model that does not include latent heat effects. In either case, however, the Venus atmospheric discontinuity is due to the cloud.
15. See figure 1.5 in J. W. Chamberlain, *Theory of Planetary Atmospheres* (Academic Press, New York, 1978), p. 14.
16. R. E. Samuelson, *Icarus* **53**, 364 (1983).
17. B. L. Lutz, T. C. Owen, R. D. Cess, *Astrophys. J.* **203**, 541 (1976); U. Fink, D. C. Beuner, K. A. Kick, *J. Quant. Spectrosc. Radiat. Transfer* **18**, 447 (1977); L. P. Giver, *ibid.* **19**, 311 (1978); L. M. Trafton, *Astrophys. J.* **195**, 805 (1975a); *Icarus* **24**, 443 (1975b).
18. V. G. Kunde *et al.*, *Nature (London)* **292**, 686 (1981).
19. Supported by the National Aeronautics and Space Administration. We thank our colleagues at Stanford and the Jet Propulsion Laboratory and the Voyager project personnel for their help and cooperation.

9 November 1982; revised 1 March 1983

Oceans on Titan?

Abstract. *If global oceans of methane exist on Titan, the atmosphere above them must be within 2 percent of saturation. The two Voyager radio occultation soundings, made at low latitudes, probably occurred over land, since they imply a relative humidity ≲ 70 percent near the surface. Oceans might exist at other low-latitude locations if the zonal wind velocities in the lowest 3 kilometers are ≤ 4 centimeters per second.*

Saturn's giant moon Titan is remarkable in that it has an atmosphere. Although nitrogen is the dominant constituent (*1, 2*), the presence of methane is well established (*2, 3*). Photolytic and catalytic dissociation of methane is rapid enough to deplete the total atmospheric abundance of methane in a time short compared to the satellite's presumed age, ~ 4.5 billion years (*4*). If the abundances of methane and other hydrocarbons currently observed in Titan's atmosphere typify those during much of its history, a source of atmospheric methane is required. Samuelson *et al.* (*5*) proposed that methane clouds also exist and provide much of the opacity in Titan's troposphere, because pressure-induced absorption by gaseous methane and nitrogen is unable to provide the infrared opacity required to account for the emission observed near 200 cm^{-1} (*6*). These considerations suggest that a reservoir of methane exists at Titan's surface, and the possibility of oceans of methane on Titan has been raised (*1, 7, 8*). In this report I examine the constraints that meteorology and the Voyager radio occulation data place on such hypothetical oceans.

An energy argument provides a lower limit on the amount of methane vapor above the surface of an ocean. Global radiative equilibrium models that are consistent with Voyager observations predict that between 13 and 33 percent of the solar irradiation is absorbed at Titan's surface (*9*). They also predict a temperature discontinuity of 1 to 3 K at the surface, which ensures that the net upward flux of thermal radiation balances the net downward flux of solar radiation. The discontinuity is unstable in the sense that the surface is warmer than the atmosphere just above it. In reality this instability generates turbulent fluxes of sensible and latent heat that provide much of the required upward energy flux and reduce the discontinuity in temperature predicted by the radiative models.

The flux of latent heat from an ocean surface can be expressed in terms of the bulk transfer relation (*10*):

$$H_L = \frac{n_a L}{\eta} C(q_s - q_a) \qquad (1)$$

where η is Avogadro's number, L is the latent heat of methane vaporization (*11*), and C is a bulk transfer coefficient. The quantity q_s denotes the mole fraction of methane saturated at the ocean surface (*12*); n_a and q_a denote total number density and the gaseous methane mole fraction at an "anemometer" level a few meters above the surface. For a positive flux of latent heat into the atmosphere, $q_a < q_s$. A globally averaged upper limit to the drop in methane abundance across the "surface boundary layer," $\Delta q = q_s - q_a$, follows from imposing an upper limit on H_L and a lower limit on C in Eq. 1. A plausible upper limit on H_L is the solar radiation absorbed at the surface: $H_L < 0.33\ S_0/4$, where S_0 is the solar constant at Titan. Since the surface layer is unstably stratified, C can be minimized by taking the free convection limit and including only the contribution to the stratification from $\Delta q > 0$ (methane is lighter than nitrogen), neglecting that from the drop in temperature: $C \geq 0.00214\ (\Delta q)^{1/3}$ m sec^{-1} (*13*). With these limits, Eq. 1 implies $(q_s - q_a)/q_s \leq 0.02$: the relative humidity of the atmosphere above the surface layer is ≥ 98 percent. The lifting condensation level (LCL), the height at which an ambient parcel of gas saturates when adiabatically lifted from the top of the surface layer, is ≤ 200 m. In Table 1 the lower atmosphere of Titan is compared with that in Earth's tropics. Typically, the relative humidity above the terrestrial surface layer is only 80 percent, and the LCL is situated 0.5 to 1 km above the surface. Although several factors contribute to these differences, one of the most important is the reduced value of the solar constant at Titan relative to Earth.

Horizontal contrasts in Titan's tropospheric and surface temperatures are small (*14, 15*). Therefore, it is reasonable to use the global constraint on the relative humidity to derive model atmospheres from the Voyager radio occultation experiment. This experiment obtained refractivity profiles [$N(z)$] at two locations, 6.2°N and 8.5°S, that were separated in longitude by approximately 180° (*1, 15*). For a specified composition, the molecular number density n can be inferred from the relation $N(z) = \alpha(z)n(z)$ (*16*). In relative units, $\alpha = 1.1$ and 1.6 for nitrogen and methane vapor, respectively (*17*); application of the Lorentz-Lorenz law yields $\alpha = 1.6$ for spherical methane droplets (*18*). For a mixture α is the mole fraction–weighted sum of the values for the individual components. The law of hydrostatic balance and an equation of state yield pressure and temperature as functions of altitude (*16*). Departures from ideal gas behavior on Titan are not negligible (*15*), and in the models presented here the Bender equation of state (*19*) is used to compute temperatures.

In the models the vertical distribution of methane varies as follows. An abundance is specified above the surface layer and the methane mole fraction is constrained to decrease with altitude to ~ 0.017 near the tropopause, corresponding to the minimum saturated mole fraction in the troposphere. With a relative humidity of ~ 98 percent near the surface, most of the troposphere is saturated. Two limiting models are used to specify the vertical distribution of clouds in the troposphere: (i) negligible condensate (Fig. 1b) and (ii) an abundance of condensed methane, which in the lowest few kilometers equals that which would be realized in a moist adiabatic ascent from the cloud base without precipitation (Fig. 1c). In terrestrial clouds the average liquid water content is generally below this limit (*20*). The thermal structure of the models in the lower troposphere is not especially sensitive to the model specification at higher altitudes.

The results for the sounding at 6.2°N are summarized in Fig. 1; those for 8.5°S are very similar. The profiles of virtual temperature T_v, which is a measure of stability in atmospheres with condensables (*21*), are of particular interest. With a relative humidity $\gtrsim 98$ percent near the surface, the profiles of T_v at low altitudes are much steeper than the dry adiabat. Such atmospheres are dynamically impossible because they are statically unstable to convective overturning. Since the lower atmosphere over methane oceans must exhibit relative humidities $\gtrsim 98$ percent, both radio occultation soundings probably occurred over dry land.

To understand the behavior of the derived temperature profiles, it is sufficient to consider them in the ideal gas limit (*16*):

$$T_v(z_0) \propto \frac{\alpha(z_0)}{m(z_0)N(z_0)} \times \int_{z_0}^{\infty} \frac{m(z)}{\alpha(z)}\, g(z)N(z)\, dz \qquad (2)$$

where z_0 is the altitude of interest and m is the mean molecular weight of the gas and condensate mixture (the remaining symbols have already been defined). The quantity α is 50 percent larger for methane than for nitrogen, and the molecular weight of methane is less. When methane saturates in the lowest few kilometers, as in Fig. 1b, its mole fraction decreases rapidly with altitude with a concomitant decrease in $\alpha(z_0)/m(z_0)$, which yields gradients in T_v that are large compared to those in a pure nitrogen atmosphere. When condensate is present and increases with altitude, as in Fig. 1c, the temperature gradients are smaller, but the decrease in total methane abundance with altitude is still large enough to imply superadiabatic lapse rates. The integral in Eq. 2 does not contribute significantly to the small-scale variation in $T(z_0)$ because it is weighted by $g(z)N(z)$ and therefore receives appreciable contributions from a full-scale height of the atmosphere above z_0. In general, decreasing the methane content near the surface results in more stable model atmospheres. Lapse rates are everywhere subadiabatic when the methane abundance in the lowest 3 to 4 km is below saturation and varies slowly with altitude. This corresponds to a relative humidity $\lesssim 70$ percent near the surface.

Can methane oceans exist at other longitudes in the tropics? If they do, then a parcel of gas at one of the radio occultation locations must be brought nearly to saturation when the zonal winds transport it over ocean and must dry out again on encountering land. Since latent heat is being supplied to the atmosphere, the allowable energy available for evaporation places an upper limit on the zonal wind velocity. Most of the methane precipitation will occur in the lowest 3 km of the atmosphere. If the atmosphere establishes a relative humidity of 70 percent above the land surface, the models indicate that ~ 15 g of methane will precipitate out per square centimeter. If this occurs over a horizontal distance comparable to the planetary radius, a simple calculation implies that the average zon-

Table 1. Atmospheric boundary layers of Titan and Earth.

Quantity	Earth tropics (*10*) (water, 298 K)	Titan global (methane, 95 K)	Titan/ Earth
Number density, n_a (cm^{-3})	2.4×10^{19}	1.1×10^{20}	4.7
Heat of vaporization, L (J $mole^{-1}$)	4.4×10^{4}	8.6×10^{3}	0.20
Solar constant, S_0 (W m^{-2})	1.37×10^{3}	15.1	0.011
Evaporative flux, H_L (W m^{-2})	160	$\lesssim 1.27$	$\lesssim 8 \times 10^{-3}$
Bulk transfer coefficient, C (m sec^{-1})	1.3×10^{-2}	$\gtrsim 3 \times 10^{-4}$	$\gtrsim 0.02$
Departure from saturation, $(q_s - q_a)/q_s$	0.2	$\lesssim 0.02$	$\lesssim 0.1$
LCL (m)	500 to 1000	$\lesssim 200$	$\lesssim 0.4$

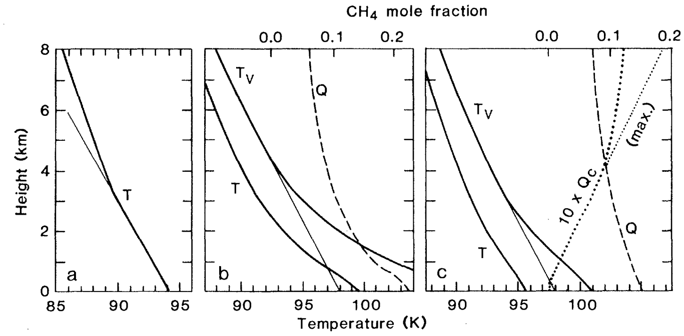

Fig. 1. Temperature and methane profiles of model Titan atmospheres. (a) Pure nitrogen atmosphere (*15*). (b and c) Nitrogen and methane atmospheres having 98 percent relative humidity at the top of the surface layer; in both cases nearly all of the lower troposphere is saturated. Heavy solid curves: atmospheric temperature (T) and virtual temperature (T_v). Light solid lines: dry adiabats. Dashed and dotted curves: mole fractions of total methane (Q) and methane condensate (Q_c). Panel (b) has negligible condensate, while (c) has the maximum allowed in the lowest 4 km, equal to that realized by adiabatic ascent from the base of the saturated region (light dotted curve). The vertical resolution of the profiles is 1/2 km near the surface.

al velocity in the lowest 3 km is $\lesssim 4$ cm sec^{-1}. This is small compared to the ~ 10 m sec^{-1} of zonal winds higher in the troposphere that have been inferred from the thermal wind relation (*14*). Moreover, organized vertical motions are probably required to effect the necessary precipitation; longitudinal structure indicative of such motions is not readily apparent in Voyager imaging or infrared data (*14, 22*).

Sagan and Dermott (*8*) argued that the presence of large land masses precludes the existence of a global ocean. The land would act as a barrier to the tidal flow of the ocean and generate too much dissipation to be consistent with the high eccentricity of Titan's present orbit. From a geological viewpoint, Titan is unlikely to possess a network of ocean basins and continents because the satellite is too small to generate any large amount of tectonic activity, and it is too far from Saturn for tidal dissipation to be very significant. This is consistent with the low relief observed on other large, icy, inactive bodies, such as Ganymede and Callisto (*23*). Thus, if oceans are absent at two locations on Titan, they may be absent everywhere.

Note added in proof: The analysis presented here was applied to methane oceans. Some of the heavier hydrocarbons produced by methane dissociation in the upper atmosphere, such as ethane and propane, are readily soluble in liquid methane, and, in bulk concentrations, could depress the methane vapor pressure at the surface. The nature and likelihood of such hydrocarbon oceans are currently under study.

F. M. FLASAR

Laboratory for Extraterrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771

References and Notes

1. G. L. Tyler, V. R. Eshelman, J. D. Anderson, G. S. Levy, G. F. Lindal, G. E. Wood, T. A. Croft, *Science* **212**, 201 (1981).
2. R. A. Hanel *et al.*, *ibid.*, p. 192.
3. G. P. Kuiper, *Astrophys. J.* **100**, 378 (1944).
4. D. F. Strobel, *Planet. Space Sci.* **30**, 839 (1982).
5. R. E. Samuelson, R. A. Hanel, V. G. Kunde, W. C. Maguire, *Nature (London)* **292**, 688 (1981).
6. R. Courtin, *Icarus* **51**, 466 (1982).
7. T. Owen, *Sci. Am.* **246**, 98 (February 1982).
8. C. Sagan and S. F. Dermott, *Nature (London)* **300**, 731 (1982).
9. R. E. Samuelson, *Icarus* **53**, 364 (1983).
10. E. Augstein, in *Meterology over the Tropical Oceans*, D. B. Shaw, Ed. (Royal Meteorological Society, London, 1978), p. 73.
11. R. D. Goodwin, *J. Res. Natl. Bur. Stand. Sect. A* **75**, 15 (1971).
12. S. Angus, B. Armstrong, K. M. de Reuck, *International Thermodynamic Tables of the Fluid State—5: Methane* (Pergamon, Oxford, 1976).
13. C. B. Leovy, *J. Geophys. Res.* **74**, 3313 (1969); ——— and Y. Minz, *J. Atmos. Sci.* **26**, 1167 (1969).
14. F. M. Flasar, R. E. Samuelson, B. J. Conrath, *Nature (London)* **292**, 693 (1981).
15. G. F. Lindal *et al.*, *Icarus* **53**, 348 (1983).
16. G. Fjeldbo and V. R. Eshleman, *Planet. Space Sci.* **16**, 1035 (1968).
17. T. K. Bose, J. S. Sochanski, R. H. Cole, *J. Chem. Phys.* **57**, 3592 (1972); R. H. Orcutt and R. H. Cole, *ibid.* **46**, 697 (1967); L. Essen and K. D. Froome, *Proc. Phys. Soc. London Sect. B* **64**, 862 (1951).
18. H. C. van de Hulst, *Light Scattering by Small Particles* (Wiley, New York, 1962), pp. 37 and 70; R. L. Amey and R. H. Cole, *J. Chem. Phys.* **40**, 146 (1964).
19. E. Bender, *Chem. Ing. Tech.* **44**, 576 (1972); *Cryogenics* **13**, 11 (1973); K. Bühner, G. Maurer, E. Bender, *ibid.* **21**, 157 (1981).
20. B. Ackerman, *J. Atmos. Sci.* **20**, 288 (1963); N. H. Fletcher, *The Physics of Rainclouds* (Cambridge Univ. Press, London, 1962), pp. 7–15.
21. The virtual temperature of a mixture of gas and condensate is the temperature at which dry gas (N_2) of the same pressure has the same mass density as the original mixture [D. Brunt, *Physical and Dynamical Meteorology* (Cambridge Univ. Press, London, ed. 2, 1952), pp. 31 and 41–44].
22. B. A. Smith *et al.*, *Science* **212**, 163 (1981); *ibid.* **215**, 504 (1982).
23. D. Morrison, *Annu. Rev. Astron. Astrophys.* **20**, 469 (1982).

24. I thank G. Birnbaum for providing invaluable references on dielectric constants and R. B. Stewart for providing equations of state. An anonymous reviewer suggested that methane clouds could contribute to the radio occultation refractivities. I also thank J. C. Pearl, R. E. Samuelson, B. J. Conrath, R. Hanel, J. A. Pirraglia, and C. B. Leovy for stimulating discussions and their critical reading of the manuscript.

30 November 1982; revised 28 March 1983

Venera 13 and Venera 14: Sedimentary Rocks on Venus?

Abstract. *Venera 13 and Venera 14 transmitted almost complete panoramic views of their landing sites. Analyses of the photographs show the presence of rock formations undergoing geomorphic degradation. The formations display ripple marks, thin layering, differential erosion, and curvilinear fracturings. Some of them are interpreted as lithified clastic sediments. The lithification could have taken place at depth or at the surface, resulting in a type of duricrust. The origin of the sediments is unknown but could be aeolian, volcanic, or related to impacts or to turbidity currents.*

In March 1982 the automatic landers Venera 13 and Venera 14 landed on the surface of Venus and transmitted to Earth panoramic television pictures. Preliminary determinations of the locations of the landing sites are latitude 7°30′S and longitude 303° for Venera 13 and latitude 13°15′S and longitude 310°9′ for Venera 14 (*1*). The television system was essentially an improved version of the system used in Venera 9 and Venera 10 (*2, 3*) with the difference that in Ven-

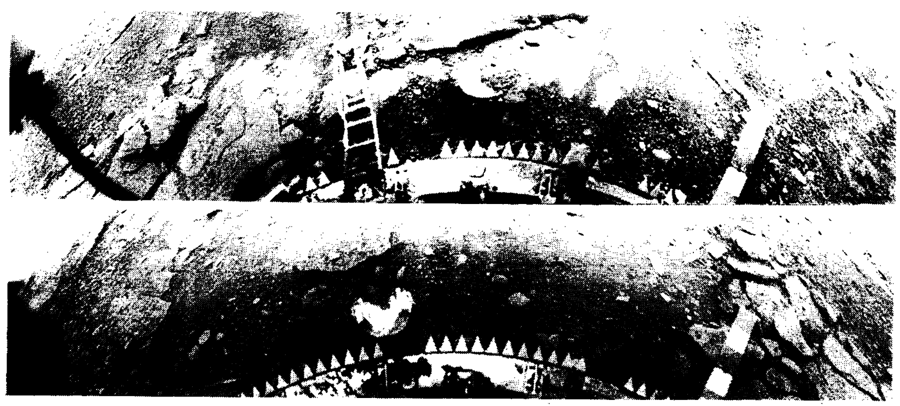

Fig. 1. Landscape photographed by Venera 13.

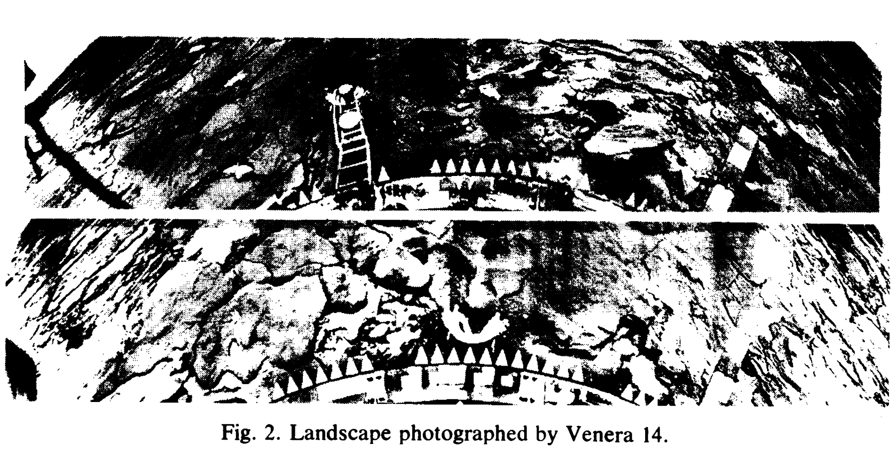

Fig. 2. Landscape photographed by Venera 14.