



Chapter 2

Early Concepts, and What It Really
Takes to Explore Alien Skies



To the ancients, the sky was the home of the birds, insects, and bats, creatures that transcended the chains of Earth's gravity to soar above the human world. It was an unreachable realm, home to gods and goddesses. To the Hebrews and early Christians, it was the "first heaven," the place from which the rains came and the winds were born. It was the

Visionaries such as Leonardo Da Vinci dreamed of their inventions flying over Renaissance landscapes. This painting depicts Leonardo's corkscrew design for a helicopter (painting © Michael Carroll)

firmament of weather, and it was a place both mysterious and magnetic. People often feared the weather, but they wanted to understand the sky, too. They wanted to go there. The Greeks penned the story of Icarus, who escaped captivity on wax-fashioned feather wings. His pride brought him too close to the Sun, melting his wings and sending him plummeting into the sea. But while the story of Icarus taught and entertained, other ancients studied the details of meteorology. Aristotle wrote about the nature of freezing water and the dynamics of wind. The first attempt at classifying climate was carried out by observers in the classical Greek period. Our word meteorology comes from the Greek *meteoros*, “high above.”

FIRST DREAMS

In his childhood, Leonardo da Vinci watched birds gliding above the Arno River from the Ponte Vecchio Bridge in Florence. In Milan, as he painted his famous *Virgin of the Rocks* and *Last Supper*, the artist continued to ponder the dynamics of flight. Years later, he watched the creatures of the air coast on updrafts over the canals of Venice. What could they see, far into that part of the world from which snows swirled and rainbows glowed?

It was not until past his thirtieth birthday that Leonardo began to carefully record his thoughts of flight in his sketchbooks. He designed flying machines similar to modern hang gliders. He drafted plans for a corkscrew helicopter, a scaled-up version of small flying toys of the time. He documented the workings of bird and bat wings. In one of his sketchbooks, Leonardo wrote, “The bird is an instrument functioning according to mathematical laws, and man has the power to reproduce an instrument like this with all its movements.”¹

In his *Codex Atlanticus*, written between 1478 and 1519, Leonardo covered over a 1,000 pages with diagrams of mechanical devices, scientific notes, and engineering studies. Within those pages, he documented the wing anatomy of several creatures, including bats, kites, and other birds.

Leonardo’s most detailed flying machine was one he called “the great bird.” The device was laid out so that an aeronaut would lie face down on a wooden plank beneath the wings. Using a system of pulleys, he would move the wings with his feet, pumping his legs much like the rider of a bicycle. The wing movements most closely resembled the movement of the wings of bats.

Leonardo seemed to understand, at least subconsciously, that the weight of the passenger must be low in comparison to the wings, resulting in a stable balance from a low center of gravity. His flapping machine was far too heavy to work under human power, but his studies of fixed wings bear similarity to later gliders by designers such as Otto Lilienthal and George Caley.

In another notebook Leonardo declared, “There shall be wings! If the accomplishment be not for me, ‘tis for some other. The spirit cannot die; and man ...shall know all and shall have wings...”

1. *Codex Atlanticus*, written 1478–1519.

As it turned out, the accomplishment would not be for him, and the first artificial flights would have nothing to do with wings. Instead, the earliest aerial voyages came at the hands of two Parisian papermakers. Joseph and Jacques Etienne Montgolfier noticed that burning paper – which they often saw because of their business – rose into the air. Joseph began to experiment with paper bags. Holding the open mouth of a bag over a fire, the bag became buoyant, floating to the ceiling. The Montgolfier brothers believed they had discovered a new gas, which they humbly called “Montgolfier gas.” The brothers experimented with burning a variety of substances. They came to believe that various materials gave off different gases, and that those gases had different buoyancies. Though they failed to realize that simple hot air was at work, they were the first to construct a vessel that could actually make use of hot air in a practical way (politicians notwithstanding).

On the morning of September 19, 1783, a distinguished crowd assembled on the lawn outside of the Royal Palace at Versailles. Among that crowd were King Louis XVI and Queen Marie Antoinette.

Before them, bobbing in an autumn breeze, floated an immense varnished taffeta bag some 38 ft across, filled with hot air and lined with paper. Golden tassels and signs of the zodiac emblazoned the surface of the royal blue balloon, a design influenced by the Montgolfiers’ sponsor, wallpaper manufacturer Jean Baptiste Reveillon. The Montgolfier brothers wisely christened it the *Aerostat Reveillon*.

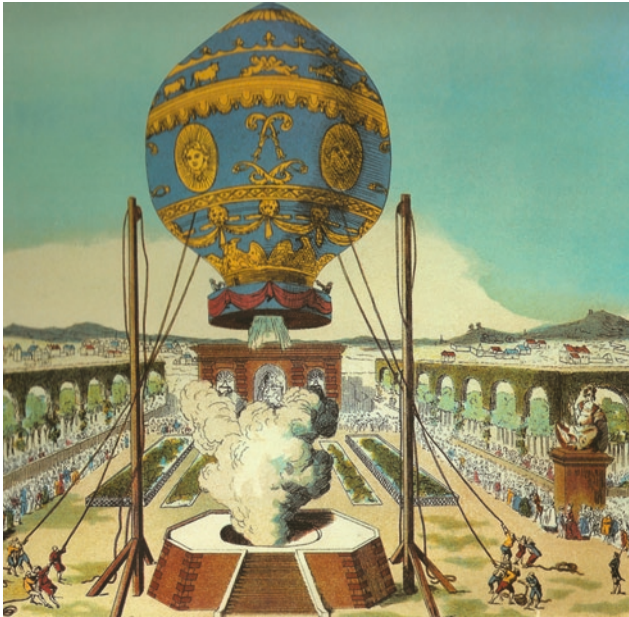
The Montgolfiers took no chances on the strength of their heated envelope. Each overlapping seam was glued together, and reinforced with a total of 1,800 metal buttons. Unfortunately for the onlookers, the inventors decided the best fuels for their first flight included a blaze of shoes and rotten meat. The King and Queen made a hasty retreat. According to one



A model of one of Leonardo's flying devices. Note its similarity to later designs such as those of Lilienthal (San Diego Air & Space Museum)



Early German air pioneer Otto Lilienthal flying one of his gliders, ca. 1895 (courtesy of Ursula Schafer-Symbolon, Historical Archive SDTB)



Engraving of a Montgolfier balloon from a contemporary eighteenth-century postcard (artist unknown, Wikipedia Commons)

contemporary publication, “the noxious smell thus produced obliged them to retire at once.”²

The hot-air balloon carried history’s first air travelers. Its crew consisted of a sheep, a duck, and a rooster. The Montgolfiers considered the duck to be a control in their experiment, as it clearly could survive in the air under natural conditions. The sheep was a land creature, and constituted a good test for a mammal accustomed to living on solid ground. The chicken was a mix, a creature of the air without the natural capacity to spend time up in it.

The momentous voyage lasted roughly 8 min, attaining an altitude of about 1,500 ft. In the end, the airship touched down in a farmer’s field 2 miles away, and the healthy travelers disembarked.

The royal court was impressed and entertained, but some of them must also have been envious of the animal aeronauts. The brother inventors certainly were, and set to work on a balloon that eventually carried the first humans. After several tethered tests, the brothers returned to Versailles on November 21, where they launched the first human-occupied balloon at the royal court. Jean-François Pilâtre de Rozier, a French teacher and physicist, accompanied an infantry officer named Marquis d’Arlandes into the skies above the French countryside.

In the following years, Jules Verne wrote of explorers who circled the world by balloon in his popular *Around the World in Eighty Days*. But Verne dreamed of skies even more distant. And while he wrote of men traveling to the Moon, his *From the Earth to the Moon* found its publication seventeen centuries late, long after another writer envisioned such a trip. In AD 160, Greek satirist Lucian of Samosata wrote of Menippus, a man carried to the Moon by a waterspout.³ Over a millennium later, German mathematician/astronomer Johannes Kepler wrote the *Somnium* (“The Dream”), the adventure of a young student whisked off to the Moon by lunar demons during a solar eclipse. Kepler used the seventeenth-century story to scientifically describe the appearance of Earth from the Moon, and to defend the Copernican (Sun-centered) view of the Solar System. Even J. R. R. Tolkien⁴ wrote *Roverandom* (1928), the story of a toy dog’s adventures on the Moon.

THE VIEW FROM AFAR

With the invention of the telescope, the planets became a serious topic of scientific inquiry. Observers in the eighteenth and nineteenth century began to wonder: do these worlds bear similarity to our own? Do they have days

2. From *Memoires secrets pour servir a l’histoire de la republique des lettres en France depuis 1762*, quoted in James Glaisher, Camille Flammarion, W. De Fonvielle, and Gaston Tissandier, *Travels in the Air* (J.B. Lippincott, 1871, p. 59).

3. Menippus’s journey is described in Lucian’s *True History*.

4. Author of the *Lord of the Rings* trilogy.

and nights, summers and winters, clouds and wind and rain? Venus seemed to be covered in clouds, and some observers thought that the distinctive brightening events on Martian plains were caused by dust storms. Jupiter certainly seemed to be a cloudy world, with its colorful streamers, ovals, and bands.

It would take centuries of focused effort to unravel the tangle of mysteries associated with weather on other worlds. Early researchers considered it likely that the closest planets, Mars and Venus, were quite earthlike. Many believed Venus was “younger” in evolution than Earth, perhaps imbued with an environment similar to Earth’s in the Carboniferous period. Mars was regarded as an ancient world, with an atmosphere thinner than ours, perhaps even a dying planet. Percival Lowell (1855–1916), an amateur astronomer who popularized the idea that Mars was an “abode” of intelligent life, said, “A planet may in a very real sense be said to have a life of its own... It is born, has its fiery youth, sobers into middle age, and just before this happens brings forth, if it be going to do so at all, the creatures on its surface which are, in a sense, its offspring...in the special case of Mars, we have before us the spectacle of a world relatively well on in years, a world much older than Earth.”⁵

And what of the gas giants – Jupiter, Saturn, Uranus, and Neptune? Through the telescope, the fuzzy planets beyond Mars seemed even more mysterious. Jupiter, closest and largest, displayed alternating light and dark



An 1865 illustration of Verne’s explorers getting their first experience with the weightlessness of translunar space. From his novel *From the Earth to the Moon*

5. *Mars* by Percival Lowell. Originally published by Houghton Mifflin in 1895, special limited reprint 1978, pp. 206–207.

Strange Parallels

Space exploration cannot happen without the visionaries, engineers, and scientists first dreaming of what might be. French writer Jules Verne is considered one of the most important futurist writers of the nineteenth century, and one of the founders of the science fiction genre. His novel *From the Earth to the Moon* is a typical example of Verne’s carefully thought out science and prescient hunches. *From the Earth to the Moon* describes the first lunar voyage. The story is rife with parallels to the first real Moon mission, the *Apollo 8* flight in 1968. Here are some of those parallels:

Jules Verne’s Moonship carried a crew of three. The Apollos carried crews of three.

Verne’s ship was shot from a cannon in Florida.

Apollo 8 lifted off at a Florida site just 213 km north of Verne’s site.

Verne’s cannon shell was made of aluminum and weighed 19,250 lb.

The Apollos were constructed of aluminum and weighed 26,275 lb.

After circling the Moon several times, Verne’s ship returned home to a landing in the Pacific Ocean, where it was recovered by a Coast Guard ship.

Apollo 8 splashed down in the Pacific Ocean, where it was recovered by a Coast Guard ship.

bands arranged parallel to its equator. As telescopes improved, nineteenth-century observers could resolve details such as streaks, ovals, swirls, and multicolored festoons that came and went, changing color over time. Saturn and Neptune both hosted their own faint versions of those bands. What were astronomers seeing? What did it mean about weather on these beehemoth worlds, and what was below? Estimates ranged from overcast swamp-worlds to vast volcanic wastelands enshrouded in chilled, poisoned gases. The planets were numbingly remote. How could we discover their natures from such a distance?

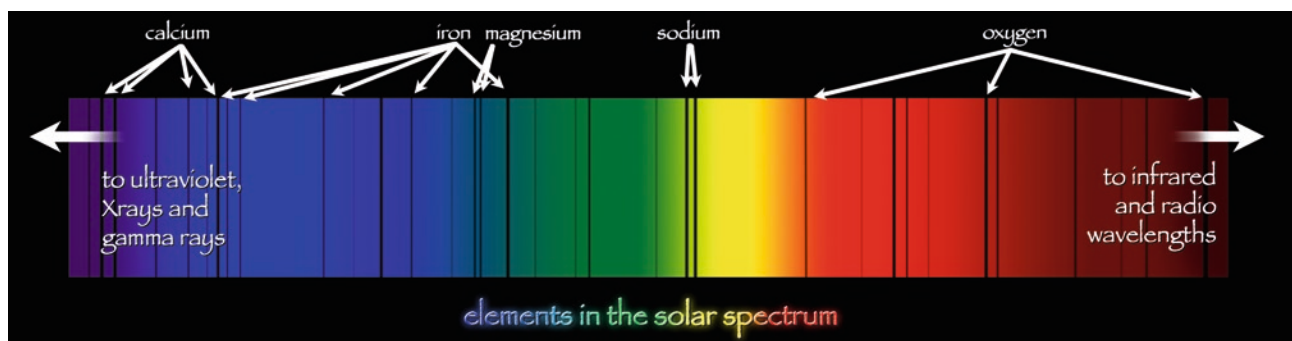
A WIDE SPECTRUM OF INSIGHTS

In 1835, the French philosopher Auguste Comte felt this same frustration.⁶ On the subject of stars, he wrote, “While we can conceive of the possibility of determining their shapes, their sizes, and their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure ... or even their density... I regard any notion concerning the true mean temperature of the various stars as forever denied to us.” A scant 14 years later, German physicist Gustave Kirchhoff discovered that the chemical composition of gas could be determined by splitting the light that it emitted into a spectrum. The new science of spectroscopy was born, and with it, astronomers had a new and powerful tool.

Telescopes began to reveal detailed information with the advent of spectroscopy. Spectroscopy, the study of all the colors in light, gave observers the first information about the constituents in those distant atmospheres. Light from distant planets held wonderful treasures, fingerprints of their components. Dark patterns called absorption lines appeared in unique patterns across the spectrum, revealing what materials were present in the objects being studied. This breakthrough enabled astronomers to send light from their telescopes through a prism. The resulting rainbow of colors enabled observers to chart the dark absorption lines from any planet or moon they wished to study. Even from millions of miles away, materials left traces on the light reflecting off the surfaces and atmospheres of distant worlds.

“Spectroscopy is one of the planetary scientist’s favorite tools because you can study atmospheres from a distance,” says Nick Schneider, researcher at the University of Colorado, Boulder. Schneider’s studies of Jupiter and Io rely on spectroscopy. Using the light signature from these worlds, Schneider can figure out if he is looking at gas rather than ice, and even gives insight into how much atmosphere is there. “It’s a subtle thing. A solid vs. a gas affects the line’s shape. A gas has the purest spectrum. Individual molecules emit and absorb at these characteristic wavelengths very precisely. But if they are bumping into each other or distorting the shape of the molecule, if you have them in a crystal where one molecule can nudge adjacent molecules, all those absorption and emission bands get fuzzed out a little.” Astronomers know that not only does the band’s shape change, but also even the exact

6. Comte was writing in *Cours de la Philosophie Positive*, 1835.



wavelength where most of the absorption happens shifts a little. “We know this because people love to take tanks of gas and cool them down to really low temperatures, shine a light through, and see what the spectrum looks like, or freeze that gas onto a surface, shine a light on it, and see what comes back. This is all confirmed to many decimal places in the laboratory.”

Spectroscopy also yields information about the speed at which an atmosphere is escaping into space, says Schneider. “I study sodium escaping from Io. It emits at the same two wavelengths as the color from yellow–orange streetlights. So the first thing I do is say, ‘Oh, here are those sodium emissions. I know how much sodium is there.’ But once I have that fingerprint of two colors of yellow–orange light at this exact spacing apart, I can use their Doppler shift to figure out if the sodium is coming or going relative to Io. I can measure how rapidly Io’s atmosphere is escaping.” In effect, scientists use a spectrograph as a speedometer.

Another tool at hand for astronomers is that of stellar occultation. MIT’s Heidi Hammel describes the technique as it was used to probe the atmosphere of Neptune’s moon Triton. “You watch a star, and as Triton moves in front of the star, instead of the starlight being blocked out instantaneously by the rocky surface, it drops off gradually and then disappears. That gradual dropoff is a measurement of the properties of the atmosphere surrounding Triton. By carefully modeling the curve as it drops off, you can infer the pressure and temperature, assuming you know the composition.”

Although telescopes provided insight into what constituents floated in alien skies, the instruments afforded only limited detail about the structures of those atmospheres. Were there clouds? Fog? Lightning? Swirling storms? Clear, deep atmospheres? Were other worlds like our own, waiting for us to set up camp?

The Space Age changed all of that. As the data from the first spacecraft trickled back to Earth from Mars and Venus, it became more obvious that there is no place like home. Early data from robotic spacecraft began to paint a more dismal picture of even the worlds close by. A 1964 episode of the popular *Twilight Zone* television series reflects the more pessimistic view science was beginning to adopt. In “The Long Morrow,”⁷ a scientist tries to convince an astronaut to travel to the nearest star because of the bleak

Elements within the Sun – simplified here – leave telltale tracks in a spectrum of sunlight (© Michael Carroll)

7. *The Long Morrow*, written by Rod Serling, © CBS, first broadcast on January 10, 1964.

Atmospheres of the planets and moons display a range of structure and depth. Left to right: Thin hazes over Mars, Earth's "medium" atmosphere, Titan's dense orange gases, and the limb of the gas giant Saturn (NASA)



outlook in our own Solar System. The character says, “And what do we know about our neighbors, Commander? Mars is a vast, scrubby desert with an unbreathable atmosphere. Pluto is poisonous and extremely cold. The Moon is barren, Jupiter volcanic. In short, Commander, our neighbors offer us only one asset: they are accessible...beyond that, they offer us nothing scientific, social, economic, anything.”

This killjoy scientist may have spoken a bit prematurely. Today, we see a menagerie of planetary atmospheres, ranging from diffuse to crushing. Although the worlds of our Solar System possess clearly hostile environments, many hold the promise of untapped resources and places well worth exploring. But how do we get there?

GETTING FROM POINT “A” TO POINT “B”

Waterspouts and lunar demons notwithstanding, the only way to get to another world with today’s technology is by brute force.⁸ Sending a craft to distant planet is like throwing a rock. All the force is unleashed at the start, so the path must be true to begin with. The power involved in casting a payload across the void is remarkable. Just getting to another planet turns out to be a violent and terrifying prospect.

Rockets, the choice of planetary exploration so far, have been around for a long time. The earliest solid rockets were nothing more than glorified fireworks. Called “fire arrows” by their first-millennium Chinese inventors, they were aimed in the correct general direction and let fly with fingers crossed. Fins added stability. Much later designs incorporated liquid fuel, which has a much more powerful impulse (thrust during a given time) than solid rocket propellant. The more advanced launchers were far more complex, and this caused problems in early exploration. Says Lockheed/Martin’s Bryce Cox, “They’d get 4 ft off the pad and just explode, or 10 ft off the pad and they’d auger over and blow up.”

Even today’s sophisticated launch vehicles face daunting challenges and subject their delicate robotic explorers to remarkable stresses. Planetary spacecraft must face the temperature extremes of space, the stresses of

8. An exception to this rule is solar ion propulsion, which uses solar energy to ionize a heavy gas such as xenon. The gas is then magnetically charged and accelerated by magnets to create a weak but steady thrust.

vacuum, and long cruise periods. But the beginning of their journey is just as dangerous.

Before launch, the delicate payload remains in an air-conditioned, carefully monitored environment. The fairing, or shroud, in which it rests atop the booster is pressurized slightly so that no debris can make its way in from the outside. Instrumentation tells ground controllers about the health of both booster and spacecraft, a luxury that early space missions did not have.

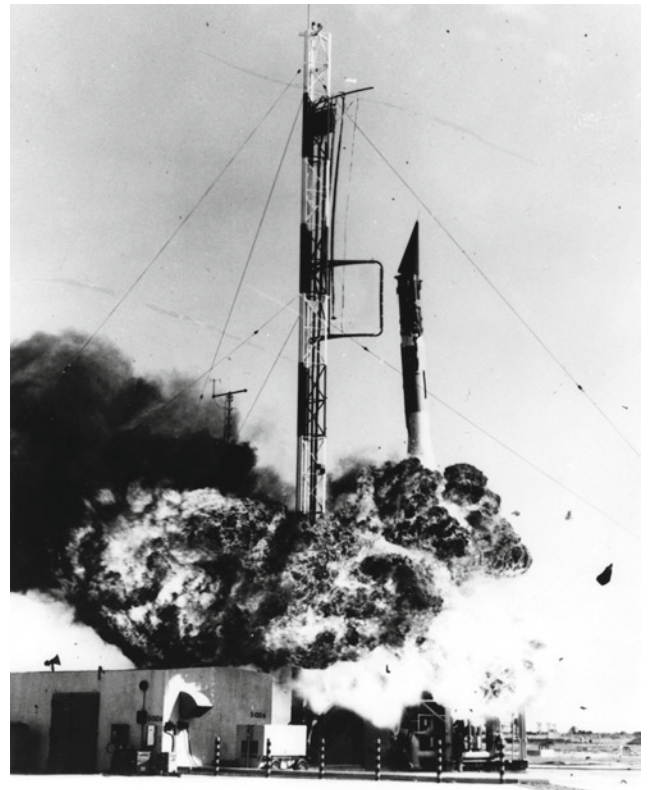
Once the launch vehicle is declared healthy, and the celestial realm is aligned for a launch opportunity, the rocket engines ignite. “You hit T-zero – ignition – and often the motor start-up can be one of the bigger shocks to the payload,” says Cox. “It can be quite a kick.”

The thunderous ignition reverberates, shaking windows miles away. This sonic tidal wave can damage equipment and booster structures. To dampen it, the launch pad is equipped with a water deluge system. Gushing water helps to soften the acoustic energy pouring from the rocket’s engines. As the vehicle ascends, the sound no longer bounces back from the launch pad, but it continues to buffet the very core of the rocket and its cargo.

Large surface areas of a payload are most susceptible to vibration. Equipment such as antennas and solar panels are clamped securely to the body of the spacecraft, often with padding to further protect them. The interior of the payload area may also be blanketed with sound-suppressing material and can even be filled with lighter-than-air gas that transmits sound more poorly than the external environment.

Once airborne, the booster pitches over into the correct flight path. Every rocket has its own frequency, expanding and contracting and flexing as it travels. Each turn and trajectory change causes it to shift like a living, breathing creature. Cox likens an ascending booster to a great undulating coil. “The launcher is like a big spring with a mass hanging off the top – the payload – plus all the other stages down below acting like more springs stacked on each other. The whole thing can get wobbly. You have to know what those fundamental frequencies (the amount of flex) of the launch vehicle are, and then you try to design so that all your thrust controllers and guidance algorithms are separated from those modes.” One tool at the designers’ disposal is called dual plane isolation. Between each stage, a donut-shaped shock absorber softens flight stresses. These isolators filter out vibration and shock.

As the speed of the craft increases, the air becomes an enemy. Dropping air pressure outside necessitates venting of the air inside the shroud. But the



America's first attempt at orbiting a satellite in 1957 was a spectacular disaster. The grapefruit-sized satellite was the Vanguard 1 (NASA)

air pressure against the front of the vehicle increases as air rushes against it, heating up the protective shroud at the vehicle's nose. Temperatures can rise more than 350°F. Some materials such as aluminum begin to lose their structural integrity as they heat up. This degrading, called thermal knock-down, comes at just the wrong time, when the vehicle is reaching its maximum stress. This period is called Maximum Dynamic Pressure (or Max Q). Many flight profiles call for reduced power during this critical time.

The shape of the nosecone can help a booster through its Max Q stage. Aerodynamically efficient shapes plow through the atmosphere with less stress than do wider payloads. Wider shrouds must be stronger to survive supersonic, then hypersonic, voyages through the atmosphere. "Think of it this way," Bryce Cox explains. "If you jump off a diving board and go in the water fairly straight, it doesn't hurt too much, but if you jump off and do a belly flop your velocity, for all intents and purposes, is nearly the same, and the density of the water is the same, but you have a lot more surface area exposed; thus the sting! The dynamic pressure is the same but the results are different. For rockets this 'difference' gets translated into structural design capability. The more surface area exposed, the heavier it has to be to be structurally capable."

As the booster and spacecraft continue into higher levels of the atmosphere, the first stage is dropped and the second fires. Along the way, the shroud is jettisoned, as it is no longer needed in the thinning air. A third stage usually follows the second. Once in orbit, the payload must survive yet another shock as it blasts onto a path that will take it to its ultimate planetary destination.

BUILDING A BETTER PLANET-TRAP

Aside from arriving in one piece, successful planetary missions were challenged by a simple lack of scientific knowledge. Early Soviet designs for Mars probes assumed a much denser atmosphere than the one we now know exists. Had their first Cosmos probes made it to the atmosphere, they would have perished under parachutes far too small to do the job. Soviet Mars and Venus probes were initially patterned after designs for the Luna program, which successfully landed on the Moon first in 1966.⁹ But as knowledge of Venus and Mars accrued, engineers realized that more robust craft were needed to visit alien atmospheres. Thus, designers drew their plans for the larger and more sophisticated Venera (Venus) and MAPC (Mars) probes.

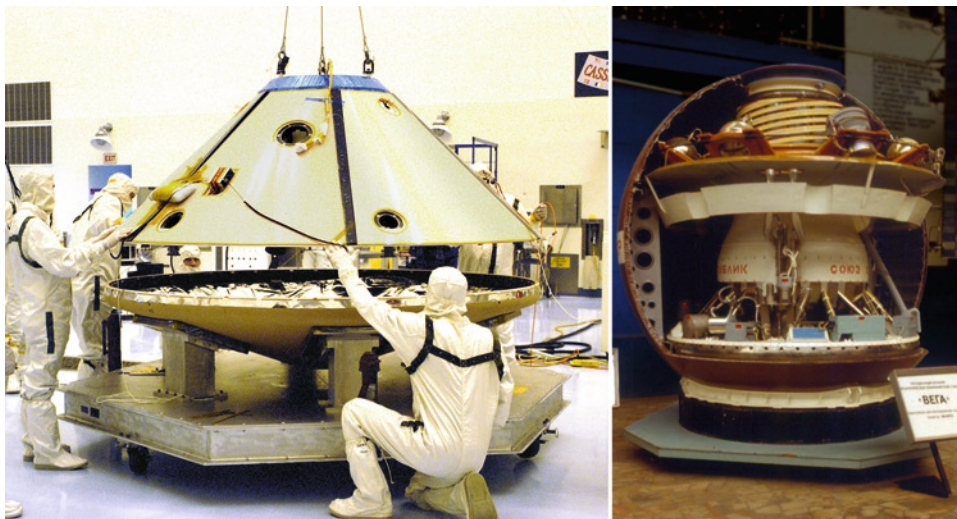
Like the Soviet Union, the United States had a burning interest in seeing what was in the clouds above the two nearest worlds. One of the engineers who worked on early planetary designs was Patrick Carroll, an aerodynamicist at Martin Marietta Corporation. "There were a lot of unknowns," Carroll remembers. "Visually, you couldn't see anything on Venus from here. It was tough to get good design data. That was true even with Viking at Mars;

9. The Soviet *Luna 9* touched down on the lunar plain called the Ocean of Storms on February 3, 1966.

we didn't know if we'd sink in up to the deck or not. It added an interesting aspect to design."

With little data to go on, scientists and engineers combined forces to try to build a probe that just might survive entry into an alien sky. As a space probe approaches any planet, it gains speed under the influence of the planet's gravity. At the point that the probe reaches the upper fringes of the atmosphere, it is usually traveling at a speed at least equivalent to the planet's escape velocity. At the time the first probes were being considered, no craft had survived an entry at such high velocity or temperatures. The proposition was intimidating. American engineers came up with a conical design for an ablative heat shield, a protective cover that would gradually burn off as the craft slowed. The flat cone provided aerodynamic stability, while being blunt enough to eventually slow an incoming craft so its parachutes could deploy. But the harrowing speeds and unknown details of atmospheric structure made designers nervous. Today, computers can model an entry profile, telling designers whether their proposed craft will survive entry or not. In the early 1960s, only the simplest of models existed, done not by computer but by paper and human creativity. Carroll's department was no exception. "Each area had one machine that was a crude computer, much like a cash register. There were punch cards and slide rules. We made do and worked on Saturdays."

Soviet engineers came up with a different design. Like a Russian matryoshka doll, their planetary robots nested inside a metallic globe. The sphere was weighted so that one side would tend to point in the direction of travel. Soviet designs also called for an ablative material to burn off as the sphere entered the atmosphere. The Soviet design worked well, but was unknown to the west for some time. The Cold War was in full swing, explains Carroll. "There was essentially no communications with the Russians, no interface except what we – or they – could steal from each other."



(Left) U.S. spacecraft entered alien skies using a conical heat shield, like this one on the Mars Exploration rovers (NASA/JPL); Soviet era and Russian planetary probes have spherical heat shields, as in this model of the Vega Venus lander (© Ron Miller)

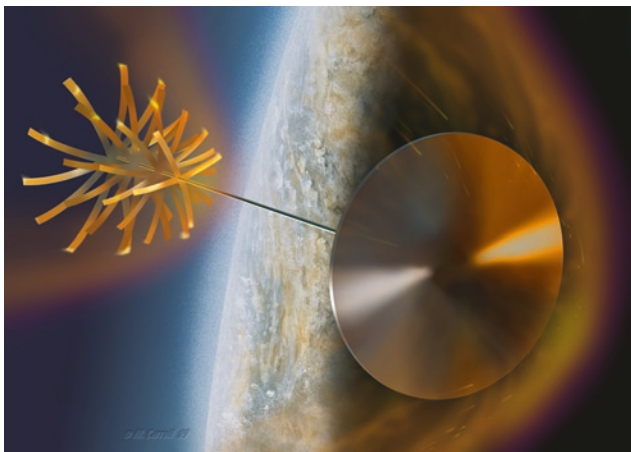
So the Soviet and U.S. programs continued on in their separate ways, with stops and starts, failures and successes. With successes of early Moon probes, scientists felt encouraged that the time would soon come for a successful exploration of planetary atmospheres. But once a probe was safely delivered to the atmosphere, what might it do? For early researchers, the sky was indeed the limit. From simple probes descending slowly on parachutes, designers' techno-dreams expanded to balsa airplane robots plying the skies of Mars and Venus. Some envisioned dirigibles tacking against alien winds for months at a time, relaying information to orbiters overhead. In a cosmic bow to Verne's *Around the World in Eighty Days*, still others preferred Montgolfier-style open-air balloons to explore Venusian clouds and Martian mists. Biophysicist Ben Clark joined planetary exploration with the Viking Mars landers in 1975. He learned of NASA's history and heritage as he walked the halls of NASA's Jet Propulsion Laboratory and later, Lockheed/Martin. "The atmosphere [of Mars] was originally thought to be 80 millibars [ten times what it really is]. We were designing Mars airplanes back then." Those stubby-winged designs were overly optimistic.

Remote sensing refined estimates of the atmospheres of Venus and Mars, forcing a shift in approaches. Venus simmered under copious blankets of dense gases, making entry – and eventual landing – relatively easy in its dense air. But Mars was a different story. Telescopic observations of star occultations, measurements of a star's dimming light as it passes behind the atmosphere as viewed from Earth, showed the Martian air to be dangerously thin, perhaps thinner than that found on Everest. Engineers such as Ben Clark began to wonder if it was even practical to land in the rarefied Mars air. "It turns out that Mars is the hardest place to land on in the Solar System. The atmosphere is thick enough that you can't do a propulsive

landing like you can on the Moon or with asteroids. But it's not thick enough to just land on parachutes like you do on Earth. You have to have an entry capsule, then a parachute to slow you down, and then you've got to get out of that aeroshell to activate your airbags or fire up descent engines. Mars is very tricky that way."

Various spacecraft planners came up with scenarios for skimming along the outer layers of atmosphere to slow down, plunging in with armored probes, or decreasing speed with clever inventions. One such invention was Pat Carroll's brainchild – a hypersonic drag device. The metallic parachute would spring open while the

craft was still traveling far too fast for conventional parachutes, and would be jettisoned, red-hot, after delivering the falling probe to the denser region of the atmosphere. There, a normal parachute could open safely. The idea would be revisited decades later as designers laid plans for the first atmospheric visitor to the outer planets, the Galileo Jupiter probe.



This concept for a hypersonic drag device, patented in 1966, called for umbrella-like strips of metal to slow a probe in the upper atmosphere of a planet (© Michael Carroll)

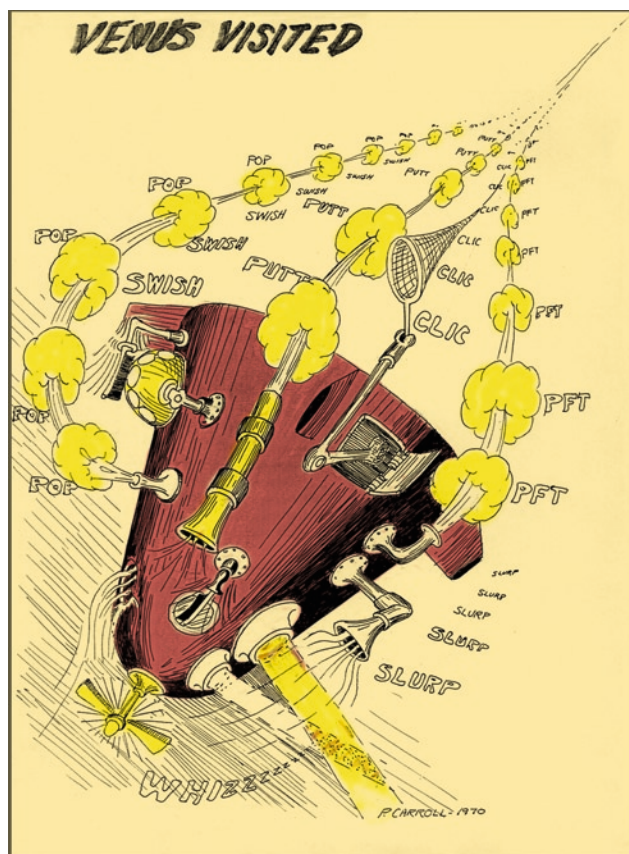
Venus inspired more designs. Because of its dense atmosphere, early plans included a balloon that would inflate to keep a probe up in the cool regions of Venus's hothouse weather. The concept was a complex and expensive one, especially for early 1960s technology, but its day would eventually come.

In the meanwhile, aerospace engineers considered what data could be collected by a descending probe, whether on Venus or Neptune. How much science could you do in the brief time that a parachuting spacecraft had? How long could a probe survive? How could you get scientific data back to Earth from a tiny craft swinging on parachute or balloon lines in alien winds? Early designs showed probes brimming with Rube Goldbergian devices. Scoops, vents, and tubes protruded at wild angles from conical probe bodies. Martin Marietta's Carroll was inspired to draw a cartoon depicting the spirit of his team's early plans. "They wanted to get all kinds of chemical measurements and heat profiles as you went in. Practically every scientist with a different specialty was interested in putting their experiment on it. You have to balance that against how much you can take. There was a lot of uncertainty as to what we were going to get once we were there. You'd be measuring stuff all the way down."

ARRIVAL

Every planet confronts explorers with a unique set of challenges because of the unique nature of its atmosphere. But all worlds share some common hazards to entering spacecraft. After a harrowing launch with vibrations that can break wires or damage instruments, interplanetary robots must brave months in the hard vacuum of space. But more stresses are to come. Aside from launch, the meteoric entry into an atmosphere is the most dangerous part of an atmospheric probe's flight. As it hits the upper fringes of air, friction envelops the spacecraft in an incandescent ball of fire. The heat of entry is more than enough to destroy the spacecraft if it were to absorb all of it. After all, meteors of stone and metal regularly burn up in our own atmosphere. For a robot explorer's survival, something must be done to dissipate the heat.

Initially, molecules of rarefied air bombard the spacecraft. The air flows freely around the craft, rushing across its face while missing sheltered parts of the structure. But as the craft descends into denser gases, air in front of



Patrick Carroll's cartoon spoofing a Venus probe study. The actual design called for even more devices than his drawing depicted (© Patrick Carroll)

the craft stacks up and heats just ahead of the craft in a shock wave. Like water before a speedboat, this superheated wave rides in front of the craft. How close these searing gases come to the spacecraft depends on the shape of the vehicle. Pointed, slender objects move through the atmosphere with a shock wave propagating directly from their point, streaming back in fairly straight lines. If the object is flatter, as in a blunt cone, that shock wave is dispersed and keeps its distance from the surface of the craft. An oblate shape seems the easy way out, but there is a problem: instability. If the protective cone – called an aeroshell – is too shallow, it will wobble and eventually tumble, breaking up in the hypersonic airflow around it. The center-of-mass of the precious cargo inside the entry shell must be forward far enough to keep it stable, and this places the delicate probe nearer the heated surface of the aeroshell.

Heat flowing around the craft, even if it is separated by a shock wave, is usually enough to severely damage whatever is inside. To get around this problem, all planetary explorers have been covered in ablating materials that gradually burn off during entry. As they vaporize, they also reduce heat by flowing into the gap between the shockwave and aeroshell, creating another boundary between the heated gases and the payload.

In many cases, the most unstable time in flight is during the transition from supersonic to subsonic flight. Because of this, many probes are spun up and/or release a small drogue parachute to keep them stable during this phase. The deployment of parachutes or various instruments can be triggered by a “g switch,” a spring-loaded accelerometer that senses the probe’s change in speed. But early researchers realized that accelerometers could also be used for science. The rate at which a spacecraft slows in an atmosphere gives clues to the changing density of the air outside. Temperature and pressure can also be estimated with a great deal of accuracy using data from accelerometers.

Once the spacecraft is safely past the highest heat and deceleration, a parachute is usually deployed to slow its descent and to free the probe from its aeroshell. The flow of air during descent can be used to force air samples into the craft for testing, and vanes can be placed around the probe to create spin for scanning instruments such as photometers (light sensors) and scanning imaging systems. Wind vanes were used on both the Huygens-Titan and Galileo-Jupiter probes.

Sometimes a probe needs to descend faster than a parachute allows. If it is falling through a thick or deep atmosphere, communications may dictate that it make it to a certain depth in a given amount of time. This is especially true if its signals are relayed to Earth by a circling orbiter or passing mother craft. Several Venus probes jettisoned their parachutes at relatively high altitudes to get to lower levels before succumbing to the surrounding heat. The Huygens-Titan probe released its larger parachute to speed its descent. Flight engineers often design free-fall into some portions of flight for probes in the outer Solar System to access deeper levels of atmosphere in a reasonable amount of time.

DEEP SPACE

More advanced concepts were needed for destinations beyond Mars. The outer planets – massive spheres of hydrogen-rich gases – orbit in the frigid realm beyond the Asteroid Belt, where air is chilled to mind-numbing temperatures, liquid gas falls as rain, and lightning crackles in miles-long incandescent streams. With Jupiter, Saturn, Uranus, and Neptune, distance was the first big challenge. No probe had survived travel to the nearest of worlds, let alone a years-long journey to Jupiter, nearest of the four gas giants. Thus, Jupiter became the focus for the handful of outer planets studies in the 1960s and early 1970s.

As early as the late 1960s, engineers envisioned spacecraft equipped to explore the gloomy outer reaches of the Solar System. Solar power was out of the question; distances from the Sun and the power required to get signals back to Earth precluded its use. Batteries were of no use on a decade-long cruise. The only energy adequate to the task was nuclear power. The first focused study, carried out by the Jet Propulsion Laboratory, took the form of TOPS, the nuclear-powered Thermoelectric Outer Planets Spacecraft. The TOPS design was dominated by a 14-foot diameter antenna. The craft would have been powered by four radioisotope thermoelectric generators, or RTGs (plutonium power sources). As it flew by each planet, the mother craft was designed to drop off atmospheric probes. Its launch weight was projected at over a ton (1,446 lb).

Distance, asteroids, and radiation all confronted the survival of the TOPS craft. But the biggest danger, the one that killed the Grand Tour even before its launch, was government budget cuts. As originally envisioned, the multiprobe TOPS was simply too expensive. NASA would need to come up with a different plan for a flyby craft, but in the meanwhile, engineers pondered the design of an atmospheric probe for the outer planets.

The biggest problem for a Jupiter atmospheric probe was speed. A typical entry profile has a probe entering the Jovian atmosphere at a speed of over 100,000 miles per hour. Some designers assumed that survival after entry was not possible, so they were tasked with designing a Jupiter turbopause probe, a probe that would return data from the uppermost atmosphere just before burning up. More daring plans called for a probe to survive the explosive entry and explore Jupiter's multi-colored cloud decks as it swung beneath a parachute or balloon.

"Scientist groups would have big roundtables trying to figure out

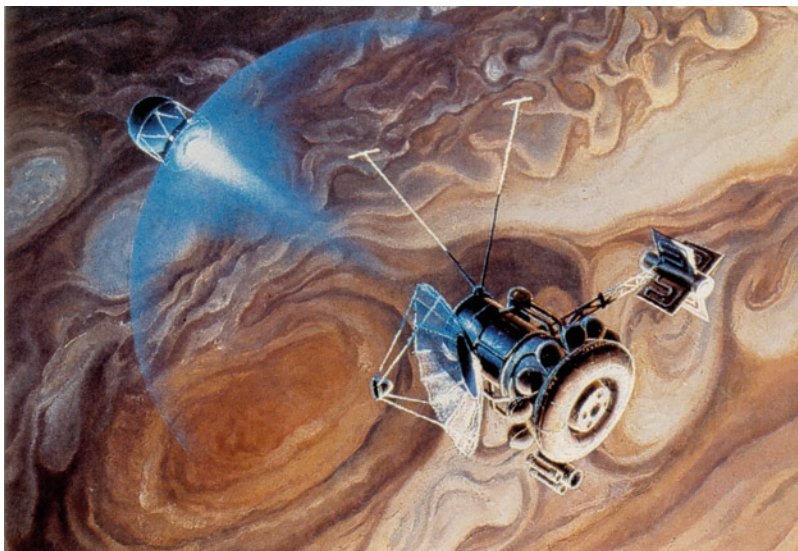
The Thermoelectric Outer Planets Spacecraft, first proposed to take the "Grand Tour" of the outer planets, was projected to be too expensive. Painting by Chuck Bennett (© Lockheed/Martin)





Jupiter turbopause probe, by Chuck Bennett (courtesy Lockheed/Martin)

Soviet design for a flyby/probe mission to Jupiter. This classic painting was done by Soviet artist Andre Sokolov



what would be the right goals, what to measure, and that sort of thing,” Carroll says. “You generally couldn’t do it all with one probe. We had to create different designs. [The scientists] were constantly discussing what to put on it. Every meeting we had, there were major changes and different emphasis. It was fun. Everybody was very cooperative. They kicked all this stuff around, and the group would compromise. They kept getting smarter with what they could do from here, with telescopes, etc., and when they learned something new it changed something for us. Things were constantly fluctuating. That’s the way you do engineering. There are advances in technology as well as advances in knowledge about the target. You want to be able to adjust your programs right up until they launch it off. Then the discussion’s over. It’s on its way, and you take what you can get.”

Soviet scientists drew their own plans. One proposal envisioned a flyby craft that could deploy an atmospheric probe. The probe would descend without a parachute in order to remain

in contact with the flyby vehicle for as long as possible.

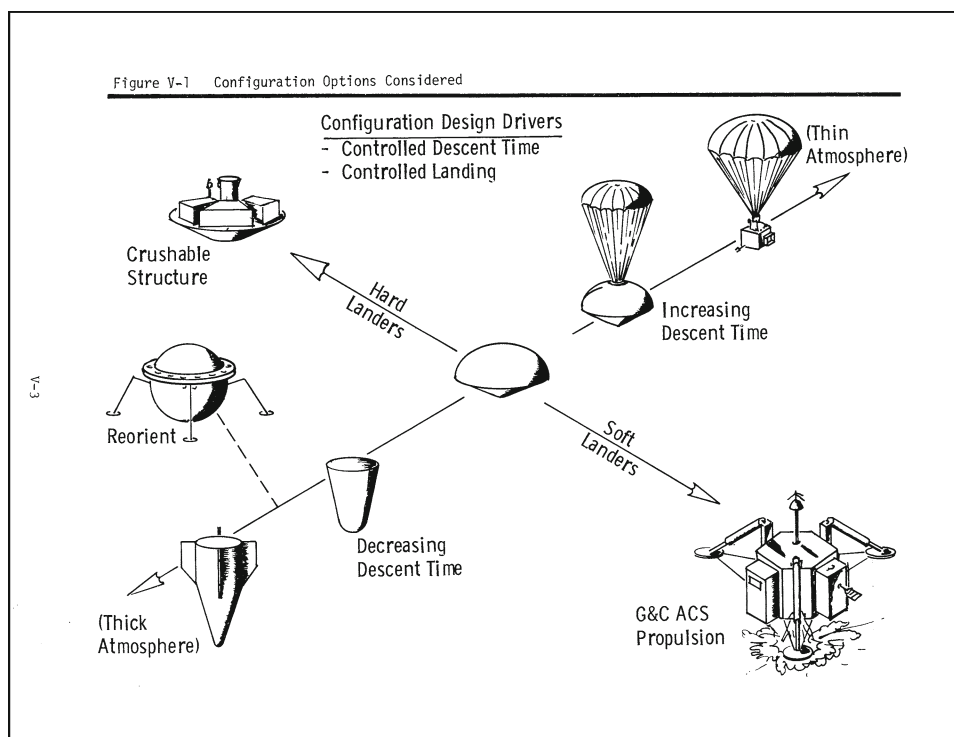
Preliminary U.S. studies were also done of atmospheric probes for Saturn and Uranus, though these were mere formalized ideas compared to Jupiter and Titan studies of the early 1970s. While some visionaries dreamed of Jovian cloudscares and Saturnian sunsets, others looked to the moons of the gas giants. Moons in the outer Solar System range from mountain-sized rocks to nearly planet-sized spheres of stone and ice. Ice reigns in the realm

of the gas giants; most moons are either covered with it or made of it. The four largest moons of Jupiter are members of this exclusive chilly club. Discovered in 1610 by Galileo Galilei, they are called, cleverly enough, the Galilean satellites. The smallest, Europa, is about the size of Earth’s Moon. The largest, Ganymede, is larger than the planet Mercury. None of the Galileans have conventional atmospheres, although rarified oxygen and hydrogen have been detected at Ganymede and Europa. Io floats in a vast cloud of sodium belched

from the throats of its hundreds of volcanoes. As a rule, no substantial atmospheres swath the 164 moons known in the outer system at Jupiter, Saturn, Uranus, and Neptune. The exception is Titan, the mysterious, planet-sized satellite orbiting Saturn.

Titan baffled astronomers from the moment they were able to resolve its spectrum in rudimentary telescopes. It was huge, reddish, and clearly had some kind of atmosphere. Christian Huygens first spied the moon in a telescope of his own design during the spring of 1655. Inspired by Galileo's work, Huygens had set out to find moons of other planets, and his search paid off at Saturn. Over the next few decades, observers calculated Titan's orbit around Saturn, and its approximate size and brightness, but not much more progress could be made for three centuries. At the beginning of the twentieth century, Spanish astronomer J. Comas Sola observed that the edge of Titan faded to a darker color than its ruddy center. This phenomenon is called limb darkening, and is common in planets with dense atmospheres. Sola suggested that Titan had such an atmosphere. He was right. The proof came through the work of Gerard Kuiper in the 1940s. Kuiper was doing a systematic study of the spectra of planets and moons. When he came to Titan, he discovered that the massive satellite reflected light consistent with methane. But Titan's spectrum could not tell him how much air it had. Estimates ranged from a thin, wispy atmosphere to a dense fog like that of Venus.

Less than three decades later, with little more information than what Kuiper had gleaned, engineers were already planning missions to Titan. Saturn is a distant object, orbiting nine times as far from the Sun as Earth



When the first studies of Titan probes were commissioned, scientists were uncertain about the density of the atmosphere. This diagram demonstrates the engineering challenges brought by the wide spectrum of possibilities considered for Titan's environment (From the collection of P. Carroll)



A probe drops a flare over the dark landscape of Saturn's moon Titan in this 1976 NASA/Ames/Martin Marietta technical study (© Michael Carroll)

does. A trip to Titan was at the edge of technological capability when, in the summer of 1976, several aerospace companies began to seriously study a robotic voyage to the frozen, dark world.

Pat Carroll was on Martin Marietta's team. "In our studies we had to design for 'what if s' of all sorts that could wipe you out, like landing in liquid. This study was done before even Voyager, so we had no idea what was down there and what conditions we would be flying through. You had to design for all those contingencies in those early studies. Of course, you didn't always have a very good solution, but you worked with the best technology and knowledge of the time."

Scientists knew that the temperature of Titan's surface is at the triple point of methane. That is, surface conditions could support methane in a liquid, solid, or gas form.¹⁰ This meant that any atmospheric probe might encounter cryogenic drizzle, fog, buffeting winds, or even lightning in those alien orange skies. Carroll's team had to take the possibilities into consideration for any design of a lander. "We were prepared to land either in the soup – whatever it was

– or a snow bank, or a solid surface. We were just trying to design the mechanics of surviving all these possibilities. We didn't have much detail. It looked complicated. The mission was a chancy one."

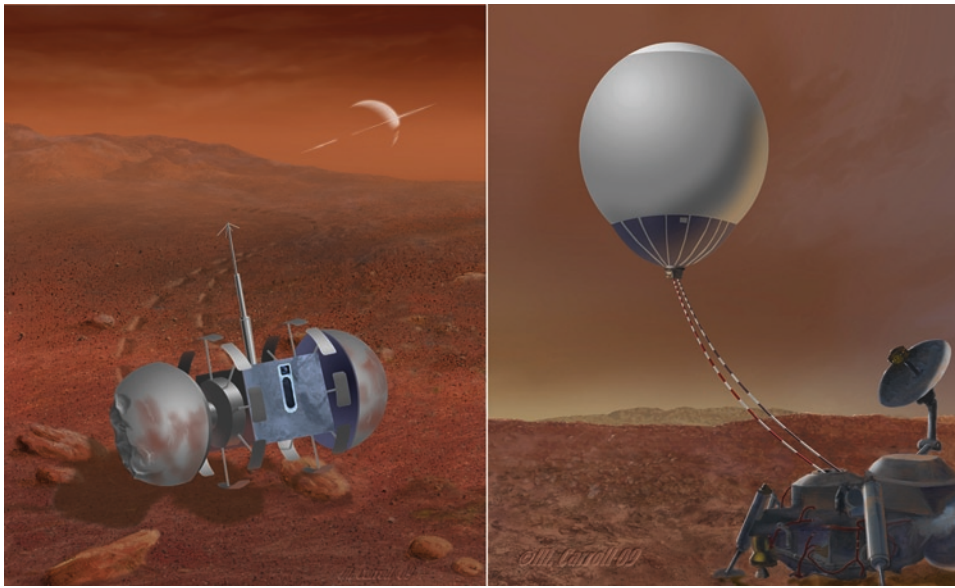
The uncertainty about conditions on Titan is reflected in a February 1975 technical proposal done for NASA Ames by Martin Marietta:

Polarization measurements by Veverka and Zellner, combined with Titan's low UV albedo, suggested the presence of optically thick clouds and raised the possibility of an extensive and spectroscopically unobserved atmosphere beneath them...the surface temperature could be as high as several hundred degrees Kelvin and the surface pressure as great as several bars. However, the opposite extreme was also shown plausible when Danielson, Caldwell, and Larach demonstrated that the anomalous infrared measurements could be interpreted as a temperature inversion in a thin atmosphere...the measurements of Titan's radius are difficult and the earlier results may have been inaccurate...¹¹

Scientific ignorance about Titan's atmospheric structure led to yet another problem – imaging. What were the light levels like? At Titan's distance, the Sun shines with a feeble one percent of what it does on Earth, and evidence suggested that at least some cloud cover could effectively block sunlight from reaching the surface, dropping noontime light levels to a dim twilight. Light amplification devices of the 1970s were impossibly energy hungry for a probe, and CCD technology was in its infancy. One clever proposal called for the probe to jettison a flare. The artificial light source would drop

10. Earth, for example, is at the triple point of water.

11. *A Titan Exploration Study – Science, Technology, and Mission Planning Options*, Martin Marietta report P75-44480-1, February 1975.



Two Early Titan studies: Left: A 1975 study of a Titan rover. The main body and spoked feet would deploy from a crushable landing sphere. The craft was to carry imaging equipment, soil samplers, and a meteorology station. Right: A lander deploys a helium balloon that carries a camera and meteorology station. The balloon's height can be adjusted for more distant views and sampling of higher layers of atmosphere (sketches © Michael Carroll, based on diagrams from Martin Marietta technical report P75-44480-1)

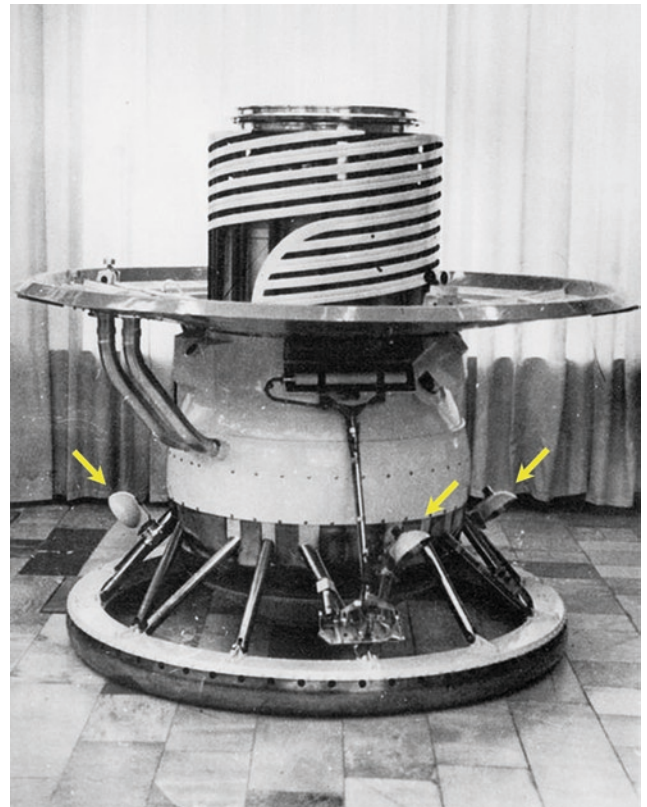
beneath the probe to illuminate close-in atmospheric structure and distant surface features.

Decades later, the European Space Agency's Huygens-Titan probe carried a light source to illuminate its immediate surroundings and was equipped with CCD imaging systems that could operate in low light levels.

Titan was not the only target for which artificial lighting was carried. Early Soviet Veneras carried small floodlights. In both the case of Titan and Venus, light levels turned out to be significantly higher than feared.

The reality of exploration has always followed the vision of a few. From Leonardo and Lilienthal to Carroll and Clark, dreamers led engineers to blaze trails that would ultimately lead to distant worlds. But the first glimpses we would have of planetary meteorology came not from within planetary atmospheres but rather from above them. Our earliest explorations of the skies over planets and moons came to us through the eyes of orbiters or spacecraft that simply flew by.

With scientists unsure of light levels on Venus, Veneras 9 and 10 carried floodlights, seen here mounted on the landing struts (NASA; NSSDC catalog/GSFC/NASA)



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