Titan from Cassini-Huygens

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Front cover figure: This false-color image of Titan is a composite of data taken by the Cassini RADAR instrument and the Cassini VIMS instrument with special emphasis on showing Titan's surface features.
Credit: U.S. Geological Survey, University of Arizona and NASA JPL, by Laurence Soderblom and Randy Kirk (Cassini RADAR) and Jason W. Barnes (Cassini VIMS)

Back cover figure: [text to be provided by Bob Brown]
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Preface

This book is one of two volumes meant to capture, to the extent practical, the scientific legacy of the Cassini–Huygens prime mission, a landmark in the history of planetary exploration. As the most ambitious and interdisciplinary planetary exploration mission flown to date, it has extended our knowledge of the Saturn system to levels of detail at least an order of magnitude beyond that gained from all previous missions to Saturn.

Nestled in the brilliant light of the new and deep understanding of the Saturn planetary system is the shiny nugget that is the spectacularly successful collaboration of individuals, organizations and governments in the achievement of Cassini–Huygens. In some ways the partnerships formed and lessons learned may be the most enduring legacy of Cassini–Huygens. The broad, international coalition that is Cassini–Huygens is now conducting the Cassini Equinox Mission and planning the Cassini Solstice Mission, and in a major expansion of those fruitful efforts, has extended the collaboration to the study of new flagship missions to both Jupiter and Saturn. Such ventures have and will continue to enrich us all, and evoke a very optimistic vision of the future of international collaboration in planetary exploration.

The two volumes in the series Saturn from Cassini–Huygens and Titan from Cassini–Huygens are the direct products of the efforts of over 200 authors and co-authors. Though each book has a different set of three editors, the group of six editors for the two volumes has worked together through every step of the process to ensure that these two volumes are a set. The books are scholarly works accessible at a graduate-student level that capture the approximate state of knowledge of the Saturn system after the first 4 years of Cassini's tenure in Saturn orbit. The topics covered in each volume range from the state of knowledge of Saturn and Titan before Cassini–Huygens to the ongoing planning for a return to the system with vastly more capable spacecraft.

In something of a departure from the norm for works such as these, we have included an appendix in each of the books featuring the people of Cassini–Huygens who are truly responsible for its success – the people behind the scientific scenes who ensure that everything works as flawlessly as it has. We dedicate the Cassini–Huygens volumes to them and to those who started the journey with us but could not finish it. We hope that all who read the books will share in the new knowledge and gain a deeper appreciation for the tireless efforts of those who made possible its attainment.

The Editors: Bob Brown, Michele Dougherty, Larry Esposito, Stamatios Krimigis, Jean-Pierre Lebreton and J. Hunter Waite

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Robert H. Brown, Jean-Pierre Lebreton, and J. Hunter Waite

1.1 Introduction

This book is the one of two volumes meant to capture the main scientific results of the Cassini–Huygens prime mission. The first book, *Saturn from Cassini–Huygens*, contains the material pertinent to Saturn, its satellites and its magnetosphere, except its largest moon Titan. This book, *Titan from Cassini–Huygens* is meant to capture the main scientific results regarding Titan, including its origin and evolution, interior, surface, atmosphere and interaction with Saturn's magnetosphere. The reason we have chosen to treat the results for Titan in a separate volume is that at the time of publication of this book, the Cassini spacecraft has flown by Titan some 62 times, including delivering the Huygens probe, which successfully landed on Titan's surface and survived for over 2 hours, transmitting a wealth of data on Titan's atmosphere and surface. The scientific results obtained for Titan are so voluminous that they cannot be properly captured as part of the "Saturn from Cassini–Huygens" volume and require a separate volume; thus, the two books.

Because there exists a three-volume series of books written prior to Cassini–Huygens' arrival in the Saturn system, that describe in great detail the Cassini Orbiter spacecraft, its science instruments and investigations, the Huygens probe and its science instruments and investigations, and the overall design of the Cassini–Huygens mission to Saturn, we will not attempt to repeat any of that material here. Instead the reader is referred to those volumes (2002, 2004a, b). We do, however, include sections in this book describing the details of the Cassini–Huygens orbital tour as it was executed through the Cassini prime mission, the Cassini Equinox mission, and the plans for the Cassini Solstice mission, because very little of that material was described in the previous volumes.

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1.2 Organization

This volume is divided into eight main sections. The first section is introductory material, including this chapter and a chapter describing knowledge of the Saturn system prior to Cassini–Huygens' and as seen from the ground. The second section deals with "bulk" Titan and contains two chapters covering Titan's origin and its interior structure. The third section covers Titan's surface, and contains two chapters describing Titan's geology and the composition of its surface. The fourth section is devoted to Titan's global systemic evolution, and contains three chapters relating to the origin and evolution of Titan's volatiles, the conversion of nitrogen and methane in Titan's atmosphere to complex polymers, and the astrobiological considerations related to Titan's evolution as a chemical system. The fifth section covers Titan's atmosphere and ionosphere, and features five chapters covering the composition and structure of Titan's atmosphere, the composition and structure of Titan's ionosphere and thermosphere, Titan's aerosols, its atmospheric dynamics and meteorology, and its seasonal cycles. The sixth section deals with Titan's magnetospheric interactions and contains two chapters covering mass-loss processes and energy deposition in Titan's upper atmosphere. The seventh section is dedicated to an exposition of the exploratory plan for Titan. It contains two chapters, one covering the past, present and future plans for Cassini's exploration of Titan, and the other discussing plans for returning to the Saturn system with new and more capable spacecraft. The final section contains Cassini-related cartographic products for Titan and a chapter depicting people who worked behind the scenes for Huygens.

Please note that what follows below is our attempt to summarize the main results that are covered in much greater

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detail in this book. The reader should assume attribution of these synopses to each of the chapters covered as part of each section below.

1.3 Synopses of the Main Results for Titan

1.3.1 Origin, Evolution and Interior (Chapters 3 and 4)

Titan likely formed in a disk of material around Saturn as a regular satellite, but it is very different than its smaller siblings in size, mass, and abundance of rock, possibly suggesting it formed in an accretion disk less massive than the disk around Jupiter from which it is thought the Galilean satellites formed. The outermost layers of primordial Titan probably consisted of water ice mixed with a small amount of ammonia, and heat from Titan's formation likely melted that layer, resulting in a transient surface of water-ammonia liquid in contact with organic molecules. The composition of Titan's atmosphere as determined by Cassini–Huygens suggests that NH_3 liberated from Titan's interior is the source of Titan's atmospheric molecular nitrogen.

Measurements of $^{13}C/^{12}C$ in hydrocarbon molecules in Titan's atmosphere indicate that the bulk of Titan's primordial carbon survived massive escape during Titan's thick-primordial-atmosphere phase, whereas measurements of $^{15}N/^{14}N$ indicate mild to major escape during the same phase. Measurements of $^{40}K/^{40}Ar$ strongly suggest that Titan has outgassed volatiles throughout its history, notably methane and argon.

To date, Cassini measurements have not detected a Titanian magnetic field, thus the actual level of differentiation of its interior is uncertain. Nevertheless, Cassini measurements have spurred the construction of new models of Titan's interior structure and evolutionary history. These models suggest that Titan is at least partially differentiated with a silicate core, a water-rich mantle, and an internal ocean a few tens of kilometers below the surface. Titan's orbit has a relatively high eccentricity, implying low tidal dissipation in its interior, suggesting that its ice crust is cold and that the putative ocean under the ice layer contains ammonia. If this ocean indeed exists and is composed of a mix of water and ammonia, it is probably separated from the core by a layer of high-pressure ices. The obliquity of Titan derived from Cassini images of Titan, however, implies an unreasonable internal structure if Titan is in a Cassini state, and this issue has yet to be resolved.

1.3.2 Surface (Chapters 5 and 6)

Observations of Titan's surface gleaned primarily from measurements by the RADAR, VIMS and ISS instruments reveal that Titan has a complex surface morphology, having many features in common with other icy satellites, many features in common with the Earth and some that seem unique to Titan. Titan has an extremely young surface, constantly modified by aeolian, pluvial, fluvial, lacustrine, cryovolcanic and tectonic processes, all in dynamic interplay, resulting in a surface composition and morphology unique in the solar system.

Displaying a wide variety of geologic features on all size scales sampled by the Cassini data, Titan's surface shows evidence of impact cratering, fluvial erosion resulting from a hydrological cycle similar to that of the Earth but driven by liquid methane, aeolean features driven by a thick and dynamic atmosphere, and tectonic and cryovolcanic features driven by heat escaping from Titan's interior and expressed in a material that is probably water ice mixed with ammonia, carbon dioxide and methane. Titan also has an apparent surficial modification process that is so far unique in planetary exploration experience. Its terrain is apparently being "veneered" by a slow and steady "rain" of complex-organic particles, producing (in most cases) a dramatically different appearance when viewed in radar versus optical wavelengths. Titan thus has a very active surface, constantly being modified by exogenic and endogenic processes.

Titan's surface shows a fair amount of topography. Relief ranges from a few tens to a couple of hundred meters in the region of the Huygens landing site, mountains on Titan range from a few hundred to a couple of thousand meters, and there are a number of regions on Titan interpreted as lakebeds whose depths range from a few tens to a few hundreds of meters. A general relationship seen on Titan is that bright units are topographically high while darker units are topographically low.

Titan shows a number of geological features interpreted as being tectonic or volcanic in origin. Features thought to be tectonic seem to be expressed as long, linear features that are chains of hills and/or tectonic ridges, modified by ongoing geological processes such as erosion and deposition. Features on Titan interpreted as volcanic in origin are globally widely distributed but, so far, small in number. Three major areas interpreted to have volcanic morphologies are Hotei Arcus, Tui Reggio and Ganesha Macula (although the cryovolcanic interpretation for the origin of Ganesha Macula has recently been called into question). There are a number of smaller features on Titan sometimes controversially interpreted as volcanic in origin, among which are clusters of quasi-circular depressions with raised rims that in many cases are thought to be volcanic calderas.

Erosional and depositional features are ubiquitous on Titan. Vast fields of dunes abound in Titan's equatorial regions, and are thought to be composed of millimeter to sub-millimeter complex-organic particles, driven by winds into low-lying areas. Their mere existence implies a large source of organic particles that is poorly understood. Other erosional features, most likely driven by fluid flow, manifest themselves as vast, dendritic channel systems, cutting across almost all types of terrains on Titan. Some of the channel systems have rough, radar-bright floors suggesting that they are dry, while others have smooth, radar-dark floors, suggesting that some may contain liquids. The morphology of the channels suggests that they have been cut through steep terrain by precipitation-driven fluid flow. Liquid methane has been suggested as the fluid responsible for the bulk of the fluvial features on Titan, and studies of its hydrological properties suggest that it could plausibly move enough material under conditions present on Titan to account for most of Titan's fluvial features.

In addition to erosional and depositional features, the idea that Titan has an active hydrological cycle is supported by the widespread presence in Titan's northern, high latitudes of apparent lakes, presumably composed of liquid methane, ethane and other simple hydrocarbons. Though it is thought that lakes on Titan are at least partially seasonal in nature, whose changes are driven by seasonal volatile transport between Titan's polar regions, lake-like features are also seen in Titan's south-polar regions, at least one of which (Ontario Lacus) has been shown to contain liquid ethane.

Impact craters, a central feature of the geology of icy satellites, exist on Titan too, but they are small in number, and only a few have been positively identified. Titan's thick atmosphere may have prevented smaller impactors from reaching Titan's surface, but cannot be responsible for the lack of larger impact craters seen on Titan, suggesting that many craters have been removed by erosion, burial, or relaxation, further arguing that Titan has a young surface, perhaps no older than 500–1000 million years.

For obvious reasons, the geology of areas at and near the Huygens landing site has been the subject of much study. No liquid was seen near the Huygens landing site, but there is abundant evidence of fluvial activity. There are complex systems of channels cut into brighter, presumably highland materials, draining into an area that is darker and smoother, and is perhaps a large, dry lake bed. The lake bed, if that it is what it is, seems much too large to have been fed by the observed, neighboring channels, and perhaps is the geological remnant of a much wetter period in Titan's history or of catastrophic flooding. Cobbles seen in what is thought to be a stream bed near where the Huygens probe landed are strongly suggestive of past fluid flow, and channel systems of various morphologies suggest fluid flow driven by precipitation and/or springs. Overall, the geology of the Huygens landing site is strongly suggestive of fluvial erosion and deposition.

Titan's thick atmosphere, with its complement of methane and nitrogen gases, both spectrally active in the near infrared where surface-composition measurements from reflected light enjoy their greatest efficacy, has made determination of the composition of Titan's surface problematic under the best of conditions. The most detailed and accurate understanding of the composition of one small area on the surface of Titan comes from the measurements of the Huygens probe immediately before and after it landed. It detected small amounts of ethane, and perhaps benzene, cyanogen, and carbon dioxide, possibility liberated by heat transferred to the soil by the probe when it landed. The most plausible interpretation of infrared spectroscopy of the surface near the probe landing site is that Titan's surface is composed of a mix of hydrocarbons, nitriles and water ice. Though controversial, one interpretation of infrared spectroscopy of Titan's surface by the VIMS instrument is that the darker units on Titan are a mixture of water ice and organics, while the bright units are mostly hydrocarbons mixed with little or no water ice. Color measurements using three bands in the infrared centered on Titan's near-infrared atmospheric windows show that there are three main compositional units on Titan, the so-called "dark brown", "dark blue" and "bright" terrains. The dark brown units correlate very strongly with the extensive dune material seen in radar images of Titan's equatorial regions, and a simple interpretation of the difference between the dark-blue and dark-brown units on Titan is the presence of a somewhat greater amount of water ice in the dark-blue materials (although this interpretation has been challenged).

Images of Titan obtained in Titan's 5-μm atmospheric window show a few, large areas with a high reflectance relative to the bulk of Titan's surface, which is otherwise quite dark in this wavelength region. Carbon dioxide or cyanoacetylene have alternatively been proposed as the agent responsible for the high reflectance, but both interpretations have problems when the reflectance of the 5 μm-bright-areas is analyzed in detail in other wavelength regions. Other materials proposed to be widespread on Titan's surface based on possible absorption features seen in infrared spectra are benzene, liquid methane and liquid ethane, possibly arising from atmospheric sources.

That organics are ubiquitous and compositionally dominant on Titan, possibly to a depth of several meters, is supported by both infrared and radar measurements. Passive microwave radiometry indicates that there are few or no exposures of bare water ice on Titan, except perhaps in the bottom of Sinlap crater. Radar radiometry supports the idea that most, if not almost all, of Titan's surface is "veneered" with a layer of organics.

Finally, Titan's lake-like features are arguably some of the most interesting components of the global array of compositional and geological units on Titan. Synthetic aperture radar images and passive microwave radiometry strongly suggest that most of Titan's lake-like features exist in Titan's high northern latitudes, and are filled with an organic liquid. Infrared spectroscopic measurements of Ontario Lacus, the largest lake-like feature known in Titan's apparently lake-poor southern polar regions indicate that the surface of Ontario Lacus is extremely smooth, and at least one component of the material in Ontario Lacus is liquid ethane, probably in solution with liquid methane and other light organics.

1.3.3 Volatiles (Chapters 7–9)

Measurements of the abundance of primordial argon and the abundance ratios of the stable isotopes of nitrogen and carbon are particularly important in understanding the origin and evolution of Titan's atmosphere. If Titan's nitrogen were originally in the form of molecular nitrogen captured from the pre-planetary nebula, the abundance of ^{36}Ar relative to N_2 should be about 11%, but Huygens' measurements show that it is rather about 6 orders of magnitude lower, strongly suggesting that Titan's nitrogen was incorporated originally as ammonia (NH_3) and was subsequently produced by photolysis of NH_3 by solar UV.

Titan's atmospheric $^{14}N/^{15}N$ ratio as measured by Huygens is roughly 2/3 that of the terrestrial value, suggesting preferential escape of ^{14}N from Titan's atmosphere due to the slightly higher average thermal velocity of lighter molecules. Assuming that Titan's $^{14}N/^{15}N$ started near the terrestrial value, and that the observed isotopic ratios are result of massive atmospheric escape, Titan's early compliment of nitrogen could have been 2–10 times larger than present.

As a result of Huygens' measurements of noble gas abundances in Titan's atmosphere, there are two leading hypotheses for the origin of methane on Titan. One hypothesis is that methane was delivered as part of the material out of which Titan formed. Nevertheless, the low Ar abundance and the non-detection of Xe and Kr by Huygens, argue against Titan's methane being delivered as part of the original material out of which Titan formed, unless the low noble-gas abundances are the result of some process that has sequestered most of those gases in the interior of Titan. An alternative hypothesis involves serpentization, a process where hydration of silicate minerals liberates hydrogen which then reacts with carbon compounds such as CO and CO_2 to form methane; which, if either, of these processes is responsible has yet to be resolved.

Regardless of its ultimate origin, methane is the second most abundant constituent of Titan's atmosphere, and without the greenhouse heating provided by the methane, Titan's atmosphere would condense. Methane has a distinct meteorological cycle in Titan's troposphere, and photolysis destroys methane irreversibly in its stratosphere and ionosphere. Thus, the long-term presence of methane in Titan's atmosphere implies a source, probably episodic outgassing from Titan's interior at levels where it can again become a greenhousing agent and participate in photochemistry.

The meteorological role of methane in Titan's atmosphere is similar to that of water vapor on the Earth. Sub-saturated parcels of air convectively ascend to a level in the atmosphere where the condensable species saturate and condense. Clouds then form, and the condensable material rains out of the atmosphere and wets the surface, where the condensable may then be heated, re-evaporate and start the whole process again. Such considerations for Titan indicate that methane rainfall in Titan's equatorial regions would be less than 10 cm per year on average (equivalent to a terrestrial desert). On 100- to 1,000-year timescales, large storms could form, and thus transient, localized rainfall could be much larger. As on the Earth, greater precipitation is expected in the polar regions; the presence of lakes existing mostly above about 80°N on Titan, combined with a 2–4 K equator-to-pole temperature difference supports this. The even larger temperature difference between summer and winter poles, suggests that seasonal changes on Titan should result in pole-to-pole circulation of large amounts of methane on time scales of 10–100 years.

Photolysis of methane combined with rapid escape of the liberated hydrogen causes irreversible loss of Titan's atmospheric methane. Assuming that Titan's atmospheric methane has been periodically replenished over its lifetime, the results of 4.5 billion years of photochemistry on Titan probably have had a profound effect on the composition, appearance and rheology of its surface materials. One major photochemical product is ethane, but its production as an end product occurs at far lower levels than previously thought. Much of the ethane is converted to heavier hydrocarbons, which materials probably compose the many aerosol layers in Titan's atmosphere.

Complex organic chemistry has been occurring in Titan's atmosphere since its formation, producing a wide variety of molecules, including complex macromolecular material similar to laboratory tholins. On Titan's surface exchange processes with the atmosphere and the sub-surface can occur, allowing macromolecular material to further evolve. For example, hydrolysis could produce a wide variety of organics and oxygenated compounds, including many of biological interest, such as amino-acids and urea. Titan's lakes may also play an important astrobiological role because they could accumulate and concentrate important macromolecular species. Additional energy sources such as cosmic rays could allow macromolecules to chemically evolve in a lake. Such chemical evolution may also occur in Titan's sub-surface ocean where early conditions inside Titan could foster the development of prebiotic chemistry and the possible emergence of life.

1.3.4 Atmosphere (Chapters 10–14)

CH_4, the second most abundant molecule in Titan's atmosphere, has an abundance of 5% near the surface, falling to 1.4% in the stratosphere, and increasing again to 12% at Titan's exobase. Titan's troposphere has a well defined tropopause and a stable lower stratosphere with high static stability. The lower stratosphere is cold over the winter pole and warm over the summer pole, while in the middle stratosphere, the temperatures are highest at the equator. Temperature profiles of Titan's atmosphere above 500 km altitude are essentially isothermal at ~170 K with 10 K thermal waves superimposed. It is not clear whether Titan has a mesopause.

CH_4 photolysis in Titan's thermosphere, catalytic reactions in its stratosphere, and dissociation of N_2 by UV and charged particles produce C_2H_6 and HCN as the dominant hydrocarbon and nitrile, respectively. Most photochemical products (except ethylene) increase with altitude at equatorial and southern latitudes, indicative of transport from a high-altitude source to a condensation sink in the lower stratosphere. Northward of 45°N, most atmospheric products are enriched as a consequence of subsidence in the winter polar vortex, particularly for nitriles and more complex hydrocarbons than C_2H_6 and C_2H_2. North of 45°N, most products have smaller increases with altitude than at low latitudes.

Titan has a substantial ionosphere even at altitudes below 1,000 km, and a rich and complex ion-neutral chemistry exists in both Titan's ionosphere and thermosphere. Titan's ionosphere hosts a very large number of ion species, both predicted and unpredicted, including the exciting discovery of negative ions. Reactions driven by solar extreme ultraviolet, x-rays, and energetic magnetospheric electrons drive a complex chemistry that has important effects all the way to Titan's lower atmosphere. Cassini measurements confirm that molecular nitrogen and methane are the major components of Titan's ionosphere and thermosphere, as well detecting molecular hydrogen, acetylene, ethylene, benzene, and propane. Cassini measurements show that electron densities and temperatures significantly exceed the temperature of neutrals in Titan's ionosphere.

Huygens measurements of the average properties of aerosols in Titan's atmosphere show the typical aerosol particle to be an aggregate of much smaller particles (monomers) roughly 50 nm across. Calculations indicate that the average haze particle in Titan's atmosphere is composed of about 3,000 monomers whose radius by equivalent-spherical volume is 0.72 μm, whereas the radius of a spherical particle with the same projected area is 2.03 μm. Titan's aerosols are strongly forward scattering, and their vertical distribution generally falls off with altitude, but there are several "detached" haze layers between roughly 500 and 600 km altitude that are time variable both in latitude and altitude. There is speculation that such variations may be the result of wave phenomena in Titan's atmosphere, but modeling is required to determine whether such speculation is justified. Seasonal variations in Titan's haze distribution, seen in Voyager data are quite similar to what the Cassini instruments found between 2004 and 2008, supporting the idea that Titan's global circulation affects the distribution of aerosols.

Titan's atmosphere is in global cyclostrophic circulation, with a strong seasonal modulation in the middle atmosphere. There are zonal winds mostly in the sense of the satellite's rotation, and a strong, winter, circumpolar vortex with maximum winds of 190 m s^{-1} at mid northern latitudes near 300 km. Seasonal effects may be responsible for stratospheric zonal winds and temperatures being symmetric about an axis that is offset from Titan's rotation axis by about 4°, and subsidence may occur in the north-polar region during winter and early spring. Meridional contrast in tropospheric temperatures at all latitudes is ~5 K at the tropopause and ~3 K at the surface, implying axisymmetric meridional circulations and efficient heat transport. The effect of the methane "hydrological" cycle on the atmospheric circulation is not well understood.

Huygens' probe measurements show, zonal winds on Titan are eastward down to 7 km, then shift westward, and eventually shift eastward again below 1 km and down to the surface. Eastward winds at Titan's surface are consistent with Titan's equatorial dune fields occurring in a mean eastward zonal wind, but unlike those of the Earth which are westward above the surface.

Spacecraft and groundbased observations since the early 1980s suggest that Titan will soon enter a period of rapid seasonal change as its season moves from equinox toward northern summer. As seen from Earth, Titan should start to appear darker as the sub-solar point moves northward. The polar vortex is expected to break up, meridional circulation is expected to reverse, haze should move from Titan's northern hemisphere to its southern hemisphere, and cloud activity, with accompanying vigorous precipitation, all should occur as northern summer approaches. So far Cassini measurements have shown little evidence of the expected change, except perhaps for the disappearance of methane clouds seen over the south polar regions immediately after Cassini's orbital insertion, and the putative loss of some of Ontario Lacus' complement of liquid hydrocarbons. This is possibly not surprising because Cassini arrived during late southern summer on Titan. Nevertheless, Cassini is positioned with its Equinox and Solstice missions to obtain data which, when combined with diligent ground-based observations, will surely reveal exciting and interesting changes on Titan as we move toward its northern summer solstice on 2017.

1.3.5 Magnetospheric Interactions (Chapters 15 and 16)

As mentioned above, Titan's $^{15}N/^{14}N$ ratio suggests a large amount of atmospheric escape. There are several atmospheric escape processes that could have contributed to Titan's low $^{15}N/^{14}N$ ratio, among which are thermal escape, chemical-induced escape, slow hydrodynamic escape, pick-up-ion loss, ionospheric outflow and plasma-ion-induced atmospheric sputtering. Cassini data indicate that hydrogen liberated by photolysis of methane is escaping from Titan. Methane and nitrogen are also escaping from Titan at rate much larger than expected, and much larger than the measured ion loss rates, suggesting that much of the present atmosphere by now should have been lost to space. Slow hydrodynamic escape models seem unable to explain the large escape rates, and neither is the composition of the magnetospheric plasma at Titan's orbit consistent with the suggested maximum loss rates for carbon.

Solar UV, Saturn's magnetosphere, solar wind and galactic cosmic rays drive most of Titan's atmospheric chemistry, aerosol formation, and atmospheric loss, with solar UV dominating at lower altitudes (roughly from about 1,200–400 km), while magnetospheric plasma interactions are more important higher in Titan's atmosphere (~1,400 km). Heavy ions can penetrate below 950 km and cosmic rays (>1 GeV) deposit most of their energy around 70 km. Titan has an induced magnetic field resulting from its interaction with Saturn's magnetosphere which channels energy into Titan's upper atmosphere. Saturn's magnetosphere displays large and systematic changes with local time driving significant changes in the character of the interaction with Titan depending upon Saturn local time. Sub-storms in Saturn's magnetosphere caused by the solar wind can, in turn, modify the magnetospheric interaction with Titan. Energy input from a number of interactions of Titan's atmosphere with Saturn's magnetosphere likely produces large positive and negative ions below ~1,100 km altitudes, some of which have masses exceeding 10,000 Da, and which may act as seed particles for the aerosols observed below 1,000 km altitude. These aerosols likely fall to Titan's surface as polymerized hydrocarbons with trapped free oxygen, possibly participating in a range of, as yet unknown, chemical interactions.

1.4 Open Questions

Chapters 17 and 18 relate both present and future plans for Cassini observations of Titan and concept studies for a return to the Saturn system with in-depth exploration of Titan using an orbiter, balloons and landers. At the time of writing of this chapter, Cassini is executing its Equinox Mission, and the Cassini Solstice Mission, which is in the planning stages, and is likely to be approved for funding soon, carrying with it the future prospect of much deeper and more comprehensive studies of Titan and the Saturn system. Nevertheless, there will be a large number of questions left unanswered, which is as it should be, since diligent scientific inquiry always raises more questions than it answers. Thus, the final section of this chapter will list a few of the major, open and un-answered questions that will likely remain after the Cassini Solstice Mission is finished. The list is not meant to be exhaustive (the reader is referred to the individual chapters for more complete discussions of such), but rather to provide the reader with a taste of the questions to be addressed by future missions and analysis of data.

1.4.1 Titan's Interior

1. How thick is Titan's ice crust?
2. Why are Xenon and Krypton not in Titan's atmosphere? Where are they?
3. Does Titan have a sub-surface ocean and how is its presence expressed in Titan's surface features or composition?
4. Where is the ammonia?

1.4.2 Titan's Geology and Surface Composition

1. What do volcanic, tectonic, and erosional/depositional features look like at optical wavelengths and at spatial resolutions of ~50 m/pixel or better?
2. What is Titan's global topography, especially around volcanoes and tectonic features?
3. What are the details of organic chemistry taking place on Titan's surface, and has Titan's surface hosted pre-biotic chemical evolution?

1.4.3 Titan's Volatiles

1. What is the origin of Titan's methane, how is it destroyed and how does it cycle through Titan's surface, atmosphere and interior? What is D/H in the surface H2O ice, $^{16}O/^{18}O$ in CO, CO2 and H2O, $^{36}Ar/^{38}Ar$, $^{12}C/^{13}C$ in CO, CO2 and surface organics? What are the abundances of Xe and Kr to at least the 10^{-10} mole fraction precision in the atmosphere and in the surface material?
2. What are the processes and pathways producing complex organic molecules in vapor, liquid and solid phases from high in Titan's ionosphere down to its surface?
3. What is detailed composition of the liquids and sediments in the lakes? How have the lakes evolved with time?
4. How do episodic events such as cryovolcanoes, fumaroles and impacts affect Titan's surface and atmosphere?
5. If Titan has a sub-surface ocean, what is its nature and astrobiological potential? Does it communicate with the surface through volcanic or tectonic processes?

1.4.4 Titan's Atmosphere and Ionosphere

1. What is the higher-mass, ion chemistry in Titan's ionosphere and how is it linked to aerosol formation?
2. What are the sources or sinks of negative ions?
3. How are higher order hydrocarbon species such as benzene formed, and what are their roles in aerosol formation, and in both neutral and ion chemistry?
4. What is the composition of Titan's aerosols, how are they formed, and what are their distributions in time and space on Titan?
5. Are stratospheric condensates important in Titan's atmosphere? What physical, chemical, and dynamical processes are important in the mesosphere above 400 km?
6. What happens to the polar vortex when the winter hemisphere moves into summer? What drives the global super-rotation on Titan? Are there planetary-scale waves on Titan? Is there really a methane hydrological cycle on Titan and do the "lakes" migrate seasonally?

1.4.5 Titan's Magnetospheric Interactions

1. What are the dominant processes responsible for atmospheric escape on Titan and what is the true escape rate?
2. As Saturn and Titan progress from southern summer to equinox, how do the various energy input processes evolve?
3. How do Enceladus' plumes affect Saturn's magnetosphere, especially if their water-vapor output varies with time?
4. How does the chemistry being driven by magnetospheric interactions changes in Titan's upper atmosphere with time and season?

The questions above are but a small subset of important questions identified in the various chapters of this book. It is hoped that they will whet the reader's appetite for the feast of knowledge that waits in the pages that follow.

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Chapter 2
Earth-Based Perspective and Pre-Cassini–Huygens Knowledge of Titan

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Abstract This chapter sets the scene for the current investigation of Titan with Cassini–Huygens, by reviewing the steps that took us there, from the first glimpses through a small telescope to the satellite observations passing by the first hints of an atmosphere about a 100 years ago.

2.1 Context/Introduction

Titan, Saturn's biggest moon, and (by a narrow margin) the second in size among the satellites in our Solar System, was discovered in 1655 and has ever since attracted a lot of attention among scientists and public alike. It has been known for a century now that Titan has a substantial atmosphere. Catalan astronomer José Comas Solà claimed in 1908 to have observed limb darkening on Titan (Comas Solá 1908). Confirmation came from spectroscopic observations by Gerald Kuiper in the 1940s, leading to the discovery of methane (Kuiper 1944), but it was not until the Voyager 1 spacecraft visited Titan in 1980 that the dominantly nitrogen-methane composition and 1.5 bar surface pressure were established. Furthermore, complex organic chemistry is active there, producing multiple layers of orange-colored haze, which render the atmosphere opaque in the optical range of wavelengths. It took a long time and a lot of effort to get a glimpse of the surface, and ground-based observations played a significant role in defining what we know today to be quite a complex landscape.

To address the many questions asked about Titan over the centuries since its discovery, a series of space probes was developed and dispatched towards this intriguing body. Pioneer 11 arrived first, in 1979, followed by Voyager 1 a year later. The scientific understanding of Titan as a planet-like object that emerged from the analysis of Voyager data was improved by ongoing Earth-based observations, using increasingly more powerful optical and spectroscopic techniques, such as radar and adaptive optics, and advanced platforms on Earth-orbiting space observatories. At the same time, new theoretical models were being developed to account for these observations, new theories proposed and debated, and old or repeated measurements re-analyzed.

The latest envoy to Titan, a large and sophisticated international space mission called Cassini–Huygens, was launched in the year 1997. It arrived in July 2004, and started gathering new measurements from an orbit around Saturn that was designed to permit multiple Titan encounters. The Huygens probe descended in Titan's atmosphere on January 14, 2005 and recorded breathtaking data, revealing an intriguing new world, and the most distant one to be landed on by a human-made machine.

2.2 Early History of Titan Observations and First Interpretations

The story of the first detection of Titan is a classic of its kind. On the night of March 25th, 1655, a novice Dutch astronomer, Christiaan Huygens, pointed his telescope at Saturn. According to his notes, Huygens (1659) saw a small star 3 arc minutes away from the planet and almost immediately guessed it was a satellite. He confirmed his guess a few days later when the 'star' had moved. Titan was soon realized to be a sizeable object. Huygens believed Titan to be the biggest satellite of all, and that is the reason for the name it was given, following a proposition by Herschel (Herschel 1847). In Greek mythology, the Titans were brothers and sisters of Kronos, the Greek equivalent of the Roman god Saturn. In that same publication, Herschel named the six other then-known moons of Saturn after individual Titans.

After Solà's claims of having observed an atmosphere around Titan in 1908, James Jeans decided in 1925 to include Titan and the biggest satellites of Jupiter in his theoretical study of escape processes in the atmospheres around solar system objects. His results (Jeans 1931) showed that Titan could have kept an atmosphere, in spite of its small size and weak gravity, if low temperature conditions — that he evaluated as between 60 and 100 K — prevailed. In this case, a

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gas of molecular weight higher than or equal to 16 could not have escaped Titan's atmosphere since the satellite's formation. Jeans' calculations demonstrated that some of the lighter gases such as hydrogen and helium should have escaped, but that several constituents could have been present in non-negligible quantities in the mix of gas and dust particles that condensed to form the Solar System and could have been retained by Titan. The thermodynamical theory of gases then points toward ammonia, argon, neon, molecular nitrogen and methane. Ammonia (NH_3) is solid at the estimated Titan temperature and could therefore not substantially contribute to its atmosphere. The others, however, are gaseous within this same temperature range. Methane (CH_4), unlike argon, neon and molecular nitrogen, exhibits strong absorption bands in the infrared spectrum, which make it relatively easy to detect.

The first formal proof of the existence of an atmosphere around Titan came in 1944, when Gerald Kuiper observed Titan with the new McDonald 82-in. telescope and discovered spectral signatures on Titan at wavelengths longer than 0.6 μm (microns), among which he identified two absorption bands of methane at 6190 and 7250 Å (Kuiper 1944). This discovery was significant not only because it requires a dense atmosphere with a significant fraction of methane, but also because the atmosphere needs to be chemically evolved, since methane requires hydrogen in the presence of carbon, and molecular and atomic hydrogen would have escaped from Titan's weak gravitational field since the formation of the solar system. By comparing his observations with methane spectra taken at low pressures in the laboratory, Kuiper (1952) derived an estimate of the amount of methane on Titan of 200 m-amagat. It was more than a factor 10 less than the current known CH_4 column density, however, not that far off when the one considers that the solar light is reflected by the haze. Kuiper searched for similar behavior in the spectra of other Saturnian satellites, but his data, obtained in 1952, did not show the methane bands. Kuiper concluded that Titan was a unique case in the Saturnian system due to the presence of an atmosphere, of a composition such that it gave the satellite an orange color.

In the years that followed, in spite of much interest, it proved difficult to make significant further progress in exploring or comprehending Titan's atmosphere.

2.3 Pre-Voyager Observations and Predictions

The pre-Voyager and Voyager observations are thoroughly discussed in Hunten et al. (1984) and Owen (1982), and will be summarized here. Until the 1970s, few significant advances were made in the study of Titan, but from 1972 to 1979 a number of scientists concentrated their efforts on seeking a better estimate for the methane abundance and the surface pressure, using observations made in the 1-to-2 μm infrared spectral region. Limb darkening was finally unambiguously observed (Elliot et al. 1975), consistent with an optically thick atmosphere. Radio and infrared measurements indicated ground temperatures that ranged from 165 to 200 K (Low 1965; Gillett et al. 1973; Briggs 1974).

At about this time, Trafton (1972a, 1975) announced the identification of a spectral absorption feature of molecular hydrogen, H_2, on Titan, for which he evaluated an abundance of 5 km-amagat (Fig. 2.1). Kuiper (1952) had already pointed out that a body as small as Titan could not retain hydrogen, and therefore Trafton's discovery clearly pointed to the presence of another gas which would inhibit H_2 escape. Introducing the idea of "limiting flux", Hunten (1973a,b) considered the possibility of methane or nitrogen as the major gas (the latter, which is the correct one, was considered following an idea first voiced by Lewis (1971)).

Trafton (1972b) further conducted observations of the $3\nu_3$ spectral band of methane at 1.1 μm, in which he found an unexpected strong absorption, indicating either a methane abundance at least 10 times higher than that inferred by Kuiper, or a broadening of the CH_4 bands induced by collisions with molecules of another, as yet undetected, but quite abundant, gas in the atmosphere. In either case, the intensity of the absorption band is a function of the methane abundance and of the local atmospheric pressure. By comparing the weak absorption bands of methane in Titan's visible spectrum with spectra of Jupiter and Saturn, in which these bands have almost identical absorption strengths, Lutz et al. (1976) derived from Trafton's measurements a 320 m-amagat abundance for methane, and an estimate for the effective pressure on Titan of about 200 mbar. The immediate consequence of this result was that methane turned into a minor atmospheric component, since even 1.6 km-amagat (Trafton's highest estimate) could only correspond to a partial pressure of methane of 16 mbar.

In spite of much effort directed at the detection of NH_3, the observers of the time failed to produce more than upper limits, which got lower and lower with successive measurements, suggesting that if any of this gas existed on Titan it must either have been photodissociated, with subsequent production of N_2 and H_2, or else trapped on the surface as ammonia ice.

All of the above led to a model (completed by Hunten (1977)), which started with the assumption that dissociation of ammonia should produce molecular nitrogen, which is transparent in the visible and infrared spectrum, in large quantities. In this model the surface temperature and pressure would be quite high (200 K and 20 bar). These high temperatures on the ground could be explained by a pronounced greenhouse effect, resulting essentially from

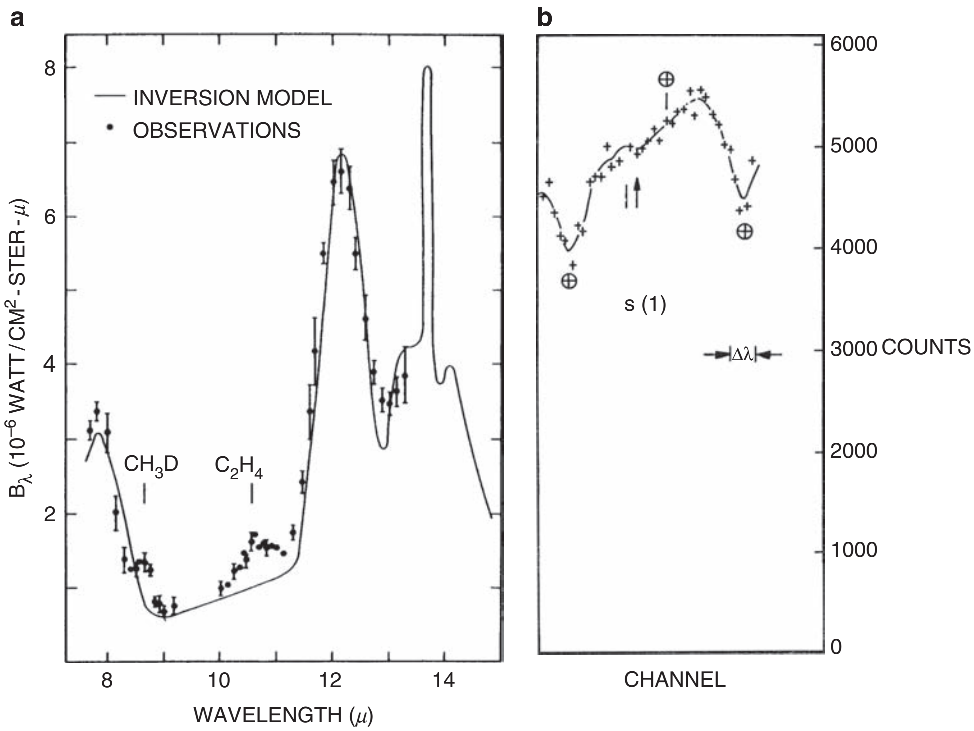


Fig. 2.1 Examples of first pre-Voyager detections of Titan's atmospheric components and models (Gillett et al. 1973 – left – and Trafton 1972a, 1975 – right —). CH_3D and C_2H_4 spectral signatures are identified in the Gillett spectra covering the thermal infrared range. In the example of the spectra obtained by Trafton, the absorption caused by the 3-0 S(1) line of H_2 at 8150.7 A is indicated by an arrow.

pressure-induced opacity in hydrogen at wavelengths longer than 15 μm (Sagan 1973; Pollack 1973).

However, the greenhouse effect was put to the test when Danielson et al. (1973) observed very low UV albedo which implied the presence of an absorbing haze. More detailed photometry (Harris 1961) identified the material composing the haze as red and UV absorbing. Polarization measurements indicated that this material is distributed as a thick layer around Titan (Veverka 1973; Zellner 1973). Indeed, the polarization sense of the reflected radiation was consistent with a deep atmosphere composed of thick haze layers, as opposed to a transparent atmosphere. Caldwell (1977) pointed out that this haze would cause significant heating of the middle atmosphere and lead to a warm stratosphere. These observations of Titan's low albedo and of the positive polarisation of the reflected light, then confirmed the presence of a thick, cloudy atmosphere, with the cloud particles present up to high altitudes. Sagan (1971) was the first to hypothesize that these layers might be composed of complex organic molecules, and this was subsequently backed up by experimental (Sagan 1973; Khare and Sagan 1973) and observational evidence. Indeed, Gillett et al. (1973) and Gillett (1975) found signatures in Titan's thermal emission spectrum not only of methane (CH_4), but also of ethane (C_2H_6) at 12.2 μm, monodeuterated methane (CH_3D, at 9.39 μm), ethylene (C_2H_4, at 10.5 μm) and acetylene (C_2H_2, at 13.7 μm), see Fig. 2.1, thus confirming the emitting stratosphere hypothesis and the chemical richness of this stratosphere. Theoretical considerations suggested that two sorts of aerosols were expected to co-exist in Titan's atmosphere: clouds of condensed CH_4, and a photochemical fog of more complex condensates. The latter would arise as a result of methane photolysis, that is, dissociation by sunlight, mostly at ultraviolet wavelengths. The fragments of methane, CH_2, CH_3 etc., combine, leading to the production of a variety of polymers that condense to form oily droplets. The quantities of organic molecules synthesized over geological time were estimated to be on the order of hundreds of g cm^{-2} (Sagan 1974; Hunten 1977; Chang et al 1979).

Just prior to the Voyager encounter, Jaffe et al. (1980) made radio telescope observations with the newly-completed Very Large Array in New Mexico, and obtained an emission temperature of the surface of 87 ± 9 K, a range that includes the modern value. This brightness temperature implied a surface temperature of about 90 K. They even suggested that conditions on Titan might support oceans of methane, an idea that was ahead of its time, but the paper failed to get the attention it deserved as it was published during the excitement of the Voyager encounter. Hunten (1978) applied the 90 K surface temperature to his model and derived a surface pressure of ~2 bar, which is fairly close to what Voyager found.

Therefore, a second model was in vogue prior to the Voyager encounter (Caldwell 1977), which favored methane as the main component (about 90%) of the atmosphere, and predicted surface conditions of T = 87 K at a pressure of 20 mbar, with a temperature inversion in the higher atmospheric levels, demonstrated by the presence of emission features of hydrocarbon gases in the infrared spectrum of Titan.

The majority of the pre-Voyager chemical models concentrated exclusively on hydrocarbons (Strobel 1974; Allen et al 1980) and, although there were several researchers (Lewis 1971; Hunten 1978; Atreya et al. 1980) considering the effect of a massive nitrogen atmosphere on these reactions, the first serious attempt at modeling Titan's atmospheric chemistry in the presence of N_2 was not made until 1982 (Strobel 1982).

Close examination of Titan's visible and near-infrared spectrum had already revealed at this time that the continuum absorption decreased with frequency, suggesting that the aerosol became more transparent at longer wavelengths. This led to the assumption that it might be possible, at certain frequencies in the near infrared, to probe all the way down to the satellite's surface. Fink and Larson (1979) thus produced the first characterization of the lower atmosphere and the surface of Titan by spectroscopic observations in what is now called the "methane windows" in the near-infrared (between 0.8 and 5 μm). At shorter wavelengths, and down to about 2,200 Å, the brightness stays nearly constant, suggesting that the aerosol is uniformly mixed at high altitudes. The measurements say little about the nature of the aerosols, their composition for example, but the fact that they are present in the atmosphere makes all attempts to interpret spectroscopic observations extremely dependent on assumptions about the haze properties.

2.4 The Voyager Mission to Titan

The previous section describes the situation before Voyager 1 flew by Titan in 1980. Voyager was not the first visitor from Earth to the Saturnian system, as the ringed planet had been visited by a small, unmanned Pioneer probe in 1979. The Pioneer 11 trajectory carried it across the orbit of Titan one day after its closest approach to Saturn, on September 2, 1979, at a distance from the satellite of 363,000 km. This was the first man-made object to enter the realm of Saturn, and it showed the way was safe for Voyager.

The Voyager 1 and 2 missions were launched in 1977. The Voyager 1 encounter with Saturn and Titan took place in November 1980, while Voyager 2 arrived in the Saturnian system in August 1981, some 9 months later. Although not without interest, the data relative to Titan obtained by Voyager 2 are not as extensive as those taken by Voyager 1, because the closest approach distance of Voyager 2 was more than 100 times greater. The closest approach of Voyager 1 to Titan took place on 12 November, 1980, at 6,969 km (4,394 miles) from the satellite's centre. The orbital plane of Titan was crossed from north to south, the spacecraft trajectory inclined with respect to the orbital plane at about 8.7°, at a speed with respect to the satellite of 17.3 km s^{-1}.

A very advanced machine for its era, the Voyager spacecraft carried 105 kg of scientific payload and was capable of operating with a high degree of autonomy at vast distances from the Earth thanks to a 3.7-km antenna used for telecommunication and radio science. For a detailed description of the Voyager missions see Stone and Miner (1981) and http://voyager.jpl.nasa.gov/index.html.

Each Voyager carried the same eleven scientific instruments, four of them mounted on the movable scan platform so they can be pointed at specific targets. The latter were the imaging experiment, consisting of boresighted narrow- and wide-angle cameras; the infrared interferometer spectrometer and radiometer (IRIS); the ultraviolet spectrometer (UVS); and a photopolarimeter-radiometer (PPR). Six other instruments were used to study fields, particles and waves in interplanetary space and near planets, including magnetometers, a plasma detector, a low-energy charged particle detector, a plasma wave detector, a planetary radio astronomy instrument, and a cosmic ray detector. In addition, the spacecraft's radio antenna provided radio scientific investigations (such as radio-occultations with the Radio Science Subsystem (RSS)).

2.4.1 Visual Appearance and Haze Properties

The arrival of the Voyager 1 and 2 spacecrafts, respectively in November, 1980 and August 1981, i.e. close to Titan's northern spring equinox, provided definite answers to many of the speculations of that time. In terms of its visual appearance (Smith et al. 1981, 1982), Titan appeared rather disappointing, being entirely enshrouded by a reddish optically thick haze that hindered images of the surface at the time (Fig. 2.2). Total optical depth of the haze was quickly estimated to be >5, and the peak haze brightness was found to occur at about 240 km above Titan's surface. Still, Titan's appearance was not completely bland. It clearly showed a hemispheric asymmetry (Fig. 2.2), with the Southern hemisphere brighter (by about 25% at blue wavelengths), less red, and more uniform than the Northern hemisphere. The latter showed hints for a banded structure and appears surmounted by an even darker polar hood. Early explanations for the hemispheric asymmetries invoked variations in haze density, particle size, and or composition. They were attributed to dynamical effects, caused by seasonal variations in the dis-

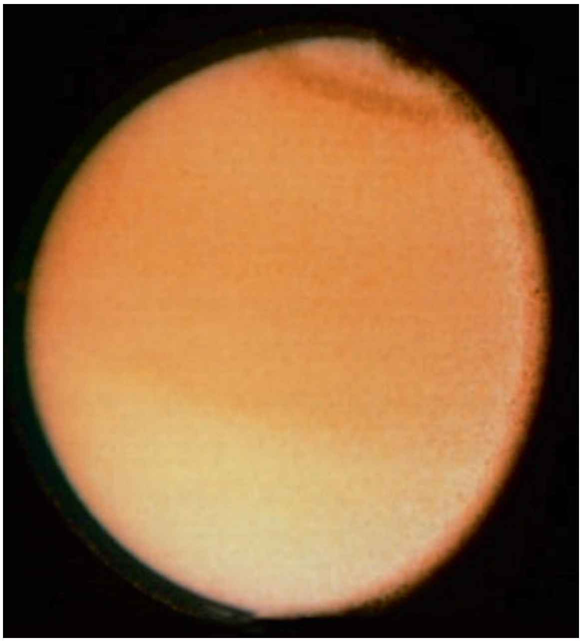


Fig. 2.2 Voyager 2 image showing the N/S asymmetry, polar collar and detached haze (Smith et al. 1982).

tribution of solar heating with a ~1 season time lag related to a long radiative time constant of the atmosphere as a whole (Smith et al. 1981). The other feature that was clearly present in the Voyager images was the "upper" (or "detached") haze. In average, the peak of the detached haze was located roughly 100 km above that of the main haze (i.e. at 300–350 km), though at high northern latitudes, the two layers appeared to merge, due to an increase of the altitude of the main haze and a lowering of the upper haze. In high phase-angle observations (Rages and Pollack 1983), haze particles were detected as high as 500 km.

Determining the haze distribution (particle size and number as a function of altitude) was the subject of considerable effort after the Voyager encounters. Data from Pioneer 11 and Voyager photopolarimetry showed large polarization at 90° phase angle, requiring small particles (<0.1 μm for spherical particles), while the Voyager phase-angle observations rather implied particle sizes of 0.2–0.5 μm. Although it was quickly noted that haze particles are not necessarily spherical (e.g. Asano 1979), models based on this idea and later on the possibility that aerosols may be composed of fractal aggregates had to await the development of more powerful computing facilities (e.g. West and Smith 1991, Rannou et al. 1995). These models, which described the haze particles as the aggregation of many tens of ~0.05 μm monomers, provided a solution to the paradox, as the large size of the aggregates permits allows for the reproduction of the strong forward scattering while preserving the large polarization. The Voyager images, in themselves, did not provide much information on the vertical distribution of haze below the optical radius. This was estimated from microphysical models and fits of Titan's geometric albedo in the visible and near-infrared (Neff et al. 1984). Results seemed to indicate a cutoff of the haze below ~70 km. This behavior was deemed reasonable due to the expected coagulation and sedimentation of haze particles in the lower atmosphere, as well as their likely scavenging by organic ices in the lower stratosphere (see below), but ultimately turned out not to be confirmed by Huygens (see Chapter 12).

2.4.2 *Atmospheric Bulk Composition and Mean Thermal Structure*

Titan's thermal structure was mostly revealed by the Voyager 1 radio-occultation (RSS) data (Lindal et al. 1983). To first order, these data constrained the ratio of atmospheric temperature T to mean molecular mass m and as such, they required an independent knowledge of the gas composition. Using Voyager infrared (IRIS) data, coupled with radiative transfer calculations, it was demonstrated that Titan's surface temperature had to be the range 94 K < T < 97 K (Samuelson et al. 1981), a result that was largely independent of atmospheric composition and opacity sources. In combination with the T/m determination from RSS, this implied that near the surface m was close to 28 amu, indicating N_2 or CO as the major atmospheric gas. In addition, based on solar occultation and airglow measurements (showing emission lines due to molecular and atomic nitrogen), the Voyager ultraviolet experiment (UVS) provided evidence that N_2 was the dominant constituent and methane only a minor constituent, and provided upper limits on argon and carbon monoxide at the several to ten percent level (Broadfoot et al. 1981; Smith et al. 1982; Strobel and Shemansky 1982; Strobel et al. 1993). These latter observations pertained to the upper atmosphere, 800–1,200 km above Titan's surface. These early findings justified that the first analyses of the RSS data were conducted for a pure N_2 atmosphere (Lindal et al. 1983). They indicated a surface pressure, temperature and radius of 1.496 ± 0.02 bar, 94 ± 0.7 K, and 2575 ± 0.5 km, respectively. A troposphere covering the first 42 km of the atmosphere was detected, with a tropopause temperature and pressure of 71.4 ± 0.5 K and 130 mbar, respectively, followed by a well-marked stratosphere extending up to at least ~200 km (~0.75 mbar), the highest level probed by the radio-occultation, where the temperature reached ~170 K. As the presence of other gases modifies the molecular refractivity as well as the mean molecular mass of the atmosphere, all the above figures are sensitive to the precise atmospheric composition. The existence of a methane-rich (a few percent of N_2) stratosphere was confirmed from the detection of 7.7

μm methane emission (Hanel et al. 1981). Lellouch et al. (1989) performed a combined reanalysis of the RSS and of the IRIS observations, accounting for the possible presence of argon as an important atmospheric constituent, and requiring the methane not be supersaturated in the stratosphere. Technically, this analysis allowed for a wide range of argon abundance (0–27%), methane surface abundance (0.5–21%, with a "nominal" surface mixing ratio and humidity of 8% and 80%, respectively), surface temperature (93–101 K), and methane stratospheric abundance (0.–3.4%). Subsequent analyses of the Voyager IRIS spectra (e.g. Courtin et al. 1995, indicating Ar < 6%, and Samuelson et al. 1997a, finding CH_4 ~ 5.7% at the surface) and ground-based observations (e.g. Lemmon et al. 2002, indicating CH_4 ~ 4% at the surface), allowed to considerably narrow this range, before final numbers could be put by Cassini/Huygens (see Chapter 10). Based on an analysis of the IRIS 20–50 μm spectra, some authors (Courtin et al. 1995; Samuelson et al. 1997a) further concluded that methane was supersaturated by a factor 1.5–2 in the upper troposphere, but this was not confirmed by Cassini/Huygens.

Constraints on the atmospheric structure above 200 km were much looser. The IRIS observations, mostly in nadir viewing, contained information on the atmospheric profile up to about 450 km (Coustenis et al. 1989a), but solution thermal profiles were not unique; for example it was not possible to unambiguously determine the altitude and temperature of the stratopause. In the upper atmosphere, temperature constraints from Voyager were even fewer, being (initially) restricted to a single temperature (186 ± 20 K)/density point at 1265 km and some abundance measurements of methane and other hydrocarbons, based on the UVS solar occultation (Smith et al. 1982). Interpolation between conditions in the upper and lower atmosphere indicated a mean ~165 K temperature, but the detailed temperature profile was uncharacterized and had to be largely deduced from theory. The methane abundance was initially measured to be 8% at 1,125 km, indicating a homopause at 925 ± 70 km (Smith et al. 1982). A reanalysis of these data by Vervack et al. (2004) led to drastically different results, with a thermospheric temperature of 153–158 K, CH_4 densities lower than previously inferred by a factor 3–7 and essentially no sign of a homopause up to at least 1,000 km.

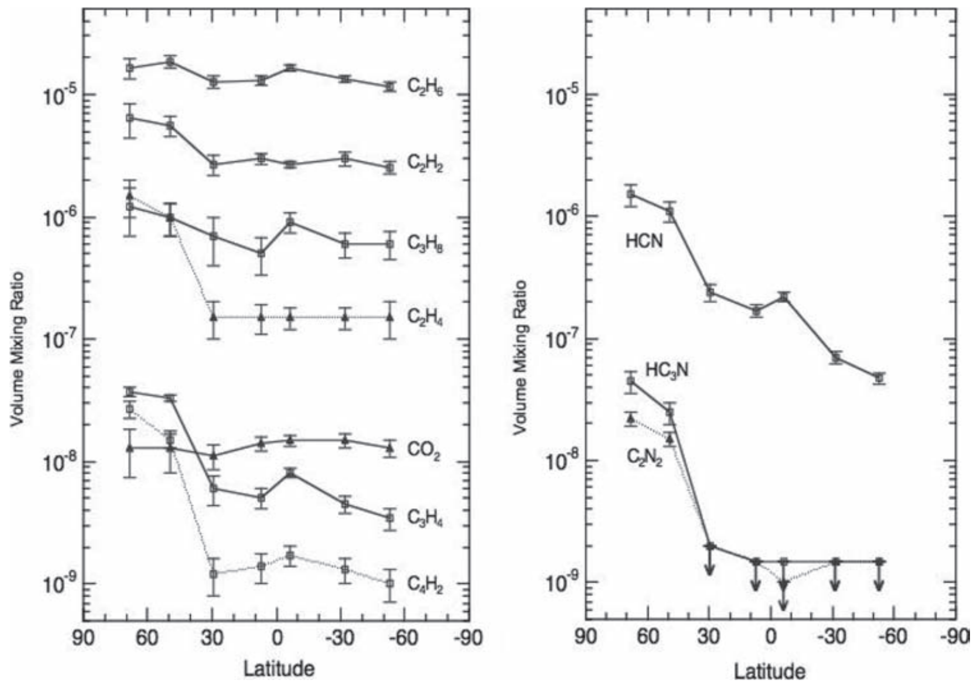
2.4.3 *Atmospheric Trace Composition and Photochemistry*

The Voyager infrared data revealed the richness of Titan's atmospheric composition (Hanel et al. 1981). In addition to N_2, CH_4, and H_2 detected in the troposphere through their collision-induced features, the IRIS spectra confirmed the presence of CH_4, C_2H_2, C_2H_6 and C_2H_4 stratospheric emissions and allowed the discovery of numerous other gases in Titan's stratosphere: the more complex hydrocarbons C_3H_8 (propane), CH_3C_2H (methylacetylene) and C_4H_2 (diacetylene), the nitriles HCN (hydrogen cyanide), HC_3N (cyanoacetylene), and C_2N_2 (cyanogen), as well as carbon dioxide CO_2. The identification of most of these gases was originally made from comparison with laboratory spectra, but the determination of their abundances was based on radiative transfer models. Early values of the molecular abundances (Maguire et al. 1981; Kunde et al. 1981; Samuelson et al. 1981; Samuelson et al. 1983) were superseded by the more comprehensive analyses of Coustenis et al. (1989a,b) which made use of broader datasets and improved spectroscopic databases.

All of these species could be mapped as a function of latitude, and most of them, with the noticeable exception of CO_2 and to a lesser extent of C_2H_6, appeared to be enhanced at high Northern latitudes (Coustenis and Bézard 1995). This study indicated that the least abundant species C_4H_2, HC_3N, and C_2N_2 show the most marked latitudinal variability (the latter two being actually only detected northward of 50°). This is illustrated in Fig. 2.3, where the reported mixing ratios indicate the mean abundance of each compound above their respective expected condensation point in the lower stratosphere at 10-50 mbar (only C_2H_4 does not condense in Titan's conditions). Finally, using a Voyager/IRIS limb sequence recorded over the North Polar region, Coustenis et al. (1991) showed that the abundance of most of the compounds actually increases with altitude, an expected behavior for species formed in the upper atmosphere and diffusing downwards to their condensation sink in the lower stratosphere. Since most species are subject to photolytic losses, an early model (Yung 1987) invoked the accumulation of nitriles in shadow during the preceding winter as the cause of their northern enhancement. It was demonstrated later (Lebonnois et al. 2001) that this explanation does not hold when proper time constants are considered. Most results obtained from Voyager 1 were confirmed by the Voyager 2 /IRIS observations (Letourneur and Coustenis 1993), and no significant variations in composition were observed between Voyager 1 and 2, an expected result given that the two flybys were separated by only 9 months, i.e. about a week of a Titan season.

Another highlight of the Voyager /IRIS observations was the observation of the 8.6 μm feature at high resolution, permitting its proper assignment as the ν_6 band of CH_3D, and allowing the determination of Titan's D/H ratio (Kim and Caldwell 1982; Coustenis et al. 1989b). A clear enrichment (by a factor of 3–12) with respect to the protosolar value was observed. However, the interpretation of this enrichment (nowadays estimated much more accurately to be a factor about 6.5) has remained difficult. Pinto et al. (1986) evaluated several fractionation processes for deuterium, such as differential photolysis and escape, condensation in clouds,

Fig. 2.3 Latitudinal distribution of gases seen by IRIS/ Voyager 1 (Coustenis and Bézard 1995).



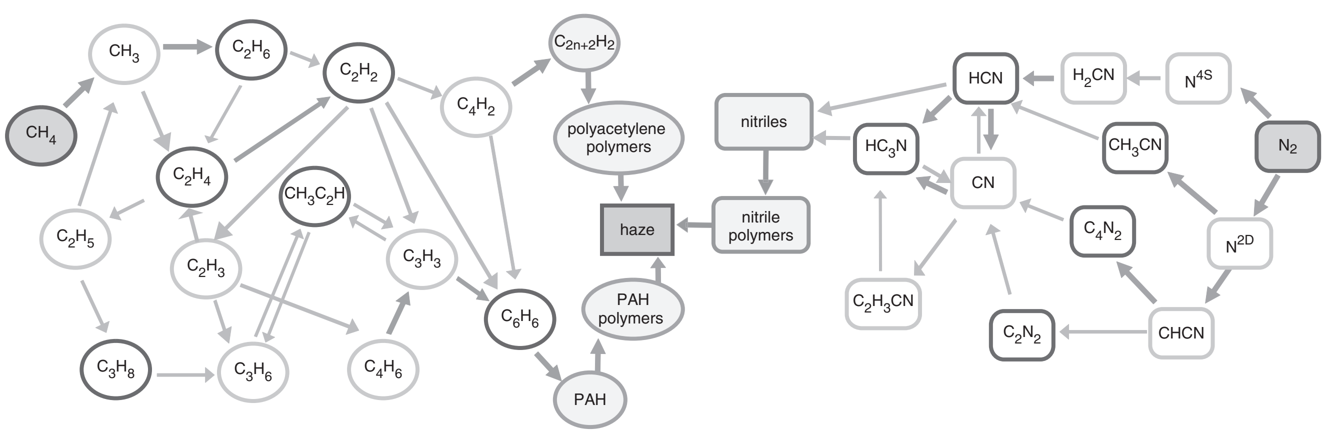


Fig. 2.4 A simplified photochemical scheme of Titan's atmosphere. From Atreya et al. 2006.

over a hydrocarbon ocean and between the ocean and a crust. They concluded that atmospheric evolution was unlikely to entirely explain the D/H enhancement, producing at most a factor ~2.2 enrichment. Lunine et al. (1999) re-examined the problem and concluded to a possible factor of 4 enhancement. This tends to imply that the D/H ratio in Titan's atmosphere was either acquired in the Saturn sub-nebula where Titan had formed, or "upstream" in the cooling solar nebula by isotopic exchange with interstellar-rich ices. More details are given in Chapter 3.

Finally, the IRIS spectra of the North Pole revealed the presence of several additional emission features, not obviously attributable to a particular gas. One of them, at 478 cm^{-1}, was identified as belonging to C_4N_2 ice (Samuelson et al. 1997b), but others, and particularly the very prominent 220 cm^{-1} feature, have remained unidentified so far.

These essential discoveries on the composition of Titan's atmosphere prompted the generation of one-dimensional photochemical models, in which vertical transport was modelled by using the phenomenological approach of eddy diffusion coefficient profile (Strobel 1982; Yung et al. 1984; Toublanc et al. 1995; Lara et al. 1996 for the early ones). The aim was to reproduce the observed composition, based on the expected chemical reactions in a N_2–CH_4 atmosphere. The main reaction schemes were quickly established (see Fig. 2.4 for a simplified but up-to-date understanding of Titan's chemistry). Hydrocarbon chemistry is initiated by the methane dissociation, that produces CH_3, CH_2 (in the $^1CH_2$ and $^3CH_2$ states), and

CH radicals. The methane dissociation occurs directly above 700 km, mostly at Ly α, or through catalytic destruction below 500 km The main photochemical product, ethane, is formed by the self-recombination of the methyl radical (CH_3); high-altitude reactions produce C_2H_4, whose high-altitude photodissociation leads to the formation of C_2H_2, which can be transported downwards to form higher-order hydrocarbons, such as C_4H_2. The C_3 compounds (C_3H_8 and CH_3C_2H) are formed from insertion of a C_1 radical in a C_2 molecule. Nitrogen chemistry is initiated by the dissociation of N_2, either from energetic (<100 nm) UV photons or from magnetospheric electrons in the upper atmosphere, and possibly from galactic cosmic ray in the lower atmosphere, producing $N(^4S)$, $N(^2D)$, N^+, and possibly N^{2+}. The most abundant nitrile, HCN, is formed from reaction of $N(^4S)$ with CH_3 or $^3CH_2$ radicals. Its photolysis leads to CN, which can react with acetylene to form HC_3N; C_2N_2 can be formed in various reactions. Finally, the presence of CO_2 required a source of external oxygen in Titan's atmosphere, in the form of water (not detected at that time), as CO_2 is best formed from CO + OH where OH is produced from the photolysis of water and CO is either of internal or external origin. With few exceptions, photolytic products are expected to condense in Titan's stratosphere and ultimately precipitate to the surface in liquid or solid form. The net results of gas-phase chemistry are thus (i) an irreversible conversion of CH_4 of N_2 into more or less complex hydrocarbons and nitriles, and (ii) the massive production of atomic and molecular hydrogen that can diffuse upwards and easily escape from the atmosphere.

These 1-D photochemical models, which were updated when more species were discovered (namely CO, CH_3CN (acetonitrile), CH_2CCH_2 (allene), H_2O, and C_6H_6 (benzene), see below), were reasonably successful as reproducing the composition of Titan's stratosphere, although for some species (e.g. CH_3CCH, HC_3N) the disagreement between the calculated and predicted abundance could reach an order of magnitude of more. A specific problem was that it turned out difficult to fit all the observed abundances with a single eddy diffusion profile. In particular, the HCN vertical profile seemed to require a larger eddy diffusion than that needed for the major hydrocarbons (Lara et al. 1996). A possible way out was to invoke an additional loss of path of HCN to the haze (Lara et al. 1999). Another important problem, still incompletely solved (see Chapter 10), was to determine the origin of the CO required to form CO_2 (and directly observed from the ground shortly after Voyager). Finally, more recent models, coupling photochemistry and dynamics (Hourdin et al. 2004), have demonstrated the limitations of 1-D photochemical models in their ability to quantitatively reproduce the composition of Titan's stratosphere and even more its latitudinal and seasonal variability.

Titan's photochemistry presumably continues to increasingly complex molecules, eventually proceeding in the solid phase to form the small particles that are the "precursors" of the haze. Evidence for that was provided in part by laboratory experiments (Khare et al. 1984) demonstrating that organic mixtures (named "tholins" after the Greek θωλ ς, meaning "muddy") produced by electron discharge in a gas representative of Titan's atmosphere composition have optical properties similar to those of Titan's aerosols, in particular their reddish colour. The agreement in fact extends over 3 orders of magnitude in wavelength and in absorption coefficient (McKay et al. 1989, 2001). However, photochemical models usually do not track the fate of heavy molecules (with more than ~6 heavy atoms). Thus, Titan's haze was quickly understood as the ultimate product of the coupled hydrocarbon-nitrile photochemistry, but essential chemical pathways are still missing, although several schemes, involving (i) polymers of acetylene and cyanoacetylene (ii) polycyclic aromatic hydrocarbons (iii) polymers of HCN and other nitriles, have been proposed, along with some parameterization (Lebonnois et al. 2002). Notwithstanding these uncertainties, microphysical and photochemical models implied that the total haze production is in the range $(0.5–2) \times 10^{14}$ g cm^{-2} s^{-1} (see review in McKay et al. 2001) and laboratory measurements performed under a variety of pressure, temperature and energy source conditions (see Coll et al. 1999 and references therein) indicated that the haze has a C/N ratio of 2–11 and a C/H ratio of 0.7–3.

2.4.4 Thermal Balance

The enormous step forward in characterizing Titan's thermal structure, composition and haze structure justified the study of its thermal balance. Based on a an analytical model, Samuelson (1983) confirmed that the temperature inversion near 40 km was due to stratospheric absorption of UV light and penetration of visible light to near the surface. Building upon these results, McKay et al. (1989) developed a radiative-convective numerical model, including a haze microphysical model, and tuned to fit Titan's geometric albedo (Fig. 2.5). They demonstrated that Titan is in radiative equilibrium in most if not all of the atmosphere, and that the key factors controlling the thermal structure below ~200 km are the absorption of sunlight by haze and the absorption of surface radiation by the far-IR pressure-induced transitions of N_2, CH_4, and H_2 in the troposphere. The haze reflects 30% and absorbs 40% of the solar light. Since it is nearly transparent in the thermal IR, it leads to an "anti-greenhouse" effect (McKay et al. 1991) amounting to −9 K and is also responsible for the well-marked stratosphere, as ozone is on Earth. The tropospheric greenhouse gases, on the other hand, warm Titan's surface by 20 K. Overall, the surface is heated by 11 K over its equilibrium temperature of 84 K. One of the crucial side results of the McKay et al. (1989) study was the demonstration that about 10% of the solar light reaches

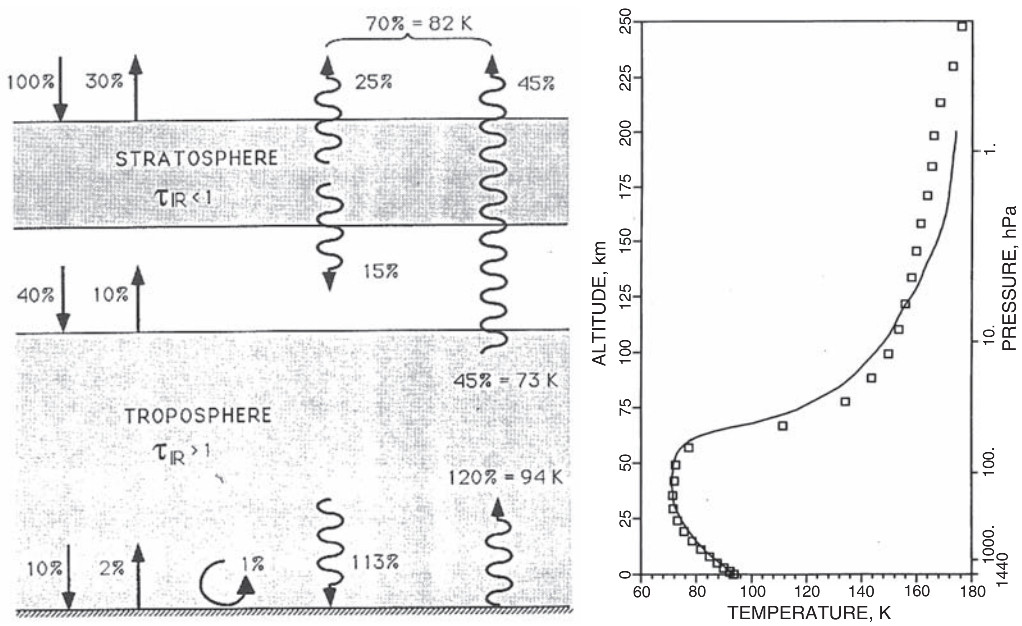


Fig. 2.5 Energy balance (left) and thermal structure (right) of Titan's atmosphere. From McKay et al. (1991) and McKay et al. (1989).

Titan's surface, i.e. that the surface would be observable at some (near-infrared) infrared wavelengths (Fig. 2.5). This turned out to be demonstrated experimentally shortly after.

In Titan's upper atmosphere, heat is transported by conduction and to some extent by radiation. Friedson and Yung (1984) first investigated the heat budget of the upper atmosphere, that appeared governed by UV heating in N_2 and CH_4, non-LTE cooling in C_2H_2, and downward conduction. They were able to reproduce the (then) UVS-derived thermospheric temperature and proposed a temperature profile above 600 km, which included a cold (110 K) mesopause at 736 km. Lellouch et al. (1990) showed, however, that this agreement was illusory due to a large error in the calculation of the heating rates, and that it was in fact difficult to reproduce thermospheric temperatures as cool as observed. The problem was revisited by Yelle (1991). His model included a large number of improvements over the previous studies, such as the inclusion of IR heating and/or cooling by CH_4, C_2H_2, C_2H_6 and the aerosols, a proper treatment of the coupling between vibrational levels, and the rotational cooling by HCN. The latter factor turned out to be key in explaining the ~186 K thermospheric temperature. Based on these models, Yelle predicted a 135–140 K mesopause near 600 km (~0.1 μbar), relatively warm because of C_2H_6 heating in this region.

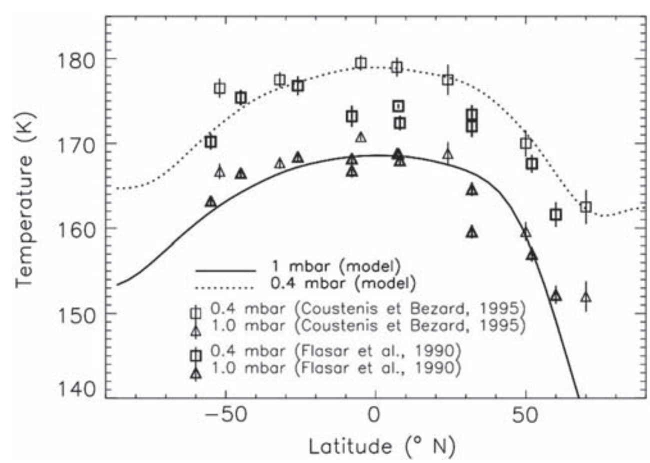


Fig. 2.6 Latitudinal temperature distribution compared to GCM model including coupling with haze. From Rannou et al. (2004).

2.4.5 Circulation and Meteorology

The Voyager IR observations provided indications on the horizontal variability of the temperatures, although with poor latitudinal resolution. Flasar et al. (1981) quickly noted a hemispheric asymmetry in the stratospheric temperatures, with the Northern hemisphere ~10 K colder than the Southern. This was confirmed in subsequent analyses of the IRIS data (Flasar and Conrath 1990, Coustenis et al. 1995, Bézard et al. 1995), indicating 0.4–1 mbar temperatures relatively uniform – to within ~4 K – in the Southern hemisphere, but decreasing sharply – by more than 15 K – from equator to 60°N latitude (see Fig. 2.6). Applying the thermal wind equation to this limited dataset, Flasar and Conrath (1990) inferred a moderate (60 m/s) zonal jet in the Northern hemisphere. Because the radiative time constant at this level is much shorter than 1 Titan year, a symmetric temperature field, tracking the insolation field, could have been expected for this (spring) season. Flasar and Conrath invoked a case of "dynamical inertia", in which the atmospheric response lags the insolation changes due to the time is takes to redistribute the axial angular momentum associated with temperature changes. Noting that the Northern hemisphere was the place of increased haze and increased abundances of radiatively-active minor species, Bézard et al. (1995) proposed instead that the temperature asymmetry was radiative in origin and related to the asymmetry of opacity sources. This issue was further explored when general circulation models started to be developed in the 1990s. These models, starting from the pioneering work of Hourdin et al. (1995), indicated that Titan's circulation near solstice is essentially characterized by meridional transport from summer pole to winter pole in the stratosphere and above, and in the opposite direction near the surface. This circulation pattern is reversed at the opposite solstice. For short periods around each equinox, the meridional circulation breaks up into two cells, with upwelling near the Equator and downwelling at high latitudes. The models indicated that this meridional circulation must induce strong, prograde, zonal winds. They further showed that a purely dynamical effect was insufficient to explain the temperature asymmetry between the two hemispheres observed by Voyager.

Rannou et al. (2002), Lebonnois et al. (2003) and Luz et al. (2003) demonstrated that strong couplings exist between the thermal field, the wind field, and the altitude-latitude distribution of haze and of the minor compounds (Fig. 2.6). Essentially, the meridional circulation driven by latitudinal temperature contrasts transports the haze to the Northern winter polar region. The accumulation of haze there leads to extra cooling, intensifying the circulation. The same is true for minor compounds, although their feedback on the circulation appears less important than for the haze. Rannou et al. (2002) were able to show that the gross features of the haze structure and temperature field seen by Voyager were consistent with these concepts. In contrast, models in which the haze production varied seasonally but which did not call for dynamical control failed to reproduce the N/S albedo asymmetry, due to too long time constants associated with haze formation and accumulation (Hutzell et al. 1993). Note finally that ground-based observations (Roe et al. 2004) indicated that the thermal field just prior Winter Solstice (Dec. 2000) was then symmetric in latitude, with Equator-to-Pole contrasts of about 10 K in the middle stratosphere.

Although it was immediately realized that methane (but not nitrogen) was a condensable species in Titan's atmosphere, the dynamics and meteorology of Titan's atmosphere remained poorly characterized for a long time after the Voyager mission because the methane vertical profile remained uncertain, temperature constraints were few in the troposphere, and clouds had not been detected yet. For a pure N_2 atmosphere, the lapse rate inferred from RSS in the first few kilometers appeared to follow a dry nitrogen adiabat, suggesting that methane condensation did not occur near the surface (Lindal et al. 1983; Eshleman et al. 1983). By considering the effect of CH_4 on the RSS data, Flasar (1983) showed that the methane surface humidity was below 0.7, otherwise the atmosphere would be unstable to dry convection. This upper limit was refined in the study of McKay et al. (1997), who showed that if allowance was made for the condensation properties of methane/nitrogen mixtures, the methane maximum humidity at the surface was closer to 0.6. Their study further showed that there is no convective zone in the troposphere (i.e. that the lapse rate follows everywhere the radiative lapse rate), and that the lapse rate is stable against dry convection and unstable against moist convection. This suggested that condensation of methane does not occur at all in Titan's atmosphere (methane supersaturation in Titan's troposphere was advocated originally in papers by Courtin et al. 1995 and Samuelson et al. 1997a) or only in patchy form, producing a mean thermal gradient intermediate between the dry and the lapse rates. This latter view was generally confirmed when clouds were discovered from spectroscopy and direct imaging (see below).

Voyager IRIS data indicated that the tropopause temperature, as measured by the 300 cm^{-1} radiance, is uniform to within 1 K (Flasar et al. 1981; Samuelson et al. 1997c; Courtin and Kim 2002), while the 510 cm^{-1} radiance, to which the surface contributes for about 60%, suggests that the surface brightness temperature varies by about 3 K from Equator to both poles. The hemispheric symmetry of the surface temperature is consistent with the very long radiative timescale of the troposphere. Noting that the annually-averaged insolation at 60° is about ½ of its equatorial value, Flasar et al. (1981) estimated that the radiatively forced surface temperatures would show a ~15 K difference between these latitudes, and that meridional winds of ~0.04 cm/s would be sufficient to reduce the contrasts to their observed value. Since then, however, general circulation models (Hourdin et al. 1995; Tokano et al. 1999) have failed to reproduce even this modest temperature contrast, which, given the expected efficiency of meridional transport, remains a challenge to modellers (Tokano and Neubauer 2002).

2.4.6 Speculations About the Surface and the Interior

Immediate post-Voyager photochemical models (Yung et al. 1984) indicated a depletion of atmospheric methane on a ~10^7 year timescale and its irreversible conversion to more complex hydrocarbons, primarily ethane and acetylene. This number and conclusion, which were essentially confirmed in later photochemical models, required that methane is supplied over geologic time from a reservoir more massive than the atmosphere. The natural idea of a pure methane ocean, however, was ruled out by the near-surface sub-saturation of methane. As ethane is liquid at Titan's surface temperature, Lunine et al. (1983) postulated a model in which methane was stored in a surface ocean, mixed with its own photolysis products (ethane and other liquid hydrocarbons such as propane) and with dissolved nitrogen. Since the atmospheric abundance of methane is a function of its mole fraction in the ocean (being lowered by the presence of ethane), it was possible to estimate the oceanic composition. In addition, the ocean depth could be constrained by the quantity of ethane having precipitated to the surface since Titan's formation. In its nominal form, the Lunine et al. (1983) oceanic model was made of 70% C_2H_6 – 25% CH_4 – 5% N_2, and had a ~1 km depth. These figures hold for a global ocean. This was based on considerations by Sagan and Dermott (1982), who argued that Titan's non-zero orbital eccentricity indicates low tidal damping, while discrete and shallow seas would result in a strong tidal erosion and orbit circularization (this argument has since then be revisited, see Sohl et al. 1995; Dermott and Sagan 1995).

A more extensive study of the oceanic composition and depth was performed by Dubouloz et al. (1989), based on the range of atmospheric models explored by Lellouch et al. (1989). This study indicated that the ocean could vary from "shallow and ethane-rich" to "deep and methane-rich", with maximum depths as high as 9 km. Such an ocean could also be a large CO reservoir, and sequester insoluble species at its bottom, in particular acetylene with an estimated ~100 m solid layer. Additional refinements were brought to the model, i.e. regarding the possible presence of other dissolved species and suspended aerosols. Nonetheless, the essential picture of a global, ethane-dominated ocean buffering the atmospheric methane, controlling the lower atmosphere meteorology and providing a sink for the dregs of the atmospheric chemistry remained the accepted paradigm of Titan's surface for about a decade after the Voyager observations. It was ultimately washed out when the first radar echos, and near-infrared lightcurves and images were recorded in the early 1990s.

2.5 Observations of Titan from the Earth and Earth-Orbit in the Post-Voyager Era

In spite of the enormous progress brought by the Voyager investigation, there was still room for other discoveries to be made remotely in the following years. Those were made possible by the advent of more sensitive ground-based instruments and space-borne observatories (e.g. HST and ISO), the development of new techniques such as heterodyne spectroscopy and adaptive optics, the long-awaited opportunity provided by stellar occultations and radar sounding, and the realization that Titan's lower atmosphere and surface were observable in the near-infrared.

2.5.1 Radar Observations

While early photochemical modeling suggested the presence of a multiple kilometer deep global hydrocarbon ocean (see above), the first radar reflectivity measurements were inconsistent with the existence of a deep global ocean. Muhleman et al. (1990) observed Titan with 3.5 cm wavelength radar on three consecutive Earth days (45° of Titan rotation). They found radar reflectivities at least an order of magnitude brighter than what they would have seen for even a shallower few hundred meter deep ocean. Further, the day-to-day measured reflectivities varied by greater than three times their estimated uncertainties, strongly suggesting that the surface was heterogeneous, which was later confirmed by ground- and space-based near-infrared imaging.

By 2001–2002 Titan had moved into the declination range able to be observed with the recently upgraded 13 cm radar at Arecibo Observatory. Campbell et al. (2003) reported the detection of specular reflections at ~75% of the 16 locations on Titan's surface probed with radar, implying materials smooth at the multi-centimeter scale and interpreted to be the sign of small lakes at the sub-Earth latitude of the time (~26°S). Campbell et al. (2003) further noted that the intensity of the specular reflection correlated with the near-infrared surface albedo, although the physical reason for this was unclear. An examination of ground-based near-infrared imaging by West et al. (2005) showed that lakes of the size suggested by the Campbell radar measurements would have been easily detected in the ground-based imaging and that the lack of any detectable specular reflection in the ground-based data placed severe constraints on the presence of open surface liquids at those latitudes accessible from Earth. While it is possible to imagine surface materials that are smooth at centimeter scales and rough at micron scales, a definitive answer that satisfies both the radar and near-infrared measurements remains elusive. As of 2008 the radar tracks acquired by the Cassini mission do not yet overlap with the sampling points of Campbell et al. (2003).

2.5.2 Near-IR and Visible Spectroscopy and Imaging

Major progress toward understanding Titan's lower atmosphere and surface was not made until the exploitation in the late-1980s/early-1990s of the spectral `windows' between strong methane absorption bands at near-infrared wavelengths (McKay et al. 1989; Griffith et al. 1991). While much of the ground-based spectro-imaging work focused on Titan's atmosphere (3.5.2.2), progress was also made during the pre-Cassini era with observations of Titan's surface (3.5.5.1).

2.5.2.1 Surface Composition and Morphology

Titan's atmosphere is a hindrance to near-infrared surface spectroscopy and imaging if the lower atmosphere and the surface are the target. Indeed, the surface is only visible in these narrow "windows" between the strong methane absorption bands and the optical properties of the haze layers varying strongly with wavelength from 'window'-to-'window'. Nonetheless several ground-based spectro-imaging observations of Titan are worth noting for their insights brought into the nature of the surface.

Observations in the methane "windows" led to the detection of Titan's surface rotation light curve (Griffith 1993; Lemmon et al. 1993, 1995; Coustenis et al. 1995; Negrão et al. 2006). In hindsight the surface of Titan was detected in earlier datasets. Cruikshank and Morgan (1980) reported near-infrared flux measurements of Titan in wideband J, H, and K filters over 70 days and at a high confidence level detected variability. This variability is now recognized to be the well-known 16-day rotation period of Titan's high-contrast surface, although this was not fully appreciated at the time. The canonical view that the Voyager flybys could not detect Titan's surface was shown to be wrong by Richardson et al. (2004), who found that careful processing of the Voyager imaging revealed the large-scale surface features.

Following previous studies suggesting the presence of "dirty" water ice on the surface (possibly contaminated with organics or tholins (Griffith et al. 1991; Coustenis et al. 1995)), Griffith et al. (2003) reported the analysis of near-infrared spectra that suggested that water ice was further extensively exposed on Titan's surface. In spectroscopy through the 4.9 μm window of Titan's atmosphere Lellouch et al. (2003) also found that Titan's surface albedo was correlated with the albedo in other windows and consistent with water ice, but that some other surface material with a sloped albedo decreasing over 4.98–5.07 μm must also be present. This result has since been confirmed by Cassini observations and is now thought to be due to the presence of benzene or other higher order aromatic hydrocarbons on Titan's surface. More progress was made toward constraining the nature of Titan's surface with recent spectroscopic observations through those same near-infrared atmospheric windows. Negrão et al. (2006, 2007) compared moderate resolution near-infrared spectroscopy with the improved radiative transfer models of Rannou et al. (2003) and found their data compatible with Titan's surface composition being again a mix of water ice and tholins, but with a third unidentified component.

Hartung et al. (2006) searched for absorption bands of solid CO_2 and constrained the surface of Titan to be covered in less than a few percent CO_2, at least the two locations sampled. At longer wavelengths Coustenis et al. (2006) observed Titan with ISO and detected for the first time the full shape of the 2.85-μm CH_4 window. These authors, once more, found their data compatible with water ice being a major component of Titan's surface, but they additionally suggested a possible CO_2 contribution near 2.74 μm.

The near-infrared 'windows' were also used by several teams of observers to obtain images of Titan's surface by using either the Hubble Space Telescope (Smith et al. 1996), speckle interferometry (Gibbard et al. 1999, 2004) or adaptive optics (Bouchez 2004; Coustenis et al. 2001, 2005; Roe et al. 2004; Gendron et al. 2004; Hirtzig et al. 2007). These efforts revealed, with increasing spatial resolution, the heterogeneous complex nature of Titan's surface, with dark and bright regions sharing the landscape. The presence of different ices and various degrees of elevations was suggested, but none of these theories was unambiguously confirmed and the nature of Titan's surface remained largely mysterious.

The near-infrared maps of Titan's surface using the Hubble Space Telescope and the largest ground-based telescopes (see for instance Smith et al. 1996; Meier et al. 2000; Roe et al. 2004; Coustenis et al. 2005) revealed details on Titan's surface down to the limits of their resolution and inspired much speculation about the nature of the surface (Fig. 2.7). However, at the modest resolution achieved, roughly equivalent to that of the unaided human eye peering up at Earth's moon, no geologic features could be definitively identified.

2.5.2.2 Atmospheric Phenomena

Titan's thick stratospheric haze layer, the end product of a complicated network of methane photochemistry, changes in appearance with season. In particular the north/south brightness ratio varies with both wavelength and seasonal phase. This variation with seasonal phase is best explained by a global circulation model (GCM) coupled with a haze microphysical model (Rannou et al. 2004), in which the haze is advected around the upper atmosphere by winds and also plays a feedback role by heating the atmosphere through solar absorption and cooling it by radiating it in the infrared. The variation in appearance as a function of wavelength is due in part to different altitudes being probed by different wavelengths and in part to the variation in optical properties of the haze particles as a function of wavelength. The haze particles are generally absorbing at visible wavelengths and shorter

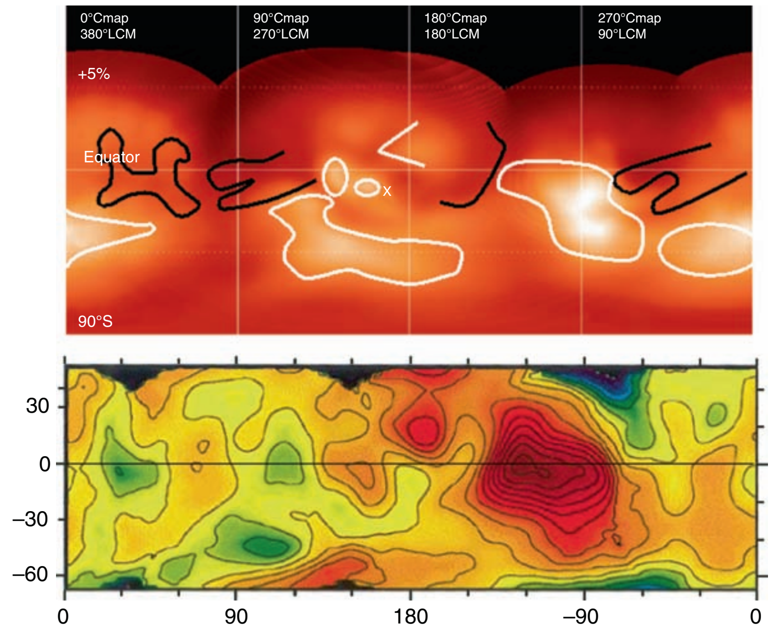


Fig. 2.7 Among the first maps of Titan's surface: two maps taken with the adaptive optics system NAOS at the VLT at 1.28 µm (*upper panel*) and the HST NICMOS at 1.6 µm (*lower panel*). The surface features are coherent from one dataset to the other. The bright areas dominate Titan's leading hemisphere, while the darker ones prevail on the other side. The large bright equatorial region has since then been named "Xanadu Regio" and is observed near 110°LCM. The Huygens landing site is marked with an "X" near 192°LCM and 10°S. Adapted from Fig. 2.7 in Coustenis (2007).

and generally scattering at wavelengths longward of visible. Additionally the haze layers are optically thick at short visible wavelengths and the opacity decreases with increasing wavelength until the haze is optically thin at ~2 µm. Numerous observations have been made at both visible and near-infrared wavelengths of the seasonally varying haze and polar collar or hood that is likely related to a high altitude polar vortex. These include imaging from the Hubble Space Telescope (e.g. Caldwell et al. 1992; Lorenz et al. 1999, 2001) and ground-based adaptive optics systems (e.g. Coustenis et al. 2001; Roe et al. 2002a; Hirtzig et al. 2007). Evidence for the north-south asymmetry reversing, starting first in the visible range, was found by Lorenz et al. (1999) and has since been confirmed in all wavelengths. This is an expected return to the Voyager situation, predicted by seasonal models (Sromovsky et al. 1981; Hutzell et al. 1993), where the south limb was bright in the visible, but dark in the infrared, anti-mirroring the northern limb situation. This situation had reversed in the 90's, showing the famous "Titan's smile" in HST and adaptive optics images (e.g. Caldwell et al. 1992 and Coustenis et al. 2001, respectively).

Initial detections of Titan's tropospheric clouds were controversial, in part due to interpretations of Voyager flyby data suggesting "rain without clouds" in Titan's troposphere (Toon et al. 1988) and methane supersaturation (Courtin et al. 1995; Samuelson et al. 1997b) wherefore tropospheric clouds should not be able to exist in a stable condition. The first published detections of clouds were the whole-disk near-infrared spectra of Griffith et al. (1998). These spectral detections use the variation in atmospheric opacity with wavelength to selectively probe different altitudes and separate surface rotation from tropospheric clouds and from stratospheric haze (Fig. 2.8). The observations revealed an enormous tropospheric storm, covering 5–7% of Titan's disk in September 1995. Griffith et al. (2000) then showed evidence for daily small-scale (covering ~0.1% of Titan's disk) clouds in similar disk-averaged spectra (Fig. 2.8).

Direct imaging of Titan's clouds first showed strong cloud activity in the south polar region in late southern spring (Gibbard et al. 2004; Roe et al. 2002b; Brown et al. 2002; Gendron et al. 2004; Bouchez and Brown 2005; Hirtzig et al. 2006; 2007). These south polar clouds (Fig. 2.9), visible especially at 2.0 µm, persisted for several years as the season progressed into early southern summer. Following a massive south polar storm system in late 2004 (Schaller et al. 2006a) the south polar clouds were observed to dissipate for an extended period of time (Schaller et al. 2006b). A new class of clouds, long, streaky, and confined to near 40°S latitude were discovered in late 2003 and reported in Roe et al. (2005a). This latitudinal clustering of clouds could be indicative of a seasonal region of uplift (see Chapter 14) and this was initially proposed as the probable explanation (Roe et al. 2005a; Griffith et al. 2005). Further observations of these mid-latitude clouds revealed them to be clustered in longitude, suggesting that some aspect of their formation mechanism was linked to the surface and the clouds could be the result of geologic injection of methane to the atmosphere by geysers, cryovolcanoes, etc. (Roe et al. 2005b). Ultimately these clouds most likely result from some combination of surface processes and seasonal circulation.

Other atmospheric phenomena have been observed in Titan's atmosphere from the Earth. A diurnal variation in

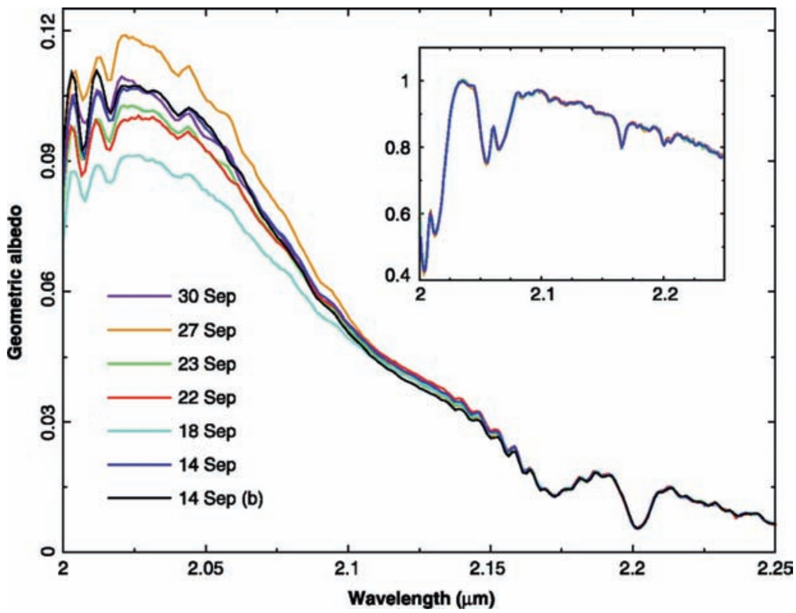


Fig. 2.8 Evidence for clouds on Titan in spectra taken over several days in 1999 (Griffith et al. 2000). Across this wavelength range the observed albedo varies inversely with the atmospheric gas opacity, which is primarily provided by methane and molecular hydrogen. At shorter wavelengths (~2.0–2.08 μm) the opacity is low and the heterogeneity of surface albedo is apparent in the spectral variations during one 16-day Titan rotation. At longer wavelengths (~2.16–2.25 μm) the opacity is high and photons do not penetrate below the stratosphere. Titan's stratosphere varies only on longer time scales and therefore this spectral region remains constant during the period of observations. At intermediate wavelengths (~2.08–2.16 μm) the gas opacity is high enough to block the surface from view but low enough to allow photons to reach the troposphere. Subtle albedo variations in this spectral region are uncorrelated with the surface rotation and indicative of variable tropospheric cloud coverage.

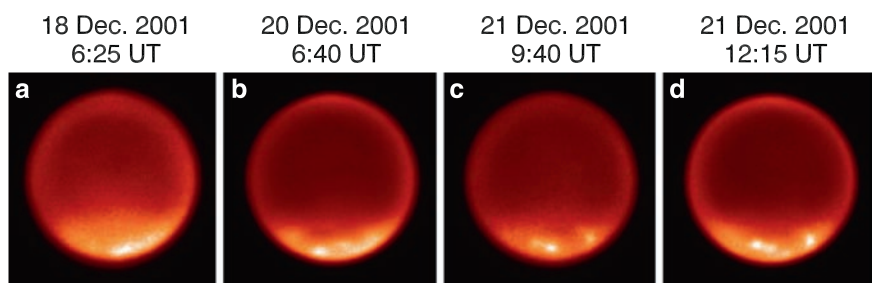


Fig. 2.9 The south polar clouds were the first to be directly imaged. In this sequence, which was typical of Titan during late southern spring, the cloud positions and brightnesses can be seen evolving over several days (Roe et al. 2002b).

the upper troposphere or lower stratosphere is apparent in the consistent brightness enhancement of the haze on the morning limb, first recognized by Coustenis et al. (2001) and confirmed in Hirtzig et al. (2006). In a careful radiative transfer analysis of a spectrally and spatially resolved datacube, Adamkovics et al. (2007) reported spectral evidence for the presence of an optically thin layer of particles at 30 km on the morning limb that was consistent with thin condensed methane clouds and the formation of widespread morning drizzle.

Titan's year is 30 Earth years long, which severely limits the historic record of observations. Few of the techniques used to observe Titan were available 30 years ago. The one long-term study of Titan that has now successfully observed a full Titan year is that of Lockwood et al., at Lowell Observatory (see e.g. Lockwood et al. 1986). In the most recent update (Lockwood and Thompson 2009) they report on 34 years of visible wavelength photometry of Titan and find that the disk-integrated brightness of Titan displays a 10% sinusoidal variation lagging the phase of Titan's seasonal extremes by 1/8 of a Titan year. Of particular interest are the most recent 4 years of observations, overlapping in seasonal phase with their first 4 years of observations. They find that Titan's brightness varied from one Titan year to the next at the same seasonal phase, in this case largely due to the high stratospheric hazes. This is an important reminder to us all that the atmosphere on Titan, much like on Earth, may display significantly different behavior from 1 year to the next.

With this caution in mind observational studies of the seasonal evolution of Titan's clouds continue. Already the shutdown of the south polar cloud system was reported in early southern summer (Schaller et al. 2006b). Global circulation modelers have begun to explore how Titan's tropospheric weather will respond to the changing seasons (see e.g. Tokano 2005; Rannou et al. 2006) and make predictions for when and where clouds should occur. The next one to two decades should see a continuing iterative refinement of these models as the database of cloud observations extends to cover an ever-increasing fraction of a Titan year.

2.5.3 *Mid-Infrared, Far-Infrared and Millimeter Spectroscopy*

Considerable progress was made over 1980–2000 in characterizing Titan's atmosphere composition and dynamics, especially from observations in the thermal infrared. The advent of cooled grating, echelle, and heterodyne spectrometers permitted to re-explore the thermal infrared range (6–50 μm) with a spectral resolution and sensitivity superior to Voyager /IRIS, in spite of the much larger distance to the target and the modest (at best) spatial resolution available. Such instruments included the echelle spectrometer IRSHELL and its successor TEXES on the IRTF, the Goddard Infrared heterodyne spectrometer (IRHS) and its successor HIPWAC on the same facility or on Subaru, and the Short Wavelength Spectrometer (SWS) of the Infrared Space Observatory (ISO), launched in 1995 and operative until April 1998. Thanks to their very high spectral ($>10^6$) resolution, heterodyne observations, both in the millimeter/submillimeter range and in the 10 μm window, were especially powerful to (i) detect weak and isotopic species (ii) determine the vertical distribution of some gases from line profiling and (iii) obtain direct wind measurements.

Shortly after the discovery of CO_2 by Voyager, a second oxygen-bearing species, CO, was detected in 1982 (Lutz et al. 1983) with a ~60 ppm abundance. CO was expected because the formation of CO_2 from an external source of H_2O involved similar formation of CO from $OH + CH_3 \rightarrow CO + 2H_2$. Although the original discovery of CO was obtained at 1.57 μm, most subsequent studies of CO were performed in the mid-infrared (5 μm – Noll et al. 1996; Lellouch et al. 2003; Lopez-Valverde et al. 2005) and in the mm/submm range (Muhleman et al. 1984; Marten et al. 1988; Gurwell and Muhleman 1995; Gurwell and Muhlemann 2000; Hidayat et al. 1998). The latter set of observations, in particular, generated a lot of controversy as to the precise abundance and vertical profile of CO, as a number of measurements indicated a depletion of the CO stratospheric abundance with respect to its tropospheric value, a behavior that was difficult to explain given the extreme chemical stability of this compound. The overall outcome of all these measurements, however, was that there is no definite evidence that CO is not uniformly mixed in Titan's atmosphere.

Other key compositional studies were performed in the mm/submm range (Bézard et al. 1993; Hidayat et al. 1997; Marten et al. 2002; Gurwell 2004). Highlights include: (i) the first – and so far only – detection of acetonitrile (CH_3CN) – see Fig. 2.10; (ii) the first vertical profiles of nitriles (HCN, HC_3N, CH_3CN) outside of the polar region, confirming the general trend of minor species, especially short-lived ones, to increase with altitude in the stratosphere; (iii) the first evidence of a strongly enhanced $^{15}N/^{14}N$ ratio (by a factor of ~4) in HCN. Initially (Marten et al. 2002), this ratio was implicitly assumed to be representative of Titan's atmosphere, and to reflect its evolution in presence of large escape. The Huygens measurements, however, have indicated that the bulk (i.e. in N_2) $^{15}N/^{14}N$ rate in enriched by a factor 1.5 only (see Chapter 10), so that the higher enhancement in HCN points to an efficient fractionation process, identified as a differential photolysis rate (Liang et al. 2007); (iv) measurements of the $^{18}O/^{16}O$ ratio (Owen 2000; Gurwell 2008), though results haven't been extensively published yet.

A wealth of results on Titan's composition was also achieved in the mid- and far-infrared. New information on hydrocarbon abundances and distributions, particularly ethane and acetylene, was obtained from the ground and from ISO (Kostiuk et al. 2005 and references therein, Coustenis et al. 2003; Roe et al. 2004). Again with IRTF/TEXES, Roe et al. (2003) were able to clearly separate and measure the 748 cm^{-1} feature of propane, partially blended with acetylene

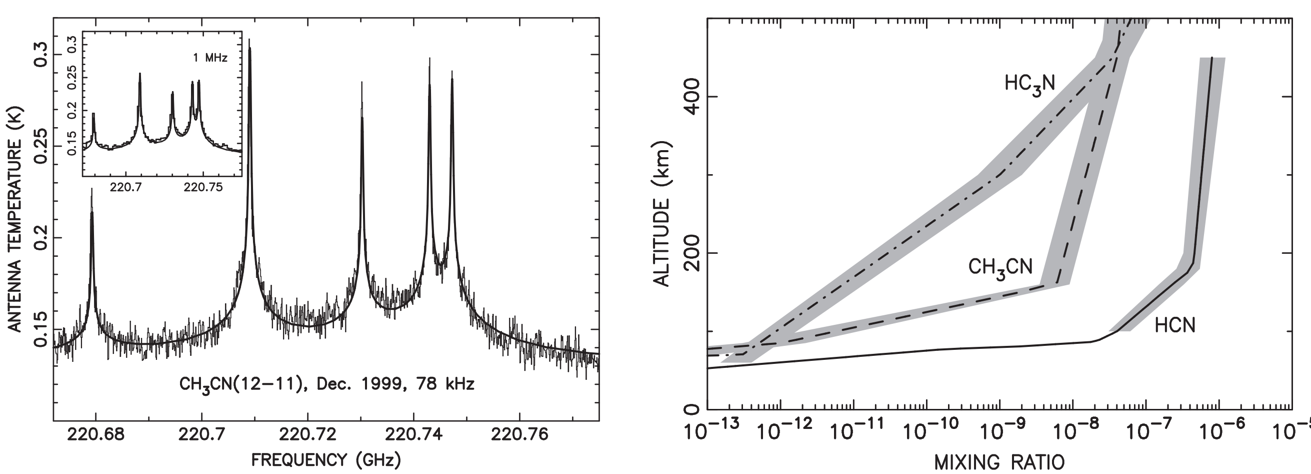


Fig. 2.10 Detection of CH_3CN, (*left*) and vertical profiles of nitriles (*right*) from IRAM-30 m millimeter observations (Marten et al. 2002).

at Voyager/IRIS (and even ISO/SWS) resolution. New measurements of the D/H ratio from CH_3D were also obtained (Orton 1992; Coustenis et al. 2003). These, however, indicated values in the range (5–10) × 10^{-5}, somewhat lower than those obtained from Voyager, than values obtained in the near-IR (de Bergh et al. 1988) and than the "modern", post-Cassini value of ~13 × 10^{-5} (see Chapter 10). In terms of novelty, however, the most important results were the detections of new species, which included water and benzene from ISO (Coustenis et al. 1998, 2003) and allene from IRTF/TEXES (Roe et al. 2004). The evidence for benzene, which followed its detection by ISO in the Giant Planets (Bézard et al. 2001) prompted an examination of the chemical schemes that could produce it at stratospheric levels (Wilson et al. 2003; Wilson and Atreya 2004; Lebonnois 2005); the proposed mechanism involves the recombination of propergyl (C_3H_3 radicals), producing isomers of C_6H_6, and presumably ultimately to benzene through isomerization. The detection of water vapor (Fig. 2.11) was the final (if necessary) proof for an external source of water vapor in Titan's atmosphere (Coustenis et al. 1998). The estimated water mixing ratio (typically 8 ppb at 400 km) and flux – (1.3–4.5) × 10^6 cm^{-2} s^{-1}, referred to flux surface – was generally in line with expectations based on the CO_2 abundance (see Hörst et al. 2008, and the Chapter 10 for an up-to-date discussion on this problem). However, the ultimate origin of water remains elusive, as water can originate either from global sources, such as interplanetary icy dust grains, or from local sources such as the sputtering of icy satellite or ring surfaces (or based on a more recent perspective, Enceladus venting). A surprising aspect is the fact that the above flux is comparable to the supply rate of oxygen into Saturn, which amounts to (4 ± 2) × 10^6 cm^{-2} s^{-1} (Moses et al. 2000), while larger fluxes may be expected at Saturn due to the gravitational focusing it exerts on interplanetary dust particles and the fact that a ring source, interior to Titan's orbit, should also favor Saturn over Titan. The presence of an external oxygen supply in Titan's atmosphere may thus point to the importance of local sources beyond Titan's orbit, but the precise origin of the dominant source (Hyperion, Iapetus, Phoebe…) is still not solved.

The post-Voyager ground-based observations also provided results on the thermal structure and especially the dynamics of Titan's atmosphere. From very high-resolution (70,000 resolving power) observations of the ν_4 band of methane near 8 µm with TEXES, Griffith et al. (2005) obtained the first infrared measurements of the thermal structure in the 300–600 km range, with the first evidence for a mesosphere above about 380 km. Thanks to their unsurpassed spectral resolution, heterodyne observations allowed the first direct Doppler measurements of winds in Titan's atmosphere. The first successful detection of winds was reported as early as 1994, based on measurements acquired in August 1993 with IRTF/IRHS. It was based on differential line position in ethane 12 µm spectra obtained on two (East and West) Titan limb positions. Albeit rather inaccurate and at a spatial resolution essentially equal to a Titan diameter, these measurements, augmented by additional measurements in 1994–1996 and ultimately published in Kostiuk et al. (2001), revealed a wind velocity of order 100 m/s in the prograde direction at 0.1–7 mbar (120–300 km), confirming the speeds inferred from stellar occultation measurements (see below) but uniquely providing their direction. Beyond its scientific impact for the understanding of Titan's super-rotation regime, this breakthrough was also of high importance for planning the Huygens mission. This result was confirmed from improved observations with HIPWAC on Subaru in 2003, indicating an equatorial wind

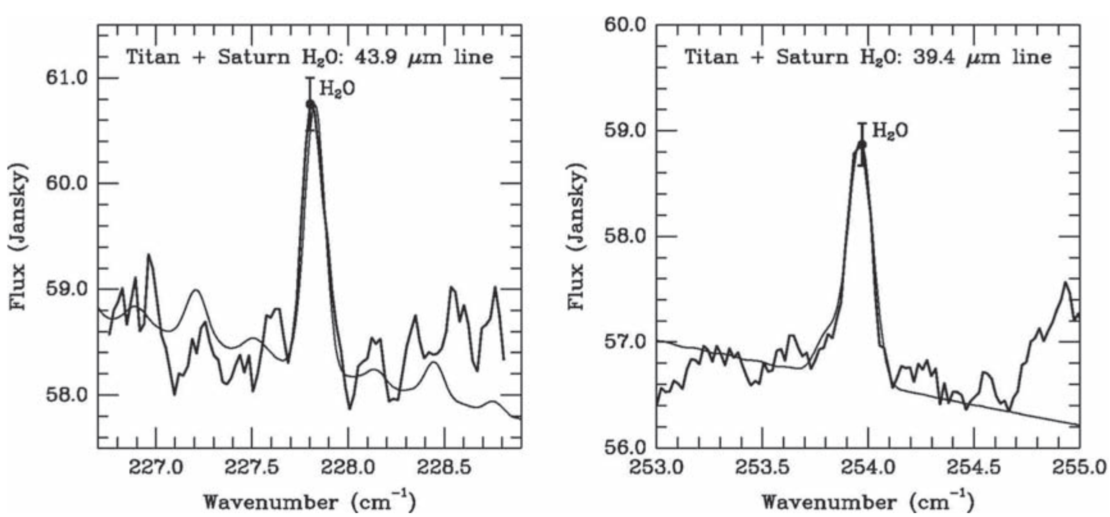


Fig. 2.11 The detection of H_2O from ISO (Coustenis et al. 1998).

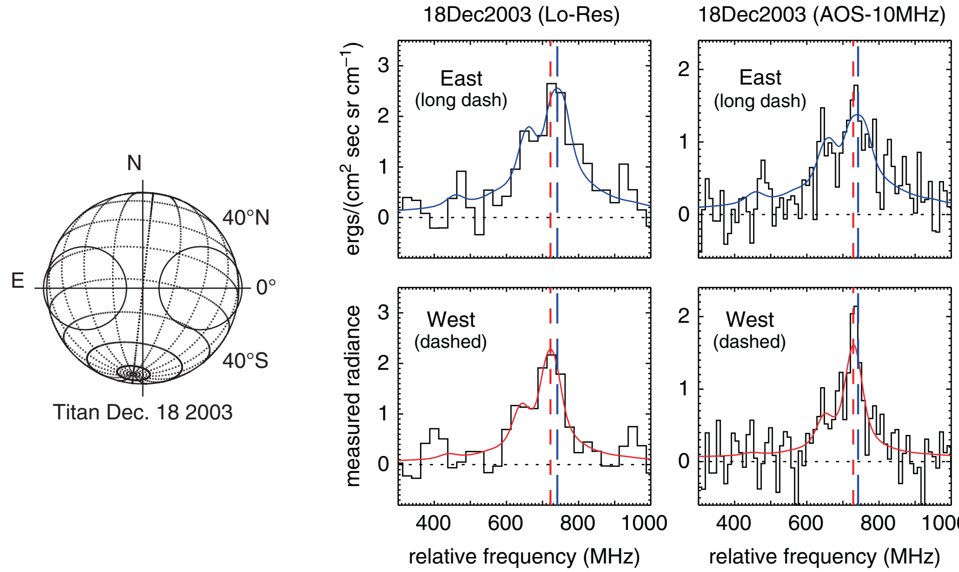


Fig. 2.12 Measurement of winds in Titan's stratosphere using Doppler shift heterodyne spectroscopy of ethane at 12 µm. From Kostiuk et al. (2005)

velocity of 190 ± 90 m/s (Kostiuk et al. 2005, Fig. 2.12). Similar measurements were recorded during the coordinated campaign in support to Huygens on January 15, 2005 (Kostiuk et al. 2006). Wind measurements were also obtained by Moreno et al. (2005), using mm transitions of HC_3N and CH_3CN mapped with the Plateau de Bure interferometer. This permitted the independent determination of the wind speed at two stratospheric altitudes, indicating v = 160 ± 60 m/s at 300 ± 150 km and v = 60 ± 20 m/s at 450 ± 100 km, i.e. a decrease of the zonal winds in the mesosphere. Winds on Titan can also be measured from Doppler-shifted visible solar lines scattered off Titan haze near 200 km (Luz et al. 2005, 2006). Such measurements, performed before and during the Huygens descent with the UVES instrument on the VLT, also unambiguously showed prograde winds, but only lower limits on the wind speed, of order 50–60 m/s, could be determined, due to the partial smearing of the Doppler signals due to seeing effects in the Earth's atmosphere. Ultimately all of these measurements proved highly complementary to the Huygens wind profile and Cassini thermal wind field in constraining the stratospheric dynamics (see Chapter 13).

2.5.4 Stellar Occultations

Ground-based stellar occultations by solar system bodies are powerful tools to probe planetary atmospheres at pressure ranges from one to some hundreds of microbar. Those observations remain rare, however. Titan, for instance, subtends only 1 arcsec or so on the sky, as seen from Earth. So the probability of the satellite passing in front of a star is small. As of today, there have been six documented ground-based stellar occultations by Titan: one on 3 July 1989 (Hubbard et al. 1990, 1993; Sicardy et al. 1990), one on 21 August 1995 (Tracadas et al. 2001), two on 20 December 2001, involving a double star (Bouchez 2004) and two on the same day on 14 November 2003 (Sicardy et al. 2006; Zalucha et al. 2007).

Ground-based stellar occultations probe the stratospheric and mesospheric regions of Titan's atmosphere, between altitude levels ~600 km down to ~250 km, corresponding to pressure levels between one microbar and ~0.25 mbar. These regions are difficult to observe using other techniques (and even with spacecraft, except with an in situ probe), as visible and IR instruments tend to probe deeper layers, while UV instruments are sensitive to higher regions. Occultations allow us to retrieve temperature profiles and especially temperature gradients, detect density, pressure and temperature fluctuations (thought to be caused by gravity waves), measure haze opacities at various wavelengths and in some case – when a so-called "central flash" is observed -, to derive the zonal wind profiles at the ~250 km altitude level (0.25 mbar pressure level).

2.5.4.1 Temperature Profiles

The star disappearance and re-appearance behind Titan provide, via an inversion procedure, the refractivity profile, then the density profile (assuming a given gaseous composition), and finally, temperature and pressure via hydrostatic equilibrium and ideal gas assumptions. Arbitrary boundary conditions make a unique temperature profile retrieval impossible, so that it is difficult to discriminate between various models (given e.g. by Yelle 1991 or Vervack et al. 2004), at least in the probed region (Sicardy et al. 2006). In any case, the