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]

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[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.

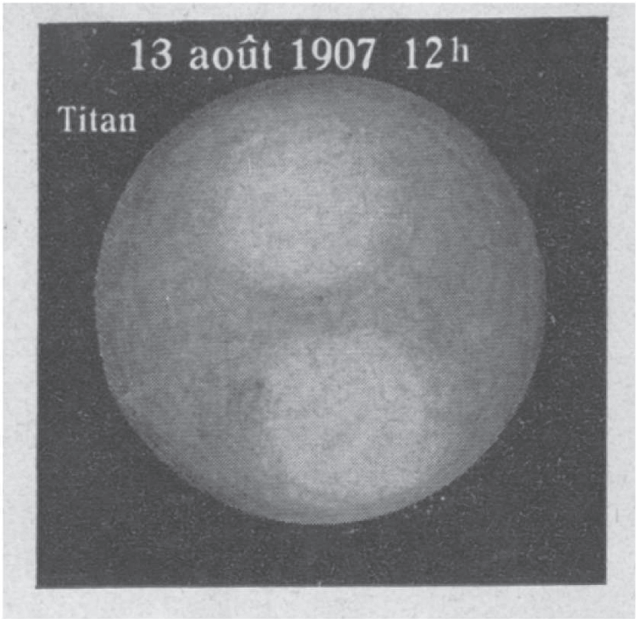

Figure 1 The hand-drawn picture of Titan by Joan Comas Solá in 1907 displaying the limb-darkening effect.

1908: an atmosphere?

In the course of a series of visual investigations of the satellites of Jupiter and Saturn, the Catalonian astronomer Comas Solá (1908) reported limb darkening on Titan that he interpreted as evidence for an atmosphere. Figure 1 shows the hand-drawn picture of Titan by Comas Solá. This observation remains controversial, given that his drawing of Titan is unlike any image obtained by the *Voyager* or *Cassini-Huygens* spacecraft. The same must be said of later drawings of Titan made by Lyot, Dollfus, and Camichel using a larger telescope at a better site (Alexander, 1962). Nevertheless, Comas Solá opened the door to considerations that Titan might have an atmosphere.[3]

1916: an atmosphere?

In his book *The Dynamical Theory of Gases*, Sir James Jeans (1954) investigated the thermal escape of gases from a planetary atmosphere. He accepted the observation that Titan had an atmosphere and pointed out that this was possible despite the satellite's small mass because of its low temperature.

1943: an atmosphere!

In 1943 Gerard P. Kuiper brought these hints, speculations, and predictions to an end when he discovered the 6190 Å and 7260 Å bands of CH_4 in spectra of Titan he recorded on photographic plates at the McDonald Observatory in Texas (Kuiper, 1944). Kuiper was systematically recording spectra of the outer planets and their satellites so it was easy for him to recognize the methane absorptions in Titan's spectrum, given their prominence in the spectra of the outer planets.

1943–1993: These major milestones in the history of Titan observations were followed by 50 years of often conflicting ideas and observations. We skip the details.

Titan is the only satellite in the solar system with a red-orange color. The cause of this color became an interesting topic. Kuiper (1944) proposed that it was the result of a chemical interaction between the atmosphere and the surface analogous to the surface oxidation of Mars. Polarization observations by Veverka (1973) showed that the orange color of Titan must actually be in a thick cloud or haze layer, not on the surface. Khare et al. (1984) proposed that the coloration was caused by aerosols composed of a mixture of complex organic molecules that indeed produced an orange color in laboratory experiments. Sagan coined the word *tholins* for such mixtures, from the Greek word $\theta o\lambda o\zeta$, meaning muddy. These tholins must precipitate, forming deposits on the satellite's surface that could have become several meters deep over 4.6 billion years.

Then there was the issue of the atmosphere itself. What other gases might be present besides methane? Lewis (1971) was the first to propose that Titan might have an atmosphere of N_2 produced by photolysis of ammonia. Atreya et al. (1978) proved that this was indeed a viable process on Titan. This led to models of thick nitrogen atmospheres, of which Hunten's was the most successful. Hunten (1978) postulated an atmosphere of 20 bars, with a greenhouse effect that could

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[3] Comas Solá made many more accurate observations, among them the discovery of a comet now known as 32P/Comas Solá. In 1965, while inspecting a photographic image of this comet recorded by S. Gerasimenko to improve its orbit, K. Churyumov discovered another comet. Their discovery is now the target of the ESA Rosetta mission. It is scheduled to orbit and deploy a lander to inspect the nucleus of comet 67P/Churyumov-Gerasimenko in 2015. So Comas Solá continues to stimulate planetary science.

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produce a surface temperature of 200 K. However, the surface was finally sensed directly by Jaffe et al. (1979), who used the Very Large Array (VLA) of radio telescopes in New Mexico to obtain a surface temperature of only 87 ± 9 K.

Titan was clearly a world worthy of further exploration and the *Voyager* encounters strongly reinforced this conclusion.

2 Titan viewed from space: Pioneer and Voyager

Pioneer 11 was the first spacecraft to reach Saturn. A small, spinning spacecraft with a limited payload, it flew past the planet on September 1, 1979. Its most important findings for our story were a confirmation of Titan's low temperature and verification that a safe passage existed through a gap in the rings.

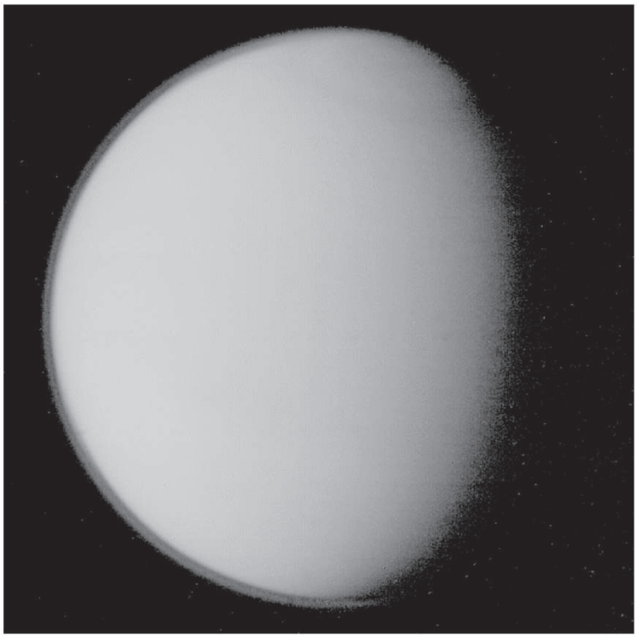

Figure 2 Titan as seen by *Voyager 1*. NASA/JPL Photo.

The big news about Titan came from the sophisticated, three-axis stabilized *Voyager* spacecraft. As the *Voyager 1* spacecraft was approaching the Saturn system in November 1980, both Daniel Gautier and Toby Owen were onsite at JPL as members of the IR spectrometer (IRIS) and imaging teams, respectively. With growing excitement, they watched closely the change of Titan's image from a faint dot to a rounded sphere surrounded by a yellow-orange smog that hid the surface (see Figure 2). It took a few days after the closest approach on November 12, 1980, to analyze the infrared spectra recorded by the IRIS and the results from the radio occultation. The *Voyager* observations showed that the main component of the Titan atmosphere was indeed molecular nitrogen, with a few percent of methane. Hunten's model was actually correct; the atmosphere was simply not as massive as he had thought. A trace amount of hydrogen cyanide (HCN) was also detected in the IRIS spectra, along with several other photochemical products. HCN is often considered to be a precursor of so-called prebiotic molecules that must have been present on Earth prior to the formation of living systems. Even though Titan was so cold, some scientists thought that the smog that hid the surface might include complex organic molecules that could shed some light on the simplest reactions that produced this fascinating chemistry. The idea emerged quite naturally that the next mission to the outer solar system should be a mission to the Saturn system that emphasized the exploration of Titan. The purpose would be to explore in detail the chemistry of its atmosphere by means of *in situ* measurements and to investigate the hidden surface. This required the launching of a probe into the atmosphere of the satellite, accompanied by radar and an infrared spectrometer that could map the surface. That hidden landscape might include oceans of ethane (Lunine et al., 1983; Flasar, 1983) and a rugged landscape constantly reshaped by active "hydrological" processes driven by precipitating hydrocarbons. Here was a satellite with an atmosphere more massive than Earth's, with active organic chemistry taking place today, a primitive world frozen in time.

The Saturnian system, with the gorgeous rings, the retinue of satellites, the majestic central planet with a fast rotating cloud system, and a giant magnetosphere of great complexity, is a miniature solar system that is itself a highly important target for exploration. Scientists quickly responded to these new observations and began planning follow-up missions that could study this intriguing system in more detail as the *Voyagers* continued their journeys toward the other outer planets and ultimately to interstellar space.

In the years 1981–1982, a number of meetings and workshops were organized by NASA to study future possible missions throughout the solar system. Tobias Owen was the chair of the Outer Planets Group of

Table 1 *The SSEC working group for outer planets*

Tobias Owen (Chairman)	State University of New York, Stony Brook
Jeffrey Cuzzi	NASA/Ames Research Center
Rudolf Hanel	NASA/Goddard Space Flight Center
William Hubbard	University of Arizona
Donald Hunten	University of Arizona
Andrew Ingersoll	California Institute of Technology
Torrence Johnson	Caltech/Jet Propulsion Laboratory
Harold Klein	NASA/Ames Research Center
Harold Masursky	U.S. Geological Survey, Flagstaff
Norman Ness	NASA/Goddard Space Flight Center
Bradford Smith	University of Arizona
Lawrence Soderblom	U.S. Geological Survey, Flagstaff
Edward Stone	California Institute of Technology
Leonard Tyler	Stanford University

NASA's Solar System Exploration Committee (SSEC) (Table 1). Daniel Gautier was frequently invited to participate in the discussions as a representative of European scientists. An important outcome of a memorable meeting at Snowmass, Colorado, was the concept of a Saturn orbiter carrying both Titan and Saturn probes, which included a radar mapper to penetrate the Titan haze. However, the NASA workshops were instructed to minimize costs, so these three components had to be proposed as separate missions. The study pointed out that with an international partner it would be possible to combine a Titan probe with a Saturn orbiter. Among its many experiments, the orbiter could carry the radar. During Titan close fly-bys, the mysterious surface of Titan would be scanned by this instrument. Working independently, Wing Ip emphasized the importance of studying Titan's interactions with Saturn's magnetosphere.

Always deeply interested in Titan, Gautier proposed to CNES (France) to build the Titan probe. CNES, after some study, concluded that such a project was too expensive for France alone. In July 1982, ESA issued a call to the European community for proposals for new missions. It was at this point that a series of dramatic events took place that eventually set the stage of the *Cassini-Huygens* mission.

3 The Cassini proposal

The first opportunity for a possible European response to this stimulus came as ESA issued a call for mission proposals in July 1982. Wing Ip, then working at the Max Planck Institute for Aeronomy, Katlenbrug-Lindau, Germany, had the idea to propose a Saturn orbiter with a probe to Saturn or Titan. He called Daniel Gautier to solicit his interest in joining forces in making a proposal for Saturn and Titan. After the introduction, Wing Ip had the impression that the conversation did not go too well. It could be that Gautier found it hard to believe that someone in Germany (let alone in Lindau) might be interested in Titan. The other part was that they had not understood each other well. At the critical moment, however, Wing Ip said to Daniel Gautier: "Dr. Gautier, do you know what this mission is going to be called? It is going to be named '*Cassini*'." Luckily for us all, after ten seconds, he said, "OK. Let's do it!"

Meanwhile, the Solar System Exploration Committee of NASA's Advisory Council recommended that NASA should include a Titan probe/radar mapper in its core program and should consider a Saturn orbiter as a candidate for later implementation. Toby Owen, with his friendship with Daniel Gautier and many others in the European community, knew their plans and engineered the following statement into the final report of his outer planets subcommittee: "The Titan Probe/Radar Mapper mission . . . objectives could be achieved simultaneously with those of a Saturn Orbiter mission by the combination of a Galileo orbiter spacecraft . . . with a Titan probe supplied by an international partner."

The ESA proposal draft was written by Wing Ip, Daniel Gautier, and Michel Combes, with the first two serving as "coordinators." Before submission, the

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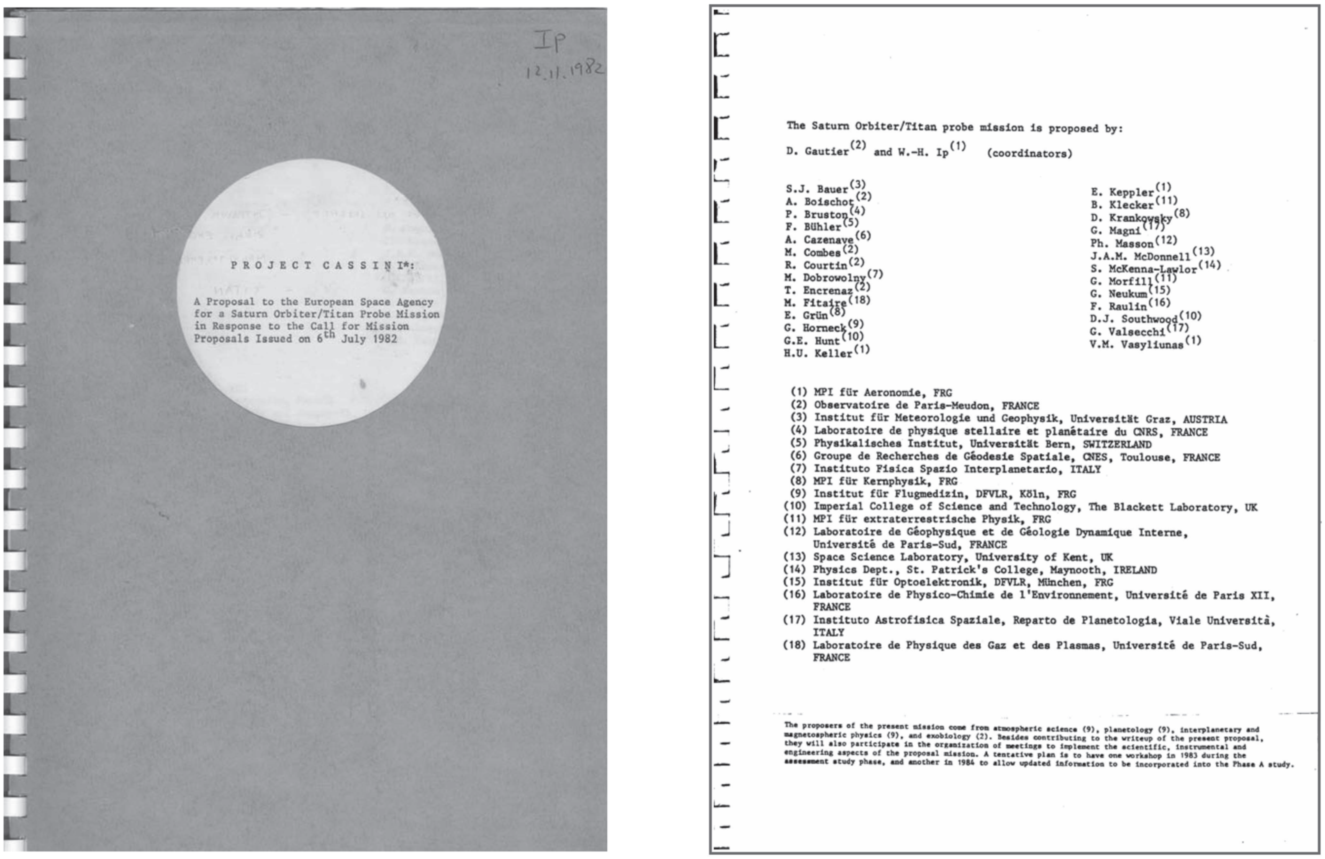

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12.11.1982

PROJECT CASSINI*:

A Proposal to the European Space Agency
for a Saturn Orbiter/Titan Probe Mission
in Response to the Call for Mission
Proposals Issued on 6th July 1982

The Saturn Orbiter/Titan probe mission is proposed by:

D. Gautier(2) and W.-H. Ip(1) (coordinators)

S.J. Bauer(3)
A. Boischot(2)
P. Bruston(4)
F. Bühler(5)
A. Cazenave(6)
M. Combes(2)
R. Courtin(2)
M. Dobrowolny(7)
T. Encrenaz(2)
M. Fitaire(18)
E. Grün(8)
G. Horneck(9)
G.E. Hunt(10)
H.U. Keller(1)

E. Keppler(1)
B. Klecker(11)
D. Krankowsky(8)
G. Magni(17)
Ph. Masson(12)
J.A.M. McDonnell(13)
S. McKenna-Lawlor(14)
G. Morfill(11)
G. Neukum(15)
F. Raulin(16)
D.J. Southwood(10)
G. Valsecchi(17)
V.M. Vasyliunas(1)

(1) MPI für Aeronomie, FRG
(2) Observatoire de Paris-Meudon, FRANCE
(3) Institut für Meteorologie und Geophysik, Universität Graz, AUSTRIA
(4) Laboratoire de physique stellaire et planétaire du CNRS, FRANCE
(5) Physikalisches Institut, Universität Bern, SWITZERLAND
(6) Groupe de Recherches de Géodesie Spatiale, CNES, Toulouse, FRANCE
(7) Instituto Fisica Spazio Interplanetario, ITALY
(8) MPI für Kernphysik, FRG
(9) Institut für Flugmedizin, DFVLR, Köln, FRG
(10) Imperial College of Science and Technology, The Blackett Laboratory, UK
(11) MPI für extraterrestrische Physik, FRG
(12) Laboratoire de Géophysique et de Géologie Dynamique Interne, Université de Paris-Sud, FRANCE
(13) Space Science Laboratory, University of Kent, UK
(14) Physics Dept., St. Patrick's College, Maynooth, IRELAND
(15) Institut für Optoelektronik, DFVLR, München, FRG
(16) Laboratoire de Physico-Chimie de l'Environnement, Université de Paris XII, FRANCE
(17) Instituto Astrofisica Spaziale, Reparto de Planetologia, Viale Università, ITALY
(18) Laboratoire de Physique des Gaz et des Plasmas, Université de Paris-Sud, FRANCE

The proposers of the present mission come from atmospheric science (9), planetology (9), interplanetary and magnetospheric physics (9), and exobiology (2). Besides contributing to the writeup of the present proposal, they will also participate in the organization of meetings to implement the scientific, instrumental and engineering aspects of the proposal mission. A tentative plan is to have one workshop in 1983 during the assessment study phase, and another in 1984 to allow updated information to be incorporated into the Phase A study.

Figure 3 The *Cassini* proposal as submitted to ESA on November 11, 1982.

draft was circulated among the twenty-seven co-signing European scientists for comments and inputs. We would like to take this opportunity to thank everyone in the proposal again. This collection of so many scientists in such diverse fields made a very strong impression. (The cover page and the list of proposers are shown in Figure 3.) The *Cassini* proposal was submitted to ESA headquarters on November 11, 1982. It was stated clearly in the proposal that this mission was meant to be a joint ESA and NASA collaboration. Because of the lack of atmospheric probe technology in Europe at that moment, the division of responsibilities was suggested to be the orbiter spacecraft from ESA and the probe from NASA.

One must say that the *Cassini* proposal was not greeted with a great deal of enthusiasm at ESA. This was partly because the relation between ESA and NASA was at a low ebb at that time, as a consequence of the cancellation of the U.S. spacecraft for the *Ulysses* mission. Beyond this, the scope of the proposed *Cassini* mission was truly daunting from many points of view. It was a credit to the ESA system that, even under these conditions, the Solar System Working Group decided to recommend to the Director of ESA for Science, Dr. Trendelenburg, that he approach NASA about the *Cassini* proposal to open the dialog for a cooperative mission.

4 The long march

In June 1982, the Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Sciences of the United States set up a joint working group (JWG) to study possible cooperation between Europe and the United States in the area of planetary science. Three candidate missions were recommended: (1) Titan probe/Saturn orbiter; (2) multiple asteroid orbiter with solar electric propulsion; and (3) Mars surface rover. An indirect boost to this developing enterprise was the appointment of Roger Bonnet, who was in favor of Europe-U.S. cooperation, as Director for Science at ESA.

In retrospect, the ESF-NAS study played a key role in facilitating the much-needed informal discussions

Table 2 *Titan joint assessment study team*

M. Allison	Goddard Institute for Space Studies	New York, NY	USA
S. Bauer	Karl Franzens Universität	Graz	Austria
J. Cuzzi	NASA Ames Research Center	Moffet Field, CA	USA
M. Fulchignoni	Università La Sapienza	Roma	Italy
D. Gautier	Observatoire de Paris	Meudon	France
D. Hunten	University of Arizona	Tucson, AZ	USA
W.H. Ip	MPI für Aeronomie	Katlenburg-Lindau	Germany
T. Johnson	Jet Propulsion Laboratory	Pasadena, CA	USA
H. Masursky	U.S. Geological Survey	Flagstaff, AZ	USA
T. Owen	State University of New York	Stony Brook, NY	USA
R. Samuelson	NASA Goddard Space Flight Center	Greenbelt, MD	USA
F. Scarf	TRW	Redondo Beach, CA	USA
E. Sittler	NASA Goddard Space Flight Center	Greenbelt, MD	USA

between the American and European planetary scientists on their common scientific goals. Even so, some of the study team members did express doubt about the practicality of a new mission to Saturn and Titan. On more than one occasion, Wing Ip was promised by very prominent scientists (names withheld) on both sides of the Atlantic Ocean a case of pricey champagne – if there were a new Saturn mission in their lifetime! We must therefore pay tribute here to the leadership of the ESF-NAS working groups, especially to Prof. Hugo Fechtig of the Max Planck Institute of Nuclear Physics and Prof. Johannes Geiss of the University of Bern for their foresight and vision in promoting European participation in NASA missions and vice versa. In the same vein, we acknowledge the critical contributions of Jeff Briggs and Ed Weiler of NASA.

By the end of 1983, as a result of the efforts in a positive direction, there was a consensus that within the framework of a joint mission to Saturn and Titan, NASA would provide the orbiter spacecraft and the launch, and ESA would provide the Titan probe. This was to serve as the blueprint of the *Cassini* mission joint assessment study as approved by Roger Bonnet for ESA and Geoff Briggs for NASA. The official joint assessment study was conducted between April 1984 and June 1985. Daniel Gautier and Wing Ip for Europe and Toby Owen for the United States were to act as lead scientists.

We still remember the first study team meeting one evening during the COSPAR General Assembly between June 25 and July 7, 1984, in Graz, Austria. The host was Prof. Siegfried Bauer, who was also the Chair of ESA's Space Science Working Group (SSWG). It was the first time that the youthful Jean-Pierre Lebreton, the ESA study scientist, and rock-solid George Scoon, the ESA study manager, were introduced to their NASA counterparts, Bill Piotrowski of NASA Headquarters (later replaced by Wes Huntress of JPL) and John Beckman of JPL (later replaced by Ron Draper of JPL). A list of study team members is given in Table 2.

The Joint Assessment Study report was completed in August 1985 and presented to the European space science community in the autumn. In February 1986, ESA's Science Program Committee (SPC) approved the study of the Titan probe of the *Cassini* mission for Phase A with a conditional start in 1987 so that the planning activity could be synchronized with NASA's. The Phase A study activities were supported by a joint Europe-U.S. science working group. The composition of this group was the same as that for the Assessment Study, except that four new members were added (see Table 3). George Scoon and Jean-Pierre Lebreton continued to be the study manager and study scientist, respectively, for ESA and Wes Huntress was the NASA study scientist.

During the Phase A study activity, we had benefited from the experience of several veteran American scientists, including the late Hal Masursky and the late Fred Scarf. In addition to this ESA-NASA joint study team, both of them were active in the ESF-NAS working groups.[4] We missed them and their pioneering spirit

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[4] Fred Scarf (TRW, Redondo Beach) in fact chaired the NAS-ESF Working Group on Outer Planets with great charm and efficiency. Besides Hal Masursky (USGS, Flagstaff), the other working group members were Hans Balsiger (Physikalisiches Institut der Universität Bern), Angioleta Coradini (Instituto Astrophysica Spaziale-Rome), Daniel Gautier (Paris Observatory, Meudon), Eberhard Gruen (MPI Kernphysik, Heidelberg), Toby Owen (then at SUNY, Stony Brook), Al Seiff (NASA Ames), David Southwood (Imperial College, London), and Darrell Strobel (NRL, Washington, DC).

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Table 3 *Joint Europe-U.S. study group new members*

Name	Organization	Town	Country
M. Blanc	Centre de Recherches en Physique de l'Environnement	St. Maur	France
S. Calcutt	Oxford University	Oxford	UK
P. Nicholson	Cornell University	Ithaca, NY	USA
B. Swenson	NASA Ames Research Center	Moffett Field	USA

when we had such success with the mission they helped to start.

5 The battle of Bruges

Together with the *Cassini* mission, four other Phase A studies were competing for the final approval by ESA. The presentations of the ESA Phase A studies were scheduled in October 1988 in Bruges. The showdown was held at a movie theatre. The atmosphere was highly charged. Of the five missions, only one would be selected. Their fates would be decided by the votes of the ESA committees at this meeting. For the *Cassini* presentations, Michel Blanc presented the magnetospheric science, and Toby Owen the planetary and satellite science. George Scoon and Ron Draper did superb jobs in reporting on the Titan probe design and the Mariner Mark II spacecraft design, respectively.

One selling point to the scientific community and the ESA committees was that European scientists would have the opportunity to fully participate in a wide range of scientific experiments on both the Titan probe and the *Cassini* orbiter. This was international cooperation at an unprecedented level and scope. The scientific case was so convincing that the SSWG of ESA voted 11 to 2 in favor of *Cassini*. The Space Science Advisory Committee (SSAC) of ESA also found it easy to pick *Cassini* over the astronomy competitor by a vote of 5 to 2. The *Cassini* selection was finalized by the decision of the Science Program Committee (SPC) at a subsequent meeting. ESA gave the Titan probe the name *Huygens* after the Dutch astronomer Christian Huygens, who discovered Titan in 1655; and from then on, the full name of this ESA-NASA mission would be *Cassini-Huygens*.

6 Addition of CRAF and on to Capitol Hill

Even though the *Huygens* project had been formally accepted as the next planetary mission for ESA, the *Cassini* orbiter part remained to be approved by NASA. It had become the task of Toby Owen to convince NASA that *Cassini-Huygens* should be its next new start for planetary exploration so it could be taken to the U.S. Congress for funding approval. If NASA failed to do that, it would miss the budget cycle by four years and ESA would then be forced to give up the *Huygens* Titan probe and do something else instead.

Throughout the years following the ESF-NAS joint working group study, the Mariner Mark II spacecraft developed at JPL was earmarked for two new missions, namely, the *Cassini* mission and the Comet Rendezvous Asteroid Flyby (CRAF) mission. It was obvious that NASA could not afford to have two new separate missions. The strategy developed by J. Beckman and J. Cassini and their colleagues at NASA and JPL was then to produce a single mission package of *Cassini* and CRAF by using the same Mariner Mark II spacecraft with many common components. In this way, it was estimated that the total cost could be reduced to 1.5 times the price of two separate missions. Len Fisk, the NASA Associate Administrator for space science, accepted this idea. From that point on, Toby Owen had to wear the extra hat of a cometary scientist and was given the task to convince the NASA administrator, James Fletcher, why CRAF-*Cassini* was such a wonderful mission and not to be missed. After some careful consideration, James Fletcher nodded to this proposal and CRAF-Cassini was given a green light for the next new start.

The next hurdle was to ask for money from Congress. Therefore, for Owen, the first step to explore the new world of Titan was to explore the brave new world of congressional lobbying. He also asked for the help of American planetary scientists to mount a letter-writing campaign to the politicians on Capitol Hill. Fortunately, enough positive interest in Congress was generated by these activities and the direct presentations by NASA to lead to the inclusion of CRAF-Cassini in the NASA budget.

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7 Subtraction of CRAF, more losses, and the ultimate threat

In a reasonable world, that would have been the end of the story, but the actions of the U.S. Congress often appear unreasonable to the citizens of its country (and, likely, other countries also). In this case, the beautiful dual CRAF-Cassini mission was soon subjected to an extreme budget cut. This resulted in the cancellation of CRAF altogether and the removal of the scan platform, the spin table, and the articulated *Huygens* probe relay antenna from the *Cassini-Huygens* spacecraft. With the remote sensing instruments and particle instruments fixed to the spacecraft, it would be much more difficult to design the observing sequences, and the plasma measurements would be plagued forever by the lack of full pitch-angle coverage. However, the alternative was far worse: no mission!

The announcement of opportunity to propose scientific investigations for the Saturn orbiter of the *Cassini-Huygens* mission was finally made by NASA on October 10, 1989, while simultaneously ESA made a parallel announcement of opportunity for scientific investigators for the Titan *Huygens* probe. Keeping to the original plan, American and European scientists and instruments were assigned to both the orbiter and the probe. The choreography of the preparation of the *Cassini-Huygens* mission on both sides of the Atlantic Ocean was interrupted by firefighting necessitated by the threat of major additional budget cuts, including possible cancellation of the mission by the U.S. Congress in 1994. The crisis was averted in large part because of a letter from Jean-Marie Luton, the Director General of ESA, to Albert Gore, Jr., the vice president of the United States, suggesting politely that a U.S. withdrawal of support for *Cassini-Huygens* would seriously jeopardize any major technological and scientific cooperation in the future.

8 Success!

This proved to be a persuasive argument, which allowed the project to continue unhindered to a perfect launch from Cape Canaveral on the night of October 15, 1997. We were all there witnessing its spectacular ascent as the Titan rocket charged through a stray cloud on the first step of its journey to exotic worlds full of mysteries patiently waiting 4.6 billion years to be explored (Figure 4).

Seven years later, at the meeting on “Titan, from Discovery to Encounter” in April 2004, at ESTEC (the European Space Research and Technology Centre) in Noordwijk, ESA and NASA at JPL (the Jet Propulsion Laboratory) celebrated the successful arrival of the *Cassini* orbiter at the Saturnian system. But it was that first picture from the *Huygens* probe showing the enchanting channels on Titan’s surface (Figure 5) that stunningly confirmed for the entire team that Titan was indeed the captivating world we all dreamed it would be twenty-three years earlier. What bliss!!

9 Afterword

We feel strongly that the international cooperation that was so tremendously successful throughout the development and the ongoing operation of *Cassini-Huygens* should serve as a model for future large-scale missions. Such cooperation will be essential for humanity to reach Titan again. We are delighted to see that this model is very much in the minds of many young American and European scientists who are already planning the next generation of Titan missions.

But the United States and Europe are not the only societies on Earth interested in the exploration of the solar system. Japan, China, India, and Russia are also reaching into space. Our dream of making planetary exploration a truly planetary enterprise is rapidly becoming a reality. Wing Ip has already suggested to Chinese colleagues that they should consider developing a new type of deep-space vehicles called Qian-class spacecraft, to commemorate Dr. Qian Xuesen (Chien Hsueh-Sen, father of Chinese rocketry), who must have dreamt of going to far away places when he worked at Caltech. The Russian space program is looking toward Europa. India is considering a flight to the Moon, Mars, and beyond. Imagine ESA and NASA working together with all these nations. So someday, someone at Meudon might receive a call from a total stranger with a strange accent asking whether he/she would be interested in a joint mission to Titan. . . .

10 Appendix: a brave new world indeed!

It is impossible to sum up in a few paragraphs the extraordinary new knowledge about Titan presented

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Figure 4 A group photo taken at the meeting on “Titan, from Discovery to Encounter” between April 13 and April 17, 2004 at ESTEC. From left to right: Wing Ip, Dennis Matson (*Cassini* project scientist), Daniel Gautier, Toby Owen, George Scoon, and Jean-Pierre Lebreton. Missing from the photo were H. Hassan (ESTEC) and Richard Spehalski (NASA/JPL), who were project managers for ESA and NASA, respectively, during the development phase of the *Cassini-Huygens* project, and Bob Mitchell (NASA/JPL), who was *Cassini* project manager during the operations phase. We thank them and all the other *Cassini* scientists, engineers, and technicians who made *Cassini-Huygens* such an overwhelming success. We single out Jean-Pierre Lebreton, who shepherded the development of the *Huygens* probe virtually every waking moment (plus the occasional nightmare!) for the 23 years required to make the mission happen.

to us by this marvelous mission. We believe *Cassini-Huygens* is successfully completing all of the observations its complement of instruments and teams of scientists could possibly accomplish. We feel as though humanity has discovered a new world. In the course of any exploration of natural environments and phenomena, there are always new questions raised that invite more exploration. In our case, the challenge is both large and extremely attractive. It is worth remembering that we have found a world slightly larger than Mercury that is half ice, half rock, 9 AU from Earth, with a thick nitrogen atmosphere, vibrantly active organic chemistry in progress, a global smog layer that produces vast fields of dunes made of precipitated aerosols, lakes, rivers, and rainstorms of hydrocarbons, and those are just the “tourist attractions” we know. There are surely more, and even these are still poorly understood. We are absolutely certain that future missions to Titan will reveal their own share of scientific and aesthetic surprises.

This book presents the latest findings in the detail they deserve. Here we just summarize a few discoveries that are personal favorites and suggest some directions for further research. As a start, we offer a table that

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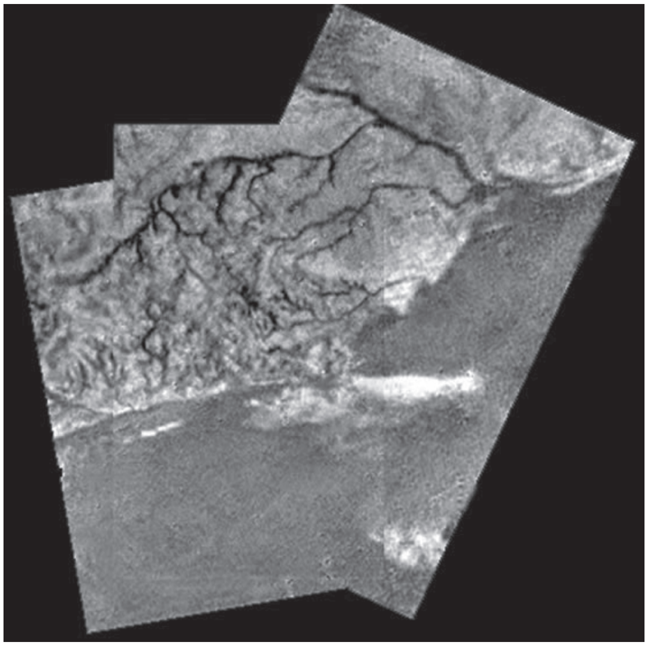

Figure 5 The landscape of dry river beds as taken by the descent imager on the *Huygens* atmospheric probe at about 8 km above Titan's surface. Courtesy of ESA/NASA/JPL/University of Arizona.

lists some basic data on Titan's atmosphere (Table 4) and another one on its general solid body properties (Table 5).

Titan is the only world in the solar system besides Earth that has a predominantly nitrogen atmosphere. It is generally assumed that the nitrogen on Titan was delivered in the form of ammonia hydrate by planetesimals and subsequently converted to N_2 by photolysis. The same process must have produced some fraction of the N_2 in Earth's atmosphere as well.

Table 4 *Titan's atmosphere as measured on the surface at the* Huygens *landing site*

Pressure[a]	1.467 ± 0.001 bar
Temperature[a]	93.65 ± 0.25 K
Composition[b]	(mole fractions; major constituent is N_2)
CH_4	$(5.65 \pm 0.18) \times 10^{-2}$
H_2	$(9.90 \pm 0.17) \times 10^{-4}$
^{36}Ar	$(2.1 \pm 0.8) \times 10^{-7}$
^{22}Ne	$(2.8 \pm 2.1) \times 10^{-7}$
Kr, Xe	$<1 \times 10^{-8}$
Isotope Ratios[b]	
N_2	$^{14}N/^{15}N = 167.7 \pm 0.6$
CH_4	$^{12}C/^{13}C = 91.1 \pm 1.4$
H_2	$D/H = (1.35 \pm 0.30) \times 10^{-4}$

[a] Fulchignoni et al. (2005)
[b] Niemann et al. (2010)

However, the origin of Titan's nitrogen is not completely clear. The *Huygens* Gas Chromatograph Mass Spectrometer (GCMS) found the $^{14}N/^{15}N$ isotopic ratio equal to 168 (Niemann et al., 2010). The terrestrial value is 273. Assuming the nitrogen on Titan was delivered with the terrestrial isotope ratio, there is not yet a quantitative model for nitrogen escape from Titan's atmosphere that could produce this fractionation.

Comets have frequently been offered as examples of the icy planetesimals that built planets and satellites. In the HCN in Comet Holmes, the $^{14}N/^{15}N = 165 \pm 40$. Unfortunately, this ratio has not yet been measured in cometary NH_3 or its daughters, NH_2 or NH. Until this happens, probably in 2015 by the *Rosetta* spacecraft, an important piece of the Titan nitrogen puzzle will be missing.

The methane in Titan's atmosphere is subject to photolysis by solar UV, which is destroying methane at a rate that will remove all of it in two to five decades. The present consensus is that methane is continually replenished from a reservoir provided by a subsurface global ocean. This needs further investigation. Methane also condenses on Titan's surface, forming lakes and rivers that participate in daily and seasonal cycles that include clouds and rain storms. Surface winds are sculpting the aerosol dunes; their speeds and directions must be part of the as-yet-undefined global circulation. This meteorology invites further study to continue investigations of similarities and differences with the hydrology on Earth and Mars.

The high reaches of Titan's atmosphere end in the exosphere. A combination of the high surface pressure of the nitrogen-rich atmosphere and the low surface gravity of Titan leads to a very extended structure with an exobase at about 1450 km, which is more than half of the satellite radius. This means that, unlike those of the Earth, Mars, and Venus, many important photochemical and dynamical processes must be considered in terms of a three-dimensional framework. The *Cassini* measurements have provided tantalizing evidence of latitudinal variations and seasonal changes in the N_2 and CH_4 density distributions of the neutral atmosphere. Another puzzling discovery by *Cassini* was the fact

Table 5 *Basic properties of Titan's solid body*

Semi-major axis to Saturn (km)	1.2218×10^6 km
Eccentricity	2.846%
Sidereal rotational period(s) if synchronous	1,377,684 ~ 15.945 Earth days
GM (km^3/s^2)	8978.133(4)
Mass (10^{22} kg)/density	13.452(2)/1.880(4)
Mean radius (R)	2574.73(9) km
Mean equatorial radius (a/b)	2574.95(6) km (2575.15/2574.78 km)
Polar radius (c)	2574.47(6) km
$q = \omega^2 R^3 / GM$	3.96×10^{-5}
Gravity acceleration (m/s^2) at the surface	1.354
Estimated radiogenic power	300−400 GW
Obliquity	0.3°

Numbers in parentheses are measurement uncertainties.
Source: From Sotin et al. (2009).

that the nightside atmosphere is hotter than the dayside, which might have to with the circulation pattern of the super-rotating atmosphere. The production of negative ions such as the O^-, O_2^- ions and negatively charged aerosols in Titan's upper atmosphere, which is closely related to the precipitation of magnetospheric ions and electrons, is another important finding.

Beyond the destruction of atmospheric methane, the strong coupling of Titan's ionosphere and the Saturnian magnetosphere leads to a richness of photochemistry and ion chemistry that was unexpected and extremely complex. For example, a long list of hydrocarbon and nitrile/nitrogen compounds with masses up to several hundred amu were found by the INMS and CAPS instruments. Careful calibrations of the observational data and detailed chemical modeling are now in progress to trace the origins of different chemicals.

The synthesis of organic aerosols (tholins) in Titan's upper atmosphere with the formation of benzene (C_6H_6) as a pathway must be the source of the aerosols making up the global smog layer. These particles are precipitating steadily, forming vast fields of dunes on Titan's surface. What are the compounds in these aerosols? How do they relate to the compounds found in the upper atmosphere? What happens to the solid particulate matter once it has landed on the surface or fallen into one of the lakes? Is there synthesis of even more complex prebiotic molecules as a consequence of cosmic ray irradiation, meteoroid bombardment, or solution in warm little hydrocarbon ponds? Obtaining the answers to these fascinating questions will require amphibious rovers that can investigate the composition of the particles in those mysterious dunes and any "pond scum" that might be found in the hydrocarbon lakes.

Such rovers must also be capable of measuring the value of D/H in Titan's ice to establish the relationship of this satellite to comets and Enceladus, providing an essential component of any serious ideas about Titan's origin. Determination of the abundances and isotope ratios of Ne, Kr, and Xe will add to the *Huygens* value of ^{36}Ar to improve greatly the existing models for the origin and evolution of Titan's atmosphere. There is still very much to do at Titan!

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