Introduction

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A brief introduction to Titan

Titan is the only known moon with a substantial atmosphere. Ten times thicker than Earth's, Titan's atmosphere is N_2 based and possesses a rich organic chemistry, including, most likely, amino acids and nucleotide bases. The organic material results largely from methane (the second most abundant constituent), which is irreversibly destroyed by photolysis, and thus must be recently supplied. Its presence in the atmosphere points to a geologically active planet. However, rather than being scarred by volcanic features, Titan's surface is shaped largely by liquid and wind erosion, with dunes, lakes, and drainage systems that weave downhill. Like the terrestrial hydrological cycle, Titan has a methane cycle, with methane clouds, rain, and seas that evolve following the processes that govern Earth's biosphere.

Presently, as a result of the ongoing international *Cassini-Huygens* mission, there is a revolution in our understanding of Titan. The *Cassini-Huygens* spacecraft, launched in 1997, is the largest, most expensive mission sent to the outer solar system. Sixteen European countries, through the European Space Agency (ESA) and the Italian Space Agency (ASI) and the United States, through the National Aeronautics and Space Administration (NASA), designed, built, and now operate the *Cassini-Huygens* mission. Equipped with an orbiter (*Cassini*) and a lander (*Huygens* probe), the spacecraft entered into orbit about Saturn in 2004. The *Huygens* probe descended into Titan's atmosphere on January 14, 2005 and made the first landing in the outer solar system. The *Cassini* orbiter and its twelve instruments are orbiting Saturn and flying by Titan every several weeks. The mission will continue until 2017.

This book discusses the current understanding of Titan's atmosphere and surface: their compositions, chemistries, dynamics, evolutions, and origins. It presents the open questions that presently fuel debate. Studies of Titan's atmosphere began and evolved to the present state in less time than that of a single scientist's career.

This introduction previews the topics covered in the chapters of this book. Science chapters (1–12) are preceded by two prologues, which describe from two different perspectives the making of the *Cassini-Huygens* mission, highlighting the efforts enabling measurements that ultimately have led to the unparalleled and ongoing scientific exploration of Titan.

Prologues

The first prologue, "The Genesis of Cassini-Huygens," introduces a personal account of three scientists who played a key role in the making of the *Cassini-Huygens* mission. Their story discusses the obstacles faced by an international flagship mission from the initial mission idea to the concept, proposal, selection processes, final approval, construction, launch, and operation of the spacecraft.

The second prologue, "Building a Space Flight Instrument: A PI's Perspective," concerns the design, construction, and testing of one of the instruments onboard the *Huygens* probe, the Descent Imager/Spectral Radiometer (DISR), under the umbrellas of several space agencies. This chapter provides a candid account of the challenges involved with the building of a complicated instrument. Setbacks occurred when individual components failed to meet test specifications and specific design problems became apparent, such as undesired interaction between imagers and spectrometers. The author compares the process of building spacecraft instrumentation to a board game in which each move can fundamentally affect the entire project in almost unpredictable ways. Dedication and persistence of the entire team ensured that the final outcome of this game was a great success.

Chapter 1: The origin and evolution of Titan

Substantial new insights into Titan's formation and evolution are provided by the data returned since 2004 from *Cassini-Huygens* with regard to interior structure, surface morphology, and atmospheric composition. The origin of Titan's nitrogen atmosphere and the source of methane constitute some of the key open questions, which as a result of the *Cassini-Huygens* mission can to be examined in significantly more detail on Titan.

Chapter 1 provides an in-depth review of present-day knowledge of the physical and chemical processes that affected the origin and evolution of Titan. It discusses three broad topics, namely (1) the present-day interior structure and dynamics, (2) the origin of the Saturnian system and the accretion of Titan, and (3) the coupled evolution of the atmosphere, surface, and interior of Titan.

Based on the currently best available evidence, including gravity measurements, Titan's interior is not fully differentiated and lacks a substantial iron core (in contrast to Jupiter's Ganymede). Titan probably possesses an internal ammonia-rich water ocean, which is covered by a conducting surface ice shell.

Among the Saturnian moons, Titan is by far the most massive, with Rhea, the next heaviest moon, having a mass only 2 percent that of Titan. Evidence suggests that several Titan-sized moons may have formed during the accretion phase, of which all but Titan have eventually migrated into the proto-Saturn, in contrast to Jupiter's four heavy Galilean moons, which were retained to present-day.

Titan's original atmosphere was likely first formed during the first hundred millions of years, no later than the Late Heavy Bombardment. This early atmosphere may have been more massive and dominated by CO_2, replaced by N_2 in the aftermath of the post-accretional cooling phase. The abundance of CH_4 is likely to have varied considerably over Titan's history as a result of the delicate balance between its source and its destruction. Titan's atmosphere may, for extended periods, even have contained no methane at all.

Atmospheric gases are readily dissolved in the internal ocean and stored as clathrates in the ice layers. Interactions among the atmosphere, icy shell, internal water ocean, and deep rock-dominated interior thus control the atmospheric composition. Evidence for the occurrence of atmosphere–ice shell interaction in particular is provided by the observed sparsity of primordial noble gases in Titan's atmosphere. Atmosphere–surface interactions cause a preferential storage of heavy noble gases in clathrates, thereby removing them from the atmosphere. These processes, during the post-accretional cooling phase, may have retrapped some atmospheric gases, including CO_2 and CH_4, in the surface.

Chapter 1 discusses the evidence for the current view that Titan's present-day atmosphere is the product of outgassing from the surface and interior, or of the release of gases stored in the ocean and ice layers. Any release of heat from Titan's core acts to melt some of the ice and thereby free part of the methane previously stored in the ice, with possible release into the atmosphere through outgassing. This scenario may explain the present-day abundance of CH_4 in Titan's atmosphere. Yet the amount of stored surface and subsurface methane cannot currently be quantified.

Chapter 2: Titan's surface geology

Titan's surface does not resemble the cratered surfaces characteristic of most planetary moons, nor does it have the smooth cracked ice of newly resurfaced moons, such as Europa. Instead, as the only moon with a substantial atmosphere, Titan has a highly eroded surface, shaped by rainfall, rivers, and winds. It is reminiscent of terrestrial and martian landscapes, yet unlike Earth and Mars, it is methane that precipitates out of the atmosphere, and, falling slowly like fluffy terrestrial snow, runs down the hills and gathers, along with ethane, as lakes on the surface. Although methane cycles between the surface and the atmosphere, as does water on Earth, over a longer timescale it is dissociated, producing more complex hydrocarbons that slowly accumulate on Titan's icy lithosphere. The surface, therefore, not only reveals the workings of the methane cycle, but also contains, in the sediments, remnants of Titan's early atmosphere, and perhaps evidence for past climates.

Chapter 2 of this book discusses measurements of Titan's surface, aimed to investigate its composition and the processes that shape the landscape. The current composition of Titan's surface indicates immediately that we do not understand the full historical picture. The main sediment that accumulates on Titan's surface, ethane, is a liquid. If Titan has had a methane-rich atmosphere for most of its existence, then 600 m of ethane would have precipitated onto the surface. The current liquid surface inventory is quite small ($\sim$2 m), and poses the question of the whereabouts of the ethane. Potentially it chemically evolved to form solids. Potentially it hides in or under the solid regolith, in aquifers. As discussed in the chapter, a number of observations point to subsurface liquids, and spectra of the polar lakes indicate the presence of ethane. Yet it is unclear whether all of the 600 m is hiding there; indeed, another possibility is that Titan's atmosphere did not always have a high inventory of methane with which to create the ethane sediments (a point discussed in Chapter 1). The question of the missing ethane is coupled to the question of the presence of methane. The methane must come from the surface, but how? As discussed in Chapter 2, there are candidate volcano features, but not yet a smoking gun.

Cassini is currently identifying distinct terrains, which are somewhat organized, as well as correlations with radar features and their near-infrared (IR) spectra, and evidence of changes such as the rain-wetted ground and lake evaporation. Although *Huygens* found evidence of liquid resurfacing from several separate events. *Huygens* landed in a curious site, one that appears to have experienced a recent deluge, but which resides, more broadly, in a vast dune field. A strong connection appears between surface terrains and atmospheric processes. Dunes are associated with low latitudes, which are predicted to be arid as a result of the circulation. Polar lakes are found to be more abundant in the north, where summers are coolest. These connections indicate the possibility of large variations in Titan's climate in the past.

Studies of Titan's surface are evolving rapidly, currently fueled by continuing *Cassini* measurements, which witness seasonal changes, and by the continued development of the analyses of radar, optical, and infrared data. Yet Titan's surface continues to remain a frontier, open to exploration.

Chapter 3: Thermal structure of Titan's troposphere and middle atmosphere

The temperature profiles of Titan's atmosphere below $\sim$500 km altitude are established at each level by the absorption and emission of radiation as well as by dynamical processes, such as convection, circulation, and waves. Albeit cooler, Titan's temperature–pressure profile resembles that of Earth. Above the surface, which is heated by the absorption of radiation, temperatures decrease as a result of radiative cooling and convection. At a pressure of $\sim$100 mbar, Titan's atmosphere, similar to those of Earth and the giant planets, reaches a temperature minimum (the tropopause). Above this level the temperature increases due to the absorption of sunlight by haze and methane. On Earth, it is largely ozone that heats the stratosphere.

While the major features of the thermal profiles of Earth and Titan are similar, temperature variations across the globe are not. Terrestrial surface temperatures have been observed to vary by 147 K, whereas measurements of Titan's surface temperatures indicate variations of only 4 K, and only between the poles and tropics, rather than with longitude or local time. Higher in the atmosphere, temperatures deviate more substantially, indicating features such as a hot spot at 0.01 mbar in the north pole, which in 2004 was $\sim$40 K hotter that the cooler latitudes.

Chapter 3 in this book presents recent *Cassini* radio, *Cassini* infrared, and *Huygens in situ* measurements of Titan's temperature fields and thermal profiles, and reviews past measurements from the ground and by *Voyager*. This chapter explores the processes that establish Titan's temperature profiles and their variations with time and position. The temperatures in Titan's troposphere are found to manifest mostly the annual disk-averaged insolation rather than the local changes in the insolation, as experienced on Earth. The lack of temporal variations in Titan's surface temperatures derive from the high mass and low temperatures of its atmosphere, which cause the tropospheric radiative response time to be longer than the duration of a Titan year

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(29.5 Earth years). At higher altitudes, where the overlying atmospheric mass is lower and the radiative response time faster than a Titan season, seasonal variations in the temperature field result from variations in Titan's composition as well as dynamical processes. Chapter 3 discusses the physical processes that establish the temperature structure of Titan's lower and middle atmosphere, including the interplay between the atmospheric composition and the atmospheric profile, the surface heating and the planetary boundary layer, and the effects of waves on the middle atmospheric thermal field.

Chapter 4: The general circulation of Titan's lower and middle atmosphere

The global wind systems in Titan's troposphere and stratosphere are discussed in Chapter 4. A strong coupling exists between atmospheric circulation and the opacity sources (gas, haze, and clouds) that are transported by the winds and modify the radiative transfer in the different regions of the atmosphere. Therefore, a comprehensive understanding of Titan's circulation requires knowledge of all three components (temperatures, winds, and composition).

Even though only a few direct wind measurements are available, the circulation can be studied remotely by tracing haze and quasi-inert gaseous species. Observations have revealed that Titan possesses a super-rotating lower and middle atmosphere, whereby observed wind speeds of up to ~200 m/s exceed the spin velocity of the moon (~12.2 m/s in the equatorial middle atmosphere). The origin of this super-rotation, a feature otherwise shared only by Venus' atmosphere, is still subject of debate; Chapter 4 reviews the current theories, highlighting the important role played by General Circulation Models (GCMs).

Theoretical work indicates that zonal jets and super-rotation are strongly affected by the strength and structure of the mean meridional circulation, itself partly a function of parameters such as planetary rotation rate, radius and latitudinal distribution of solar heating. General circulation models originally designed to understand Venus' atmosphere, and later applied to Titan, show that meridional circulation and resulting transport of angular momentum play a key role in understanding the origin of super-rotation on Venus and Titan. Poleward meridional winds transport angular momentum to high latitudes, and angular momentum conservation leads to the formation of observed high-latitude jets. When equatorward edges of these jets become barotropically unstable, barotropic waves form and propagate equatorward at lower heights, transporting angular momentum equatorward. The resulting excess of angular momentum at low latitudes generates the super-rotation there. Whereas these processes are best understood with GCMs, special attention needs to be paid to the numerical conservation of angular momentum. Excessive horizontal numerical dissipation in GCMs will inhibit the formation of super-rotation in the simulated atmosphere.

In addition to super-rotation, Titan's middle atmosphere features a global circulation cell that spans from pole to pole, with downwelling over the winter pole. The existence of this cell is indicated by observations of haze and trace constituents, which accumulate around the winter pole owing to the local downwelling, or subsistence. *Cassini-Huygens* is currently tracing, for the first time, the seasonal changes in Titan's middle atmosphere after the equinox that occurred in August 2009. The reversal of the global circulation is accompanied by changes in temperature, composition, and cloud position.

Chapter 5: The composition of Titan's atmosphere

Like Earth, Titan's major atmospheric component is molecular nitrogen and, similar to that of Earth, Titan's surface pressure is 1.47 bar. Beyond that, atmospheric compositions are strikingly different. Molecular oxygen, the second major species of our atmosphere – and also a significant compound for Mars – is entirely absent in Titan, whose atmosphere is chemically more reductive. Indeed, the second most abundant constituent in Titan's atmosphere, and actually the first one to have been detected, back in 1944, is methane. Water vapor, which can reach several percent in the Earth's atmosphere and governs its weather, is actually present in Titan, but in very tiny amounts and with no comparable importance.

Chapter 5 of the book presents a detailed overview of the current knowledge of Titan's atmospheric composition, mostly from an observational perspective. The *Voyager 1* fly-by in November 1980 spectroscopically revealed a rich stratospheric chemistry with the discovery of a suite of hydrocarbons and nitriles, along with carbon dioxide, which permitted a first insight into the chemical routes at work. The *Cassini-Huygens* mission considerably amplified these findings. Species discovered by *Voyager* are extensively mapped and monitored with time. Most of Titan's stratospheric compounds show strong horizontal, vertical, and temporal variability, an effect of the interplay between the seasonally varying atmospheric circulation and the chemistry. Yet, perhaps the most spectacular result comes from *in situ* measurements during the *Cassini* passes through Titan's upper atmosphere. Samples of Titan's composition around 1,000 km altitude indicate that this region is chemically even more abounding than the stratosphere, holding many heavier and more complex carbon-nitrogen species. *In situ* measurements from the *Huygens* probe are also invaluable, as they reveal the humidity of Titan's atmosphere (albeit at one spot and time) and the abundances of species undetectable from spectroscopy, such as isotopes and the noble gases, which bear information on the satellite's origin and outgassing history.

Chapter 6: Storms, clouds, and weather

In Titan's atmosphere, the second most abundant constituent, methane, exists as a gas, liquid, and solid, and cycles between the atmosphere and surface. Similar to Earth's hydrological cycle, Titan sports clouds, rain, and lakes. However Titan's cycle differs from its terrestrial counterpart, and reveals the workings of weather in an atmosphere that is ten times thicker than Earth's atmosphere, is two orders of magnitude less illuminated, spins more slowly, and involves a different condensable. The *Cassini-Huygens* mission is still ongoing, and knowledge is still limited by the paucity of observations. For example, there is only one measurement of the methane humidity profile for Titan's atmosphere, that measured by *Huygens* as it descended into Titan's atmosphere on January 14, 2005 and landed on the surface at 10°S latitude and 192°W longitude. Yet studies of the moon's weather, circulation, surface composition and geology are mature enough to begin syntheses of this diverse body of work. How physical processes shape the methane cycle on Titan differently from the water cycles on Earth and Mars is gradually emerging. However, the observations, simple physical arguments, or complex models do not yet provide a comprehensive picture of Titan's methane cycle. Instead, the field is at a more interesting point, where observations often indicate several sometimes conflicting explanations.

Chapter 6 discusses the physical processes that control the methane cycle on Titan. The aim is to explore how the basic properties of planetary atmospheres control weather, climate, and transport of volatiles. Toward this end, it is interesting to compare Titan's methane cycle with the hydrological cycles on Earth and Mars. Observations clearly indicate unique characteristics of Titan's weather. On Titan, the hazy skies are generally cloudless, and when clouds appear they are restricted to specific latitudes that change with the season. Although clouds usually cover only ∼1 percent of the disk, occasionally hurricane-sized storms blossom and envelop 15 percent of Titan's surface. In contrast, on Earth, clouds cover 50 percent of the disk and persist over a range of latitudes. Similarly, Titan's segregation of large bodies of liquid to the polar regions contrasts the nearly pole-to-pole ocean on Earth, but resembles the Martian concentration of surface volatiles at the poles. Chapter 6 explores the physical processes that underline the differences between the weather on Titan, Mars, and Earth, integrating observations of the temperature profile (Chapter 3), composition (Chapter 5), clouds, rain, and the surface (Chapter 2) with physical models of the microphysics, thermodynamics, local cloud dynamics, and general circulation (Chapter 4).

Chapter 7: Chemistry of Titan's atmosphere

In any planetary atmosphere, the detailed gas composition reflects the partial conversion of the major compounds to secondary species. The process is usually initialized by the dissociation or ionization of the major species, either by solar irradiation or by other energy sources, such as electron impact or lightning. The result is a wealth of reactive atomic, radical, and ion species that can further interact to build up new molecules. In Titan's atmosphere, the photolytic dissociation of the two major constituents – nitrogen and methane – explains the rich composition of Titan's atmosphere.

Chapter 7 quantitatively examines the chemical pathways that lead to observed composition as depicted in Chapter 5. It includes a detailed description of the major sources and sinks for the various compounds, discussing uncertainties in the chemical routes, associated reaction rates, and missing experimental data. An important aspect, largely overlooked before the *Cassini* discoveries, is the influence of ionospheric chemistry on the neutral composition. About 50 positive ions in the mass-to-charge range m/z = 1–100 were detected and, often, chemically identified. Even more baffling, heavier positive (m/z up to 350) and negative (m/z up to 4000) ions were discovered. Positive ions are obviously a significant source of neutral species through electron recombination. Yet chemistry alone does not define atmospheric abundance profiles, as vertical mixing transports species away from their production region, enhancing their chances to react with molecules present in other levels, and to condense in the lower stratosphere, the ultimate fate for most species. By combining the effects of chemistry and transport, photochemical models are able to reproduce the abundance and profiles of most of the simple species and evaluate their precipitation rates onto the surface. The *Cassini* data combined with laboratory studies are used to study the complexity of the organic chemistry.

Chapter 8: Titan's haze

Titan is shrouded by dense and pervasive haze layers that obscure it from view in visible light, and can be penetrated clearly only at infrared and radio wavelengths. Even before *Voyager*'s images, the haze was realized to be of photochemical origin, essentially the end-product of Titan's carbon-nitrogen atmospheric chemistry. Whereas the *Voyager* encounter revealed the gross haze features, its complete characterization had to await the *Cassini* multi-instrument, time-extended, observations, and, in particular, the unique *in situ* measurements provided by the Descent Imager and Spectral Radiometer (DISR) during the *Huygens* descent from 170 km down to the surface.

Chapter 8 of this book presents the current knowledge of the optical and physical properties of the haze particulates, as well as their vertical and horizontal density structures. Observations of these physical properties indicate the production and evolution mechanisms of the haze. The post-*Voyager* view that aerosol formation took place right above the main and detached haze layers (i.e., near 350 km) had to be revised in the light of *Cassini* discoveries. The upper atmosphere measurements of heavy ions indicate that a perpetual molecular growth takes place near ~1,000 km, terminating with the production of aerosols. Questions remain, however, about the dominant gas-to-solid pathways at work. Ironically, one of the key issues, the chemical nature of haze particles, remains unknown, and, surprisingly enough, aerosols produced in the laboratory under simulated Titan conditions do not appear to show optical properties consistent with Titan's haze spectrum. Similarly, several prominent ice features present in far-infrared spectra lack chemical identification. On the other hand, the fate of the small aerosol particles after their production is better understood. Models of charging and growth into fractal aggregates indicate optical properties that match those observed during the *Huygens* descent, and at high altitudes at other latitudes. The microphysics of Titan's haze at high latitudes and below 100 km requires additional observations and their analyses.

The impact of the haze on the atmosphere's energy budget, dynamics, gas chemistry, and condensation is also discussed in this chapter. In a mechanism known on Earth as the "anti-greenhouse" or "nuclear winter" effect, Titan's haze absorbs a significant amount of solar light but is relatively transparent to thermal radiation from the surface. The net effect is a warming of the stratosphere and a cooling the surface by about 10 K, and a resulting additional forcing of atmospheric dynamics.

Chapter 9: Thermal structure and dynamics of Titan's upper atmosphere

Titan's thermosphere, located above 950 km, forms the transition region between the chemically and radiatively dominated lower atmosphere and the space environment, which hosts high-energy charged particles in the presence of Saturn's magnetic field. Solar extreme ultraviolet (EUV) and far ultraviolet (FUV) radiation is absorbed by primarily CH_4 and N_2 in the thermosphere, leading to local dissociation and ionisation, and thermal heating. Thermospheric temperatures range from ~ 200 K near 1000 km to an average exospheric value of ~150 K.

Titan's thermosphere has been explored *in-situ* with the composition measurements by the *Cassini* Ion

Neutral Mass Spectrometer (INMS). These measurements revealed the region to be highly variable in temperature and composition from one *Cassini* fly-by to the next. Although limited coverage by *Cassini* does not allow one to fully separate variations with time from those with location within the atmosphere and location of Titan within Saturn's magnetosphere, the variability is most likely the result of combined effects from regions below (the troposphere/stratosphere/mesosphere) and above (the space environment).

The influence from below is most likely linked to the presence of atmospheric waves that have been observed at thermosphere heights by the descending *Huygens* probe and identified in INMS data as well. Gravity waves propagate upward from below, partly reaching critical amplitudes in the thermosphere and depositing their energy and momentum there. From above, Saturn's magnetospheric plasma precipitates into Titan's upper atmosphere, causing local ionisation and excitation. The relative importance of these influences from below and above in Titan's thermosphere is as yet unknown and the subject of considerable ongoing research. Although, in a globally averaged sense, the temperatures in Titan's thermosphere can be reproduced with solar heating alone, the *Cassini-Huygens* measurements of high variability have indicated that the energy balance in Titan's upper atmosphere is more complex than previously thought. Qualitatively, a correlation was found between variations in temperature and magnetospheric parameters, but quantitatively solar energy flux is mostly larger than magnetospheric energy flux, thus leaving unresolved the question of origin of thermospheric variability.

Model simulations have shown that thermosphere winds may play an important role in redistributing energy and material horizontally and vertically. The dynamics of Titan's thermosphere cannot be measured directly and can currently be inferred only from the thermal profiles and atmospheric density structure. Because of the unknown contribution from below, though, these inferred wind speeds are still poorly constrained. Strong coupling between dynamics and the distribution of constituents such as CH_4 implies that observed variability in composition is most likely linked to variability in thermospheric winds as well.

Although *Cassini-Huygens* has significantly advanced our understanding of Titan's upper atmosphere, important basic questions such as the principal energy source and the origin of strong variability remain open challenges.

Chapter 10: Titan's upper atmosphere/exosphere, escape processes, and rates

Chapter 10 explores the transition from the thermosphere to the exosphere – that is, from a region where the atmosphere can be treated as a fluid to a quasi-collisionless region where the mean free path of particles exceeds the atmospheric scale height.

One puzzling finding from *Cassini* measurements is the large inferred escape rates of H_2 and CH_4. Escape rates of H_2, inferred from *Cassini* Ion Neutral Mass Spectrometer (INMS) measurements with diffusion models, are around 1.5 times the Jeans (thermal) escape rate. The escape of H_2 is limited in theory by the maximum rate at which H_2 diffuses through Titan's atmosphere (defined as Hunten's limiting flux – a criterion required to satisfy continuity in the atmosphere). The analysis of INMS H_2 densities has revealed this gas to be escaping at the rate of its Hunten limiting flux.

For CH_4 the inferred escape rates are even larger than for H_2 (though below the CH_4 Hunten limiting flux), and indicate the as yet unresolved difficulty in understanding the vertical profiles of these gases on Titan. Although CH_4 profiles can theoretically also be reproduced by assuming a small escape rate and instead vigorous mixing in the atmosphere, this interpretation is contradicted by available measurements of Ar, which suggest moderate atmospheric mixing only. On the other hand, the option of significant CH_4 escape from Titan is undermined by the lack of detection of carbon-bearing ions in the outer magnetosphere of Saturn, which would be expected if escape is significant.

Chapter 10 also examines the energy balance of the thermosphere/exosphere region. Observations of energetic neutral atoms (ENAs) by the *Cassini* Magnetosphere Imaging Instrument (MIMI) ideally complement the INMS measurements by providing a means of characterizing particle populations at large distances from Titan from their interaction with the energetic ions. Earlier studies had qualitatively pointed toward Saturn's magnetosphere as being an important driver of Titan's upper atmosphere and its variability of density and temperature. Comprehensive analysis of INMS and MIMI observations however reveal that magnetospheric particle precipitation plays a more important role in the ionization of the atmosphere, and a lesser role in its heating. Observed and derived magnetospheric power inputs to the upper atmosphere are overall smaller than solar EUV and comparable only on rare occasions.

Chapter 11: Titan's ionosphere

Ionospheres are partially (~1% or less) ionized plasmas that coexist with the neutral upper atmospheres of planets and satellites. Taken together, the thermosphere, exosphere, and ionosphere are part of the transition between the dense lower atmosphere and the tenuous external medium (e.g., interplanetary space or, for Titan, Saturn's magnetosphere). The formation of an ionosphere requires the absorption of ionizing photons (i.e., solar extreme ultraviolet or soft X-ray radiation) by the neutral atmosphere or impact ionization of the neutrals by energetic charged particles originating from the external plasma environment (i.e., Saturn's magnetosphere for Titan). Once created, ionospheric composition (see Chapter 7) can be altered by ion-neutral chemical reactions. Ionospheric density profiles (vertical or horizontal) are controlled by the balance of ionization with electron-ion recombination. Transport of ionospheric plasma is also important. Chapter 11 reviews our current understanding of the ionosphere of Titan, its formation, its composition, its dynamics, and its energetics (i.e., electron and ion temperatures).

An ionosphere on Titan was first seen by the radio occultation experiment during the *Voyager 1* fly-by in 1982, but the first *in situ* measurements took place when the *Cassini* Orbiter passed through the ionosphere in October 2004. During this event the Langmuir Probe (LP) sensor on the Radio and Plasma Wave Spectrometer (RPWS) detected a substantial ionosphere, and the Ion and Neutral Mass Spectrometer (INMS) measured neutral N_2 and CH_4 as well as hydrocarbon- and nitrogen-bearing neutral species. The presence of negative ions was also discovered by the Electron Spectrometer (ELS) sensor of the *Cassini* Plasma Spectrometer (CAPS). The positive ion composition in the ionosphere was first measured by INMS in April 2005, which revealed the existence of a large number of hydrocarbon and nitrogen-bearing ion species. The ion chemistry was shown to be very complex (see Chapter 7). Electron density profiles have also been measured by the *Cassini* Radio Science (RSS) experiment.

Cassini data combined with theoretical models provide a good understanding of many aspects of the ionosphere. For example, solar radiation accounts for about 90 percent of the formation of the ionosphere. Precipitation of energetic electrons and ions from the magnetosphere is thought to be important for the formation of the nightside ionosphere, together with transport of plasma from the dayside. Our knowledge of ionospheric chemistry at Titan has greatly advanced (Chapter 7). Some key issues still require further research, including the high abundance of ion species with mass numbers exceeding 100, the electron loss processes, and the transport of ionospheric plasma into the nightside and into the magnetotail. The behavior of the magnetic field deep in the ionosphere, as measured by the *Cassini* magnetometer (MAG) experiment, also is not entirely understood, nor is the nightglow measured by the UltraViolet Imaging Spectrograph (UVIS) experiment.

Chapter 12: Titan's magnetospheric and plasma environment

Chapter 12 reviews Titan's interaction with the plasma and fields in the external medium. The chapter begins with a description of the types of external conditions in which Titan can find itself. Titan's orbital position of 20 Saturn radii usually places it within the outer magnetosphere of Saturn, although on a couple of occasions the solar wind conditions were such that Titan was located outside the magnetopause in the magnetosheath (that is, the shocked solar wind) during *Cassini* fly-bys. The nature of the magnetospheric plasma depends on whether one is in the dense, higher-pressure plasma sheet or in the lower-density magnetospheric lobe regions. The plasma sheet is tilted and can "flap" up or down so that Titan can find itself in a variety of magnetospheric environments.

Chapter 12 reviews pertinent data from several relevant instruments onboard the *Cassini* orbiter. Thermal plasma properties are measured by the RPWS Langmuir Probe, the INMS, and by the CAPS plasma spectrometer. Energetic electron and ion fluxes are measured by the MIMI sensors. Magnetic fields are measured in the vicinity of Titan by the magnetometer (MAG). Owing to complex spatial and temporal variations, the interpretation of these data requires numerical plasma simulations such as global magnetohydrodynamic (MHD) models and hybrid codes (particle ions and fluid electrons), which are reviewed in the chapter along with data-model comparisons and the resulting interpretations.

The magnetospheric plasma (and its embedded magnetic field) flows by Titan at speeds of about 100 km/s. The flow makes a transition to a dense, cold, and slow ionospheric flow (also see Chapter 11) over a region on the ramside that is about a Titan radius in extent. The interaction is controlled by pressure forces and by mass-loading of the flow associated with ionization of neutrals in the upper atmosphere and exosphere (Chapter 10). An important part of the interaction is the generation of induced magnetic fields in the vicinity of Titan, including in the ionosphere (Chapter 11) and in the magnetotail (or wake). Alfvén wings are prominent features found in the tailward portion of field lines that drape around the satellite. Another interesting phenomena are fossil fields seen in the ionosphere and in the tail. Some parts of the Titan environment evidently have a rather long memory (i.e., hours) of the plasma and magnetic field (e.g., field direction) conditions that were present upstream at earlier times.

The loss of Titan-originating plasma due to pickup by the magnetic field (mass-loading) of the external flow and due to loss in the wake makes a contribution to the overall atmospheric loss (Chapter 10) from the satellite. The introduction of fresh material into the outer magnetosphere probably makes some contribution to the dynamics, although this is still poorly understood.

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Prologue 1
The genesis of *Cassini-Huygens*

W.-H. IP, T. OWEN, AND D. GAUTIER

1 Introduction: Titan viewed from Earth

The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man.
– *George Bernard Shaw*

The exploration of the solar system has become an important part of the glory and dreams of our civilization. The study of the Saturnian system and Titan itself can be traced back more than 400 years to when Galileo first pointed his telescope to the night sky to seek the mysteries of the universe. The *Cassini-Huygens* mission represents the first time in human history that a spacecraft was sent to spend time in the Saturnian system for close-up observations, bringing humanity to the surface of one of Saturn's satellites. We believe that this extraordinary achievement will be remembered as a major milestone in planetary exploration 400 years from now. More than that, it is also the first planetary science project of truly global scale, with scientists from three continents joining the effort. How did it come about?

To begin, let us first summarize what we knew about Titan before the birth of the *Cassini-Huygens* mission. Comprehensive descriptions of Titan studies during the period from its discovery in 1655 to the landing of the *Huygens* probe in 2001 have been published by Fortes (1997) and Coustenis et al. (2009). Here we simply present a few highlights in chronological order.

1655: discovery

Christian Huygens discovered Titan on March 25, 1655, when he was 26 years old. He used a telescope 12 feet long that he had made with the help of his brother Constantjn, Jr. The objective lens was 2.24 inches in diameter with a focal length of 10.5 feet. This focal length was required to overcome the chromatic aberration of the uncorrected lens. Using a magnification of 50, Huygens noticed a small "star" to the west of Saturn, and used another star in his field of view to establish its location relative to the planet. The next night he saw that the "star" had moved through the sky with Saturn and realized that he had discovered the planet's first known satellite (Huygens, 1656; Alexander, 1962). He confirmed his discovery by watching the satellite move around the planet on subsequent nights, eventually determining its period of revolution.[1] These must have been difficult observations, given the long focal length, small diameter, and mediocre quality of the objective lens. The name "Titan" was given to this satellite in 1847 by Sir John Herschel (son of Sir William, who had discovered Uranus). The Titans were ancient deities who, together with a race of giants, were defeated in battles with the Olympian gods when the latter made their home in Greece.[2]

[1] With becoming modesty, Huygens (1689) described his discovery as far less important than Galileo's:

> The moons about Jupiter, it is well known, we owe to Galileo, and any one may imagine he was in no small rapture at the discovery. The outermost but one and brightest of Saturn's, it chanced to be my lot, with a telescope not less than 12 foot long to have the first sight of in the year 1655.

[2] Classical scholars have suggested that the legendary battle between the Titans and giants with the Olympian gods symbolized the conquest of the indigenous people by the Greeks when they moved into the peninsula we now call Greece. The legend tells us that the goddess Athena personally defeated the giant Enceladus and buried him in Sicily under the volcano we call Mt. Aetna. His struggles to get out of this grave caused the earthquakes and eruptions of this volcano, an astounding coincidence with the behavior of the satellite of Saturn that bears his name.