TITAN'S ATMOSPHERE AND SURFACE: PARALLELS AND DIFFERENCES WITH THE PRIMITIVE EARTH

A. COUSTENIS
Dept. of Space Research
Paris-Meudon Observatory, 92195 Meudon, France

Abstract. In spite of a marked resemblance with our planet, Titan should not be hastily considered as another Earth but rather as a useful tool in the study of chemical and physical processes in the primitive Earth.

1 Introduction

There exist only 3 or 4 planetary objects that have N_2 atmospheres in our Solar System (Earth, Titan, Triton and perhaps Pluto). The present state and chemical evolution of the atmospheres of Titan, Triton and Pluto is explained in Lunine, Atreya and Pollack (1989) and references therein. For purposes of comparative planetology, I have compiled from the various sources referenced in this paper Tables 1 to 4. This article, however, is mainly focused on Titan vs Earth comparisons. Because Titan has a substantial atmosphere with molecular nitrogen as the major component, the satellite is evidently the best laboratory available to scientists at this time for studying the chemical evolution of an atmosphere similar to that of the primitive Earth. For an extended review of the satellite's characteristics, see Hunten *et al.* (1984). Although the satellite is half our planet's size (Table 1), its atmosphere is denser and larger than the Earth's reaching out in the space up to about 1500 km from the surface (Table 2). Other properties of Titan were more precisely determined following the Voyager 1 encounter: the total mass of the satellite is about 1.4 $\times 10^{26}$ g, or 1/50 that of the Earth's; the surface gravity is about 7 times less than on Earth; its obliquity is assumed to be 26.7, while the Bond albedo of the satellite is estimated to be around 0.25; at a distance of 1.3 $\times 10^{6}$ AU from the Sun, Titan receives only 1.1% of the solar flux that reaches our Earth.

2 Parallels between Titan and the primitive Earth

Many similarities, discussed hereafter, between Titan and our planet, can be considered as arguments in favor of regarding Ttian as a good early Earth analogy.

Earth, Moon, and Planets **67**: 95–100, 1995.

TABLE 1. Planetary and Satellite Orbital Data

	Titan	Earth	Triton	Pluto
Semi-major axis of orbit (*A U*)	9.54	1	30.06	39.44 (29.7 now)
Radius (*km*)	2575	6378	1352	1208?
Rotation period (*day*)	16	1	5.9	6.4
Sidereal period (*yr*)	29.46	1	165	248
Surface gravity ($cm\ s^{-2}$)	135	979	78.1	59.7

TABLE 2. Atmospheric Structure/Temperature Data

	Titan	Earth	Triton	Pluto
Surface temperature (*K*)	94	288	38	35-55
Albedo	0.2-0.3	0.3	0.7	0.2-1.
Surface Pressure (*bar*)	1.45	1	14×10^{-6}	3×10^{-6} ?
Temperature 1 mbar (*K*)	150-170	190	41	104±21
Tmax (*K*)	185±20	600-1500	102±3	?
$\lambda = r/H = mgr/kT$ **at 1 mbar**	68	1140	84	21
Exobase height (*km*)	1500	500	930	?
$r_{exobase}/r_{planet}$	1.6	1.08	1.7	>>3 ?

Cautiousness is advised, however, in hastily subscribing to this analogy, because of the important differences which also exist, as explained in Section 3.

2.1 THE ATMOSPHERE: THERMAL AND CHEMICAL COMPOSITION

Nine times farther from the Sun than our planet, Saturn's largest moon exhibits

TABLE 3. Chemical Composition of Atmospheres

		Titan	Earth	Triton	Pluto
Major constituent (%)	N_2	90-97	78	99	99 ?
Minor species (%)	O_2		21		
	H_2O	? ($<10^{-9}$)	0.1-3	?	?
	Ar	? (<10)	0.93	?	?
	CO_2	10^{-8}	0.034	?	?
	CO	10^{-6}-10^{-4}	10^{-5}	$2x10^{-4}$	?
	CH_4	2-3 (strat.)	$1.5x10^{-4}$	10^{-4}	?
	H_2	0.2		10^{-4}	?

a thermal structure much like the Earth's but much colder (the solar radiation reaching Titan's haze top is about 100 times less than on Earth). The effective temperature at which Titan radiates to space is 83°K and corresponds to about 73% absorption of the incident solar energy in the upper atmosphere. The temperature decreases in the stratosphere as one descends from 600 to 40 km of altitude (Lellouch *et al.*,1989) and reaches the tropopause, where the minimum value of 71°K is attained (Lindal *et al.*,1983). There, a temperature inversion occurs, as a moderate greenhouse effect heats up the surface to 94°K for a pressure of 1.5 bar (Table 2). The meridional temperature distribution at the time of the Voyager encounter (spring equinox) was not symmetric about the equator and latitudinal variations show the north polar region to be 15-20°K colder than the equator or the south polar regions (Flasar and Conrath 1990). This implies that Titan's atmosphere may be controlled by dynamical inertia, to account for the atmospheric lag behind the solar input, or/and that the temperature asymmetry could be due to compositional variations (Coustenis and Bézard 1994).

Both our planet and Titan support active organic chemistry in their atmospheres (Earth is also biologically controlled). After N_2, CH_4 is the most abundant species on Titan (0.5-3.4% in the stratosphere), followed by H_2 and others (Table 3). Carbon-containing species and nitriles exist on Titan in detectable quantities. Voyager 1 and ground-based measurements have detected hydrocarbons (ethane, acetylene, propane, etc...) in complex forms, nitriles (HCN, HC_3N, C_2N_2, CH_3CN...) - some of which are prebiotic molecules -, and two oxygen compounds (CO, CO_2). However, the latter are scarce, and oxygen exists on Titan only in trace amounts (Table 3). Water has not yet been detected. The minor species in Titan's atmosphere were found to show latitudinal variations, much like on Earth, which could be due to seasonal effects (Coustenis and Bézard 1994).

2.2 ATMOSPHERIC CONDENSATES AND SURFACE

The orange-yellow haze that globally covers the satellite suggests the presence of aerosols in its atmosphere, as on Earth. The nature and size of the aerosols is not yet well defined, but we know that the molecular fragments and other components produced by photolysis and energetic electrons in the upper part of the atmosphere form polymers, as suggested by laboratory studies (Sagan *et al.*,1984). All the hydrocarbons and nitriles produced by N_2-CH_4 reactions (Yung *et al.*,1984) condense in the coldest region of the atmosphere and form solid suspended particles which probably sink lower into the deeper atmosphere, collide and form aggregates dropping even faster to finally land on the surface of the satellite, where they may rest or be absorbed by a porous surface material and end up stored in a reservoir underneath the "ground". Methane clouds, instead of water vapor ones, may exist near the tropopause, although it has been suggested recently that supersaturation of methane could occur, leading to a partially aerosol-free troposphere instead (Samuelson 1994, Courtin *et al.*,1994).

Recent observations of Titan put a question mark on previous theoretical models which suggested the presence of large liquid hydrocarbon reservoirs on the surface (Lunine *et al.*,1983). The mystery remains unsolved, but efforts to reconcile observational data and theory set forth various possibilities which include a frothy aerosol-contaminated ocean, a non-global smaller ocean, or parts of dry land and lakes (Lunine 1993). A mostly solid surface is likely based on radar measurements (Muhleman *et al.*,1990) and on near-infrared observations compiled in Table 4, (Lemmon *et al.*,1993; Griffith 1993), perhaps covered with dirty water ice, or with a porous icy or rocky regolith in which the hydrocarbon reservoir is stored (Stevenson 1992; Coustenis *et al.*,1994).

3 Differences with the primitive Earth

Organic gases, aerosol layers, condensation and perhaps methane clouds exist in Titan's atmosphere, and a liquid ocean (or lakes) as well as ices and minerals have

TABLE 4. Surface Composition

	Titan	Earth	Triton	Pluto
Ocean	Hydrocarbons (C_2H_6-CH_4-N_2)	H_2O	Frozen	Frozen
Ices	C_2H_2,CO_2, H_2O, ?	H_2O	N_2,CO, CH_4,CO_2	N_2, CO, CH_4
Crust	dirty ice, minerals?	minerals		

been suggested to cover its surface. However, conditions on present day Titan do not replicate with precision those on primordial Earth and some of the reasons are the following. *(a)*: The major composition on Titan (N_2-CH_4) is different from the Earth's (N_2-CO-CO_2). *(b)*: The low temperature on Titan, due to less visible radiation (100 times) than that reaching the Earth, certainly slows the chemical reactions considerably and may have up to now prevented the formation of complex molecules required in the life-chain. *(c)*: Water, although suspected in solid form, has not yet been firmly detected. *(d)*: The state of oxidation between the inner and the outer solar system atmospheres is very different. C is present in its fully oxidized state, CO_2, in all the terrestrial planets and in its fully reduced state in most of the outer Solar System objects. This difference could reflect the ability of water to buffer the oxidation state of the carbon species in the atmospheres of the terrestrial planets, while the oxidation state of the C in the outer Solar System atmospheres may be primordial (Lunine *et al.*,1989). The present-day Earth is an extreme case in this regard due to the high abundance of O_2. This apparently reflects the Earth's unique position in the solar system as an abode of life. *(e)* The infall of carbonaceous material (meteorites, comets, etc...) on a planet, is smaller today than in the past. *(f)* the Earth being larger than Titan, its atmosphere has evolved significantly over its lifetime due to volcanic and tectonic changes with time. Titan, by way of contrast, may have undergone early dramatic changes followed by tectonic quiescence. Subsequent evolution would be externally driven by photochemical processes perhaps by tectonical activity (Lunine and Stevenson 1987).

4 Conclusions and perspectives

All this may signify that the satellite will never be more than a good model for the early Earth, but Titan is undeniably a valuable tool to the study of some chemical and physical processes. The *Cassini/Huygens* mission to Saturn and Titan (to be launched in 1997) will arrive at Titan in 2004 to make orbital and in situ measurements for four years, bringing new insight to the Earth-Titan resemblances/differences. In the expectation of the wealth of data from this mission, astronomers will still use all available means from the ground and satellites (such as *ISO, Infrared Space Observatory*) to study this fascinating and promising object.

5 References

Atreya, S.K. (1986) *Atmospheres and Ionospheres of the Outer Planets and Their Satellites*, Springer-Verlag (eds.), New York, 145-197.

Coustenis, A., and Bézard, B. (1995) Titan's atmosphere from Voyager infrared observations. IV. Latitudinal variations of temperature and composition. *Icarus* , in press.

Coustenis, A., Lellouch, E., Maillard J.P., and McKay, C.P. (1995) Titan's surface: composition and variability from its near infrared albedo. Submitted to *Icarus*.

Courtin, R., Gautier, D., and McKay, C.P. (1994) Titan's thermal emission spectrum: re-analysis of the Voyager infrared measurements. *Bull. Am. Astron. Soc.* **26**, 1182.

Flasar, F.M., and Conrath, B.J. (1990) Titan's stratospheric temperatures: a case for dynamical inertia? *Icarus* **85**, 346-354.

Griffith, C.A. (1993) Evidence for surface heterogeneity on Titan. *Nature* **364**, 511-514.

Hunten, D.M., Tomasko, M.G., Flasar, F.M., Samuelson, R.E., Strobel, D.F., and Stevenson, D.J. (1984) Titan. In *Saturn*, T. Gehrels and M.S. Matthews (eds.), University of Arizona Press, Tucson, 671-759.

Lellouch, E., Coustenis, A., Gautier, D., Raulin, F., Dubouloz, N., and Frère, C. (1989) Titan's atmosphere and hypothesized ocean: A re-analysis of the Voyager 1 radio-occultation and IRIS 7.7 μm data. *Icarus* **79**, 328-349.

Lemmon, M.T., Karkoschka, E., and Tomasko, M. (1993) Titan's rotation: surface feature observed. *Icarus* **103**, 329-332.

Lindal, G.F., Wood, G.E., Hotz, H.B., Sweetnam, D.N., Eshelman, V.R., and Tyler, G.L. (1983) The atmosphere of Titan: an analysis of the Voyager 1 radio-occultation measurements. *Icarus* **53**, 348-363.

Lunine, J.I. (1993) Does Titan have an ocean? A review of current understanding of Titan's surface. *Rev. of Geophys.* **31**, 133-149.

Lunine, J.I., Stevenson, D.J., and Yung, Y.L. (1983) Ethane ocean on Titan. *Science* **222**, 1229-1230.

Lunine, J.I., and Stevenson, D.J. (1985) Evolution of Titan's coupled ocean-atmosphere system and interaction of ocean with bedrock. In *Ices in the Solar System*, J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski (eds.), D. Reidel (Publ.), Dordrecht, 741-757.

Lunine, J.I., and Stevenson, D.J. (1987) Clathrate and ammonia hydrates at high pressure: application to the origin of methane on Titan. *Icarus* **70**, 61-77.

Lunine, J.I., Atreya, S.K., and Pollack, J.B. (1989) Present state and chemical evolution of the atmospheres of Titan, Triton, and Pluto. In *Origin and Evolution of Planetary and Satellite Atmospheres*, S.K. Atreya, J.B. Pollack, and M.S. Matthews (eds.), The Univ. of Arizona Press, Tucson, 605.

Muhleman, D.O., Grossman, A.W., Butler, B.J., and Slade, M.A. (1990) Radar reflectivity of Titan. *Science* **248**, 975-980.

Sagan, C., Khare, B.N., and Lewis, J.S. (1984) Organic matter in the Saturn system. In *Saturn*, T. Gehrels and M.S. Matthews (eds.), Univ. of Arizona Press, Tucson, 788-807.

Samuelson, R.E. (1994) Methane supersaturation in Titan's atmosphere. *Bull. Am. Astron. Soc.* **26**, 1183.

Stevenson, D.J. (1992) Interior of Titan. *ESA SP-***338**, ESTEC, Noordwijk, The Netherlands, 29-33.

Y.L., Allen, M., and Pinto, J.P. (1984) *Astrophys. J. Supp.* **55**, 465-506.