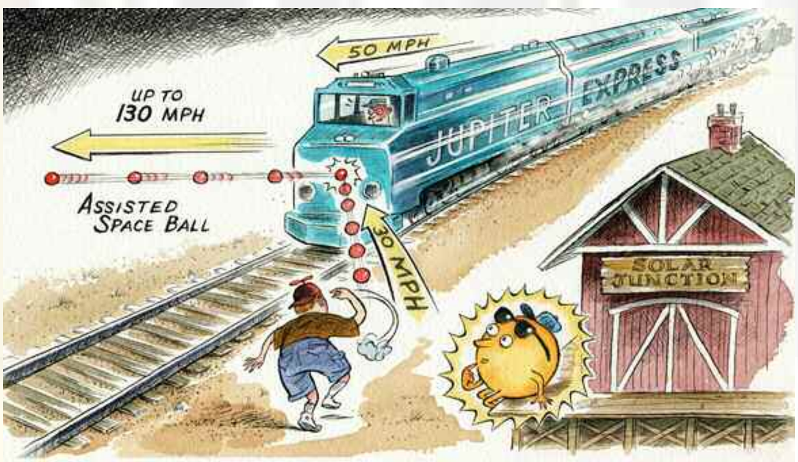
More than six years have passed since I dashed from the control center to watch *Cassini-Huygens*' perfect launch from Cape Canaveral at 4:43 a.m. EDT on October 15, 1997. The ensuing journey has been a long one, given the need to set up four gravity assists en route—two from Venus, one from Earth, and one from Jupiter. Even with the mighty Titan-4B/Centaur expendable launch vehicle, one does not send a 5,550-kilogram (12,235-pound) spacecraft directly to Saturn. Instead, it must be forced to gain a total of 21 kilometers (13 miles) per second from four clever slingshot maneuvers, robbing each of the assisting planets of minuscule amounts of its own speed about the Sun. Insertion into Saturn orbit is scheduled for June 30, 2004 (PDT). With the NASA/JPL *Cassini* spacecraft orbiter and its attached European Space Agency (ESA) *Huygens* Titan probe in excellent health, we anticipate an exciting four-year tour of Saturn, its great rings, and its many moons.

I had joined the NASA/JPL *Mariner Mark II* (*MMII*) team half time after the *Voyager 2* encounter with Uranus in 1986, becoming full time in late 1989 following the epic flybys of Neptune and its large moon Triton. At the time, the *MMII* program consisted of two missions—one to Saturn and Titan (known initially as SOTP, or Saturn Orbiter Titan Probe) and another to an asteroid and a comet (CRAF, or Comet Rendezvous Asteroid Flyby). Under the umbrella of the *MMII* program, these missions were to use as much common hardware as possible to keep costs down. Unfortunately, this was not the way the federal budget office saw matters, and CRAF was canceled in late January 1992. Several months later, Dan Goldin became NASA administrator and resolved to usher in a new era of "faster, better, cheaper," threatening to cancel *Cassini-Huygens* as well in late 1993.

With many countries participating in this great mission, none of us could imagine Goldin taking this drastic step and damaging our country's relationship with the Europeans. To our joy, on June 14, 1994, Jean-Marie Luton (then director general of ESA) sent a powerful letter to Vice President Al Gore, with copies to the US secretary of state, key office directors, and of course Dan Goldin. It did the job in saving *Cassini-Huygens,* particularly through its penultimate paragraph, which read, "Europe therefore views any prospect of a unilateral withdrawal from the cooperation on the part of the United States as totally unacceptable. Such an action would call into question the reliability of the U.S. as a partner in any future major scientific and technological cooperation." Goldin allowed *Cassini-Huygens* to remain on schedule.



In this down-to-Earth analogy, the tennis ball plays the role of the spacecraft, the moving train that of the assisting planet, with the Sun fixed on the station platform. The train engineer sees the ball approach and leave at a relative speed of roughly 130 kilometers, or 80 miles, per hour (for a head-on throw and a perfectly elastic collision). The Sun sees the ball initially traveling at 48 kilometers (30 miles) per hour, only to bounce off the train at an amazing 210 kilometers (130 miles) per hour! The big gain in speed relative to a fixed observer is achieved by a minuscule reduction in the train's speed. Were the assisting body at rest, there would be no net speed gain after the encounter.

Illustration: Gary Hovland, based on a concept by the author

Left: This image of Saturn from 111 million kilometers (about 69 million miles) was taken by Cassini*'s narrow-angle camera on November 9, 2003. Exposures through different spectral filters were combined to yield the natural color seen. In addition to faint banding in Saturn's atmosphere, the planet's shadow on the rings also may be seen. As the spacecraft closes in on the planet, pictures will become much more detailed and will show storms, wave patterns, and spots. Five of Saturn's icy moons were also detected. Fourteen camera-team scientists from the United States and Europe will use the two* Cassini *cameras to investigate many features of Saturn, its moons, and its rings.* *Photo: JPL/NASA/CICLOPS*

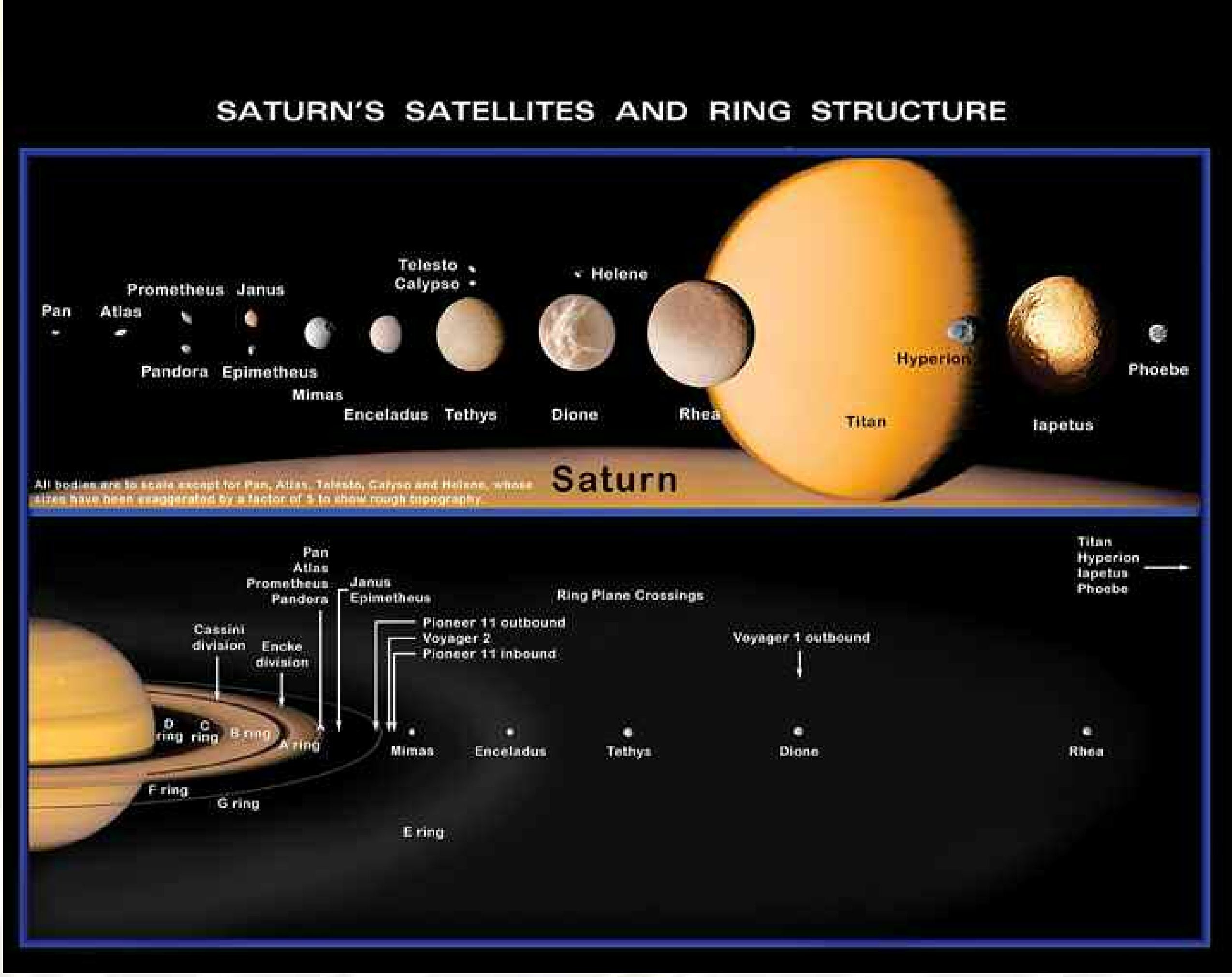
The flight spacecraft, nearly 7 meters tall, in the JPL solar thermal vacuum test chamber. When loaded with more than 3,100 kilograms (about 6,830 pounds) of propellant, its total launch mass was roughly 5,550 kilograms (about 12,235 pounds). Also seen in this photo are the 4-meter-diameter high-gain antenna (top of photo) and the attached 2.7-meter-diameter Huygens *Titan probe (in gold-colored thermal blanket wrap at photo center). Many of the 12 scientific instruments aboard the* Cassini *orbiter appear below the antenna, with the 6 instruments aboard the* Huygens *probe inside the probe payload behind the blanket-covered heat shield.* *Photo: JP/NASA*

The *Cassini-Huygens* international mission has been undertaken by NASA, ESA, the Italian Space Agency, and numerous academic and industrial partners—peaking at nearly 5,000 people before launch, scattered in 18 countries and 32 US states. The orbiter is named in honor of the French-Italian astronomer Jean-Dominique Cassini, who discovered the prominent gap in Saturn's main rings as well as several icy moons. The probe is named for Dutch scientist Christiaan Huygens, born into a prominent family deeply involved in the sciences, literature, and music. Huygens discovered the large moon Titan in 1655 and four years later found that the strange "arms" around Saturn noted decades earlier by Galileo were actually a set of rings.

GRAVITY ASSIST PAR EXCELLENCE

Launch energies to go directly from Earth to Saturn are great, so JPL mission designers had to devise alternate routes. Normally, one would simply use the powerful gravity assist from Jupiter, as did the *Voyager*s in 1979. The Earth-Jupiter-Saturn gravity-assist alignments occur roughly every 20 years, so 1997 was promising. Unfortunately, the heavy *Cassini-Huygens* spacecraft could not be launched to Jupiter with the largest expendable launch vehicle available, so other tricks were needed. This usually calls for swingbys first of Venus and Earth to pick up the speed needed to coast to Jupiter. JPL's Roger Diehl had previously masterminded *Galileo*'s great feat of interplanetary billiards to reach Jupiter, ultimately flying a Venus-Earth-Earth-Gravity-Assist.

Roger combined his formidable talents with those of Chen-Wan Yen to allow *Cassini-Huygens* to reach Saturn by using a Venus-Venus-Earth-Gravity-Assist. This resulted in Sun-relative "delta-Vs" of about 6, 7, 6, and 2 kilometers per second for the en route swingbys, respectively. The small gain at Jupiter (normally many times greater) resulted from the delay in reaching Jupiter and consequent need to fly past at a much greater range to avoid being deflected too much inside and ahead of Saturn's orbital position. This trip plan will cause *Cassini-Huygens* to arrive at Saturn around 7:38 p.m. on June 30, 2004 (PDT at the spacecraft)



Saturn's system of moons and rings is vast, with rings labeled in order of discovery. The faint but far-reaching E ring is thousands of kilometers thick but composed mostly of micron-sized particles that do not pose a threat to the* Cassini *orbiter. The currently known 31 moons exceed the number shown. Most of the more recent discoveries are relatively small, distant, irregular bodies.

Photo: JP/NASA

after firing its main engine for 97 minutes to brake into a loose capture orbit. Never at a loss for seizing opportunities, mission designers have planned a close 2,000-kilometer flyby of distant Phoebe nearly three weeks earlier on June 11.

The *Huygens* probe will be released on December 24, 2004, and after a coast of three weeks, it will enter Titan's atmosphere on January 14, 2005. Originally, the probe was to have arrived at Titan several weeks earlier, but a problem in the probe's receiver aboard the orbiter required a later, more distant flyby to reduce the Doppler shift between the orbiter and probe during the relay link. After recovery and playback of the probe data, the orbiter will continue on its tour, making a total of 75 orbits about the planet by nominal end of mission on July 1, 2008. During the tour, the orbiter will use precision navigation to achieve 45 close encounters of Titan; 3 close flybys of Enceladus; 1 close flyby each of Hyperion, Dione, Rhea, and Iapetus; and several more distant flybys of other moons. Flyby altitudes will be as close as 950 kilometers (590 miles) for Titan and 500 kilometers (310 miles) for some of the targeted icy satellite flybys.

Gravity-assist gains from each Titan swingby are typically in the range of 600–850 meters per second (1,340– 1,900 miles per hour), with the total gain of 33 kilometers (20 miles) per second from the 45 Titan swingbys exceeding that of the four cruise-phase planetary swingbys by 57 percent! Through the use of Titan gravity assists, with Saturn as the central body, *Cassini*'s orbits will be varied to permit excellent viewing of equatorial and polar zones, including the huge but invisible magnetosphere of energetic particles trapped by Saturn's magnetic field. Because scan platforms were eliminated to reduce costs, the entire spacecraft must turn to point the cameras and other sensors at particular targets. More than half of each Earth day will be spent maneuvering to the desired pointing attitudes and collecting scientific data on the solid-state recorders. For the rest of the day, *Cassini* will point at Earth and play back the recorded data.

SATURN

Within our solar system, Saturn is second in size only to Jupiter, but it is considerably larger than Uranus and Neptune. With a diameter more than nine times that of Earth, it could enclose nearly 750 Earths if they were reshaped to fit without empty spaces. With a density less than that of water, however, the planet could float in a vast ocean. Unlike the inner planets, Saturn does not have a rocky surface but is made of gases. Hydrogen and helium predominate, with methane, ammonia, acetylene, propane, and phosphine also present. The gases become denser and hotter as one descends from the cloud tops to the interior. Near the equator, wind speeds reach 500 meters per second (1,100 miles per hour), mostly eastward, but slowing at higher latitudes and even alternating east and west poleward of about ±35 degrees.

We see Saturn as banded in pastel yellows and grays. Interestingly, the colors of the four gas giants differ, partly as a result of their varying distances from the Sun (and hence their temperatures). Jupiter's colors run toward tans and reds, and the more distant Uranus and Neptune appear as shades of pale blue where considerable amounts of methane absorb red light. Saturn radiates about 80 percent more energy than it receives from the Sun, with one explanation suggested by the less-than-expected amounts of helium in its outer atmosphere. Perhaps the missing helium, long ago condensed out of the cool upper atmosphere, has been sinking slowly toward the planet's interior, converting gravitational energy to heat when the fall of the helium raindrops is eventually stopped.

A SEA OF RINGS

The ring systems of Jupiter, Uranus, and Neptune pale in comparison with that of Saturn, so often depicted by space artists. Saturn's rings are a frigid cast of trillions of particles and icebergs ranging in size from that of fine dust to that of houses. They march in orbits around their captor in a vast sheet of amazing expanse and thinness. It is believed that the ring fragments are primarily loosely packed snowballs of water ice, but slight colorations suggest the presence of small amounts of rocky material, possibly even traces of rust (iron oxide). Although the distance from the inner edge of the C ring to the outer edge of the A ring is about 13 times the distance across the United States, the thickness of the ring disk is not more than a few tens of meters, with waves or "corrugations" in this sheet rising and falling by 1–2 kilometers.

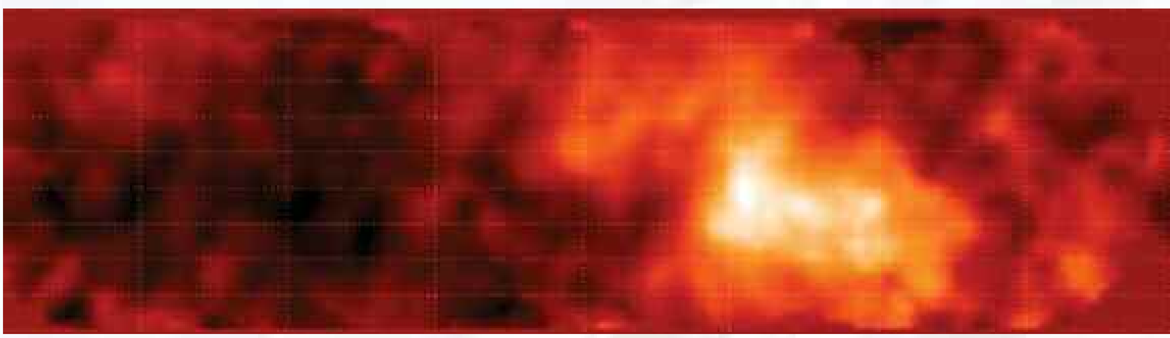
Numerous patterns, both simple and complex, are formed within this rotating sea of icy fragments. They are variously described as circular rings, eccentric rings, kinky rings, clumpy rings, resonance gaps, spokes, spiral density waves, bending waves, and shepherding moonlets. Within the ring sea may orbit tiny moonlets too small for the *Voyager* cameras to have detected. The elaborate choreography of this complex ring system is orchestrated by the combined gravitational tugs from Saturn and its moons that lie out beyond the ring sheet, as well as by the tiny tugs and gentle collisions between neighboring ring particles. The formation and dissipation of the amazing ring "spokes" has been explained by electromagnetic forces acting on charged dust grains dislodged from ring bergs when struck by meteoroids.

How did the rings form in the first place? If one could collect all the particles and icebergs into a single sphere, its diameter would not exceed about 300 kilometers (185 miles), roughly midway between the sizes of the moons Mimas and Phoebe. Are the rings simply leftover material that never formed into larger bodies when Saturn and its moons condensed eons ago? Or, as suggested by the *Voyager* data, are they the shattered debris of moons broken apart by meteoroid impacts? If the impact theory is valid, small orbiting ring moons may be awaiting that moment when they too will be struck and transformed into magnificent rings. Recent findings suggest that the ring system originated shortly after Saturn's formation, with the material in the rings gradually changing and being replenished.

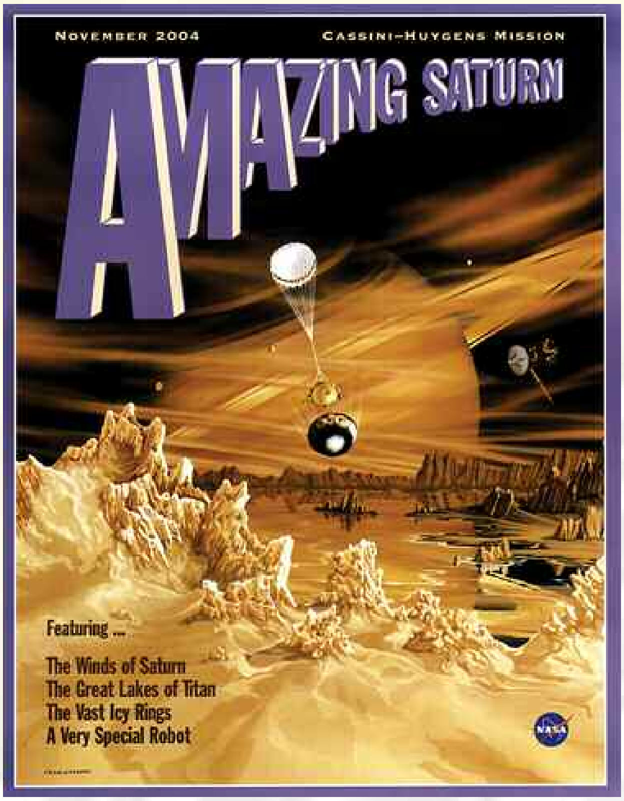
TITAN

Of Saturn's 31 known moons, Titan is not only the largest (bigger than Mercury and slightly smaller than Mars) but also the most intriguing. Its dense atmosphere hides a frigid landscape that may contain mixed-hydrocarbon oceans of liquid ethane and methane sprinkled over a thin veneer of frozen methane and frozen ammonia, which in turn probably overlies a mantle of frozen water ice. These are the latest scientific speculations arising from various hypotheses and from Hubble Space Telescope infrared images of Titan that show bright and dark regions possibly related to continents and oceans. Radar observations from Earth also hint at such a possibility. It could be that rains of ethane and methane, rather than water, fall on Titan's alien surface.

Scientists are fascinated by Titan's brownish-orange haze, which is believed to be made of complex organic (carbon-based) molecules. They are formed in Titan's atmosphere by the bombardment of nitrogen and methane molecules by ultraviolet radiation and high-energy particles. Further reactions can lead to such chemicals as acetylene, hydrogen cyanide, cyanogen, and longer molecular chains known as polymers. These organic polymers



A hydrocarbon-based smog in Titan's dense atmosphere hides the surface in photos taken in the visible spectrum. So in late 1994, Peter Smith of the University of Arizona and his colleagues used Hubble Space Telescope images in the near infrared to glimpse the surface (all longitudes, and latitudes from about 45 degrees South to 60 degrees North, with a newer map in publication to show more of the southern hemisphere). The bright and dark features may represent continents, impact craters, or perhaps oceans. The brightest areas may be highlands washed clean of organic sludge by methane rains, with the darkest areas possibly seas of liquid methane and ethane. Eons of organic chemistry make Titan a dramatic point of interest for the **Cassini-Huygens** ***mission.*** *Image: Peter Smith, University of Arizona/NASA*



A Cassini *poster, fashioned after the* Amazing Stories *science fiction magazine, with the original idea by Mary Beth Murrill, the Titan-Saturn painting by artist Craig Attebery, and overall direction by the author. A designer always faces the tough balancing decision between scientific accuracy and artistic license. In this case, an inspirational impact was chosen, but with the Titan surface probably too spiky and the passing spacecraft too close for scientific precision . . . but very popular with schools and space fans.*

Photo: JPL/NASA

would clump together into larger particles, raining slowly down on the unworldly surface below. If this process has been going on for a few billion years, the accumulated layer could be as deep as several hundred meters!

It is true that organic molecules provide basic building blocks for life, but they are not necessarily produced by life. Even though the Titan environment may resemble the chemical factory of primordial Earth, scientists expect it to be lifeless due to the extremely cold surface temperatures near –180 degrees Celsius (–292 degrees Fahrenheit). With the sensor-equipped probe's slow 2–2.5-hour descent through the atmosphere, as well as the orbiter's 45 flybys of this large and cloaked world, perhaps the findings will shed light on the chemistry of early Earth. Jean-Pierre Lebreton, the *Huygens* project scientist, is particularly excited about the possibility of landing in an ocean and floating upright long enough to analyze the liquids and transmit these tantalizing results to the orbiter before it disappears over the Titan horizon.

SATURN'S OTHER MOONS

Titan may be Saturn's most intriguing satellite, but several of the smaller moons have their own peculiar mysteries. The surface of Enceladus is coated with unusually pure water ice, with much of its surface smooth and uncratered. Could tidal stresses have heated the moon's interior and melted much of the surface, erasing most of the early impact craters? Saturn's distant E ring has an increased particle density in the vicinity of Enceladus' orbit. Could tidal stresses also have created geysers of water or water ice to feed the E ring?

Iapetus is equally interesting. As dark as asphalt on its leading face (as it orbits the planet) and as bright as snow on its trailing face, it perplexed early astronomers by disappearing on the left side (approaching the observer) of Saturn and reappearing on the right side. Arthur C. Clarke chose to feature this moon in his novel *2001: A Space Odyssey,* with its famous journey to the "eye of Iapetus," as it reminded him of a beacon. Has the dark material been swept up from the outside, or did it emerge from the moon's interior?

Many of the other Saturnian moons have their own telltale features, whether large impact craters (Mimas and Tethys), long trenches (Tethys), smaller moons in the same orbit (Tethys and Dione), or even the F-ring shepherding moonlets (Prometheus and Pandora). The "braids" in the F ring have been explained by the gravitational interactions with the shepherding moonlets.

S. S. Sheppard discovered the 31st moon in 2003. A team led by Brett Gladman of the Observatoire de la Cote d'Azur in Nice, France, discovered the prior dozen moons, classifying them as "irregulars," most smaller than 50 kilometers (30 miles). These irregular moons circle Saturn in distant, inclined, elliptical, often retrograde orbits, suggesting capture from the widespread icy debris in the young solar system. Like Hyperion and Phoebe, most of these probably are not in gravitational lock (same side facing Saturn) like the major moons. All in all, Saturn's icy moons are members of an interesting club that *Cassini* will explore with its broad array of sensors.*

THE *CASSINI* ORBITER

The orbiter is a large and sophisticated collection of high-quality hardware and software, integrated very carefully to meet a special challenge. It is three-axis stabilized with the primary purpose of carrying the many scientific sensors to the Saturn system and providing them with such essential services as power, attitude control and pointing, sequencing, environmental control, precision navigation, and data collection and broadcast to Earth.

The orbiter design is the result of years of brainstorming and performance trade-offs, subject of course to budget limitations. New technology is also folded in by way of such advances as solid-state data recorders with no moving parts, very high speed integrated circuit (VHSIC) chips, powerful application-specific integrated circuit (ASIC) parts for onboard computers, and reliable solid-state power switches to eliminate transients that usually occur with conventional power switches.

Cassini can provide some 700 watts of power from the output of its three RTGs (radioisotope thermoelectric generators) to its engineering and scientific subsystems. It can point its sensors to accuracies of a tenth of a degree

The author thanks his friend and colleague Ellis Miner for reviewing the scientific content of this article.

and maintain stability levels ten times slower than the motion of a clock's hour hand. It can control subsystem temperature levels to 10–40 degrees Celsius (18–72 degrees Fahrenheit), navigate to accuracies of 10 kilometers (6 miles) or better, store some 4 billion binary bits of information, and broadcast data to Earth at rates as high as 165,900 bits per second. The 18 instruments aboard the *Cassini-Huygens* spacecraft support 27 different scientific investigations.

THE *HUYGENS* PROBE

The 2.7-meter-diameter probe will enter Titan's atmosphere at about 6 kilometers per second (13,400 miles per hour). It will use a silica-based, shuttle tile–like heat shield to dissipate a heat energy input of 35 kilowatt-hours in less than a minute, reaching peak deceleration levels of 12.6 Earth *g*s and temperatures on its ablative front surface as high as 1,800 degrees Celsius (3,270 degrees Fahrenheit) in the process.

Shortly thereafter, the main parachute, which is 8.5 meters in diameter, will be deployed at an altitude of 170 kilometers (105 miles), followed 30 seconds later by the release of the heat shield and its supporting structure. This will allow the central module of scientific sensors to descend slowly through the murky atmosphere. At an altitude near 110 kilometers (68 miles), the main chute will be released and a smaller drogue chute will provide stability for the remaining descent to the alien surface.

The probe carries accelerometers to measure drag forces in the upper stratosphere, as well as other sensors to measure temperature and pressure. It also carries an instrument to measure the structure and physical properties of the atmosphere, an aerosol collector and pyrolyzer to examine clouds and suspended particles, a gas chromatograph and mass spectrometer to measure the chemical composition of gases and particles in the atmosphere, a Doppler wind experiment to study the effects of winds on the probe, and a descent imager and spectral radiometer to take 1,100 pictures of Titan's clouds and surface in order to learn about aerosols, cloud structure, and the nature and composition of the atmosphere and surface.

The probe's primary mission will be conducted during its atmospheric descent of 2–2.5 hours, but there is always the chance that it might survive touchdown, given a landing speed of only 5 meters per second (about 11 miles per hour). If it doesn't tip over too far, and if it can continue to function on battery power until the orbiter flies over the horizon, it may be able to use the instruments in its surface science package to tell us more about that surface. Its tiltmeter can measure wave motion if it lands in an ocean, and another device will be able to measure the liquid's index of refraction, providing clues to the composition of the ocean. A sounder can even give readings of ocean depths of less than a kilometer.

For more information about *Cassini-Huygens*, visit *http://saturn.jpl.nasa.gov/index.cfm*

Charley Kohlhase was science and mission design manager for the Cassini-Huygens *mission from near inception through launch. He was awarded NASA's Distinguished Service Medal in 2003 for mission design contributions spanning 40 years. Besides part-time consulting for several NASA/JPL missions, he is active in wilderness preservation, photography, and digital artwork—of which samples may be seen at* http://artshow.com/kohlhase *and* http://homepage.mac.com/kohlhase.

This 12- by 20-foot canvas, painted in 1995 by eight East Los Angeles muralists from the Academia de Artes Yepes, ages 8 to 17, depicts the mythological god Saturn removing a veil to allow the* Cassini-Huygens *spacecraft to explore the Saturnian realm in 2004–2008. The mural has been on display at several major museums throughout the United States, including the Kennedy Space Center.

Photo: JPL/NASA