Can Galileo Take the Heat?

On its long, long road to Jupiter, the spacecraft will have to pass through sunlight so hot it could fry; will the fragile Galileo survive its hazardous journey?

AFTER 12 YEARS OF DESIGN, development, and seemingly endless delay, the National Aeronautics and Space Administration's Galileo spacecraft is finally on the launch pad, nestled tightly in the payload bay of the space shuttle Atlantis. If all goes as planned, Galileo could begin its 6-year voyage to Jupiter as early as 12 October. And the mission engineers who have labored so long and so hard to get it to this point are ecstatic.

They are also anxious. Even if the launch goes perfectly, everyone involved with the project is acutely aware that Galileo will have to follow a bizarre, multiloop trajectory that first carries it sunward past Venus, and then outward again past Earth—twice—before it even begins to head for Jupiter. This will be the most cumbersome and perhaps the most risky trajectory ever undertaken by any NASA space probe: one misstep on the sunward leg could fry the spacecraft dead in the solar heat. As one engineer with extensive experience in the project put it in an off-the-record conversation with *Science*, "I think the mission team has convinced themselves that they can handle it"—but there are a lot of crossed fingers, nonetheless.

NASA has invested quite a bit in Galileo over the years—$1.2 billion—and from all reports, it shows. "Galileo is the Rolls Royce of spacecraft," declares Clayne M. Yeates, deputy science and mission design manager of Galileo at the NASA Jet Propulsion Laboratory (JPL). "There'll never be another one like it."

Indeed, Galileo promises to be impressive even by the standards set by the spectacular Voyager flybys of Jupiter in 1979. When the spacecraft reaches Jupiter in December 1995, it is slated to drop a probe into the giant planet's atmosphere and then go into orbit, looping among the icy moons with instruments a generation more advanced than Voyager's. It will carry cameras and infrared spectrometers capable of mapping the Jovian moons with a resolution 20 to 1000 times better than Voyager's—in fact, with as much clarity and information content as the Landsat images of Earth. It will pack more computer power than any unmanned space probe before it, and will carry software capable of diagnosing and fixing a multitude of faults automatically. Its very structure is unique: a slowly spinning top half will carry the particles and field instruments that sample Jupiter's fierce radiation belts; a stationary bottom half will carry the cameras and spectrometers; and a joint that gave the engineers fits to design will steadily rotate between them. Galileo will be, says mission operations and engineering manager Neil E. Ausman, Jr., "the most complex spacecraft JPL has ever flown, probably the most complex spacecraft ever."

However, none of this technical virtuosity can guarantee Galileo a safe ride around the sun. And indeed, says Ausman, given a choice, no one would have opted for such a trajectory. But after the Challenger accident of January 1986, NASA had no choice.

Before the accident, the agency's plan had been to send Galileo on a much more direct trajectory that would have gotten it to Jupiter in only 2½ years, starting from a scheduled launch in April 1986. However, that would have required the use of a powerful liquid-fueled Centaur booster rocket, which would have had to ride along with the spacecraft in the shuttle's payload bay. And in the aftermath of Challenger, NASA headquarters ruled that the Centaur's liquid hydrogen and liquid oxygen propllents made it far too risky for the shuttle to launch. Galileo would have to use a safer solid-fueled booster known as the Inertial Upper Stage (IUS)—which, unfortunately, has nowhere near enough power to get Galileo to Jupiter.

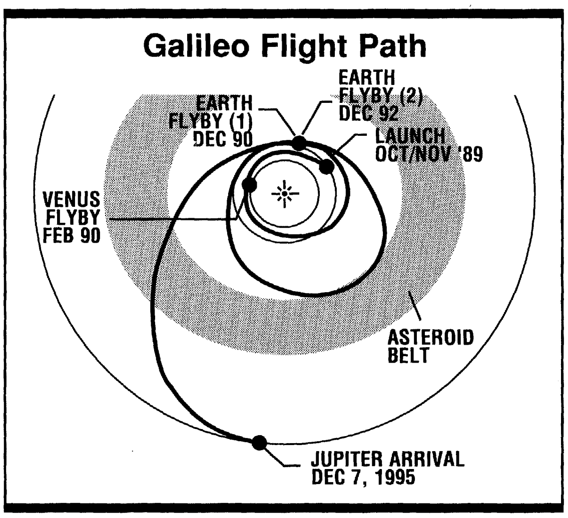
On the other hand, the IUS *can* get Galileo to Venus. Thus the detour: the workings of celestial mechanics are such that a close pass by that planet can end up giving Galileo a substantial amount of extra kinetic energy for free. Two more loops around the sun, together with two more close passes by Earth itself, can then give it enough energy to make up the shortfall from Centaur and set it on the outward course it would have had originally. This long, looping path is known as a VEEGA trajectory, for Venus-Earth-Earth Gravity Assist.

But therein lies the problem, says Ausman. Leaving aside the fact that the VEEGA trajectory forces Galileo to spend an extra 3 years or so en route—meaning an extra 3 years for things to go wrong—the inbound leg exposes it to at least twice as much solar heat as it was designed for. How was Galileo supposed to stay cool enough to survive?

The answer had to start with Galileo's 4.8-meter wide high-gain antenna: the lacy, golden dish that dominates the top of the spacecraft and that is essential for beaming back the streams of data from Jupiter. This antenna is perhaps the most vulnerable single element on the spacecraft.

"At the closest approach to Venus," says

The journey begins. *In this artist's conception, Galileo's solid-fueled booster starts it on the long path to Jupiter. The bulbous spine in front is the high-gain antenna, folded under its little sunshade. A larger sunshade at the base of the antenna shields the rest of the spacecraft.*



NASA/Jet Propulsion Laboratory

Loop-de-loop to Jupiter. *After its launch this autumn, Galileo has to spend 3 years making two loops around the sun before it finally gets kicked out to Jupiter. Along the way, however, it promises to be one busy spacecraft. Highlights include ■ infrared and ultraviolet search for deep cloud patterns and lightning during the flyby of Venus (February 1990). ■ Composition mapping of the far side of the moon during the two Earth encounters; possible imaging of the antarctic ozone hole (December 1990; December 1992). ■ Possible close observations of two asteroids, Gaspra (October 1991) and Ida (August 1993). Once Galileo arrives in December 1995, it will be busier still. The atmospheric probe will sample the temperature, pressure, and composition of the atmosphere and cloud decks. The orbiter will then spend the next 20 months taking measurements of the Jovian magnetosphere and radiation belts; performing remote studies of the Jovian atmosphere; and producing high-resolution imagery and composition mapping of the Galilean satellites.*

Ausman, "the bonding material used to hold the mesh to the ribs would lose adhesiveness in a very short time [a few tens of seconds] if exposed to the sun." The mesh would then begin to pull loose, eventually transforming the antenna into a misshapen, unusable blob.

JPL's solution is to keep the antenna tightly furled in its launch position like a collapsed umbrella, and then to keep the spacecraft as a whole pointed precisely at the sun during the whole first year of flight until it completes the inner loop of its trajectory and returns to Earth. Assuming that nothing happens to spoil Galileo's aim, the furled antenna can then rest safely behind a small, circular sunshade that has been added at the tip. The body of the spacecraft should likewise stay safe behind a much larger sunshade added at the base of the antenna.

However, as Galileo spacecraft manager A. Earl Cherniack points out, the decision to keep the antenna furled creates another problem: How is Galileo supposed to communicate with Earth? There is a separate, smaller, "low-gain" antenna on board, he says. But it is located at the tip of the high-gain antenna, where it will be uselessly pointed at the sun. "So we had to add a second low-gain antenna for the Venus leg," he says. Sticking awkwardly from the back of the spacecraft, it is a thin spine looking exactly like what it is: an afterthought.

Unfortunately, it functions a bit like an afterthought, too. Transmitting data over interplanetary distances through a small antenna like this one requires a lot of power. And power is in very short supply aboard Galileo.

"Our biggest constraint is that we were really unable to modify the RTGs," says deputy spacecraft manager Matthew R. Landano. Galileo's two RTGs—Radioisotope Thermoelectric Generators—were designed to produce roughly 600 watts of electrical power for the spacecraft from the decay heat of plutonium-238. Unfortunately, says Landano, the RTGs were originally fueled in preparation for the 1986 launch attempt and have been decaying ever since at the rate of about 16 watts per year. And since refueling them for this launch would have cost $110 million, more than NASA headquarters was willing to spring for, "We've had to develop a number of power switching and power sequencing schemes" to make sure the scientific instruments get everything they need.

In communications terms the power limits mean that Galileo's new low-gain antenna will be restricted to transmitting at a data rate of just 40 bits per second as it approaches Venus and just 10 bits per second during the period of closest approach in February 1990. For comparison, the high-gain antenna is capable of transmitting at 134 kilobits

"Stop the Plutonium Shuttle!"

The plutonium-238 pellets that power Galileo's Radioisotope Thermoelectric Generators (RTGs) are encased in graphite aeroshells designed to survive an accidental reentry into Earth's atmosphere. Inside that they are clad in iridium for resistance to corrosion by seawater. They have been fabricated as a virtually insoluble plutonium oxide ceramic that—unlike the highly carcinogenic, bone-seeking plutonium metal—will generally pass through the body without being absorbed. In laboratory tests, they have survived shocks ten times more severe than they would have experienced in the payload bay of the exploding Challenger. They are, proclaims NASA, quite safe for launch aboard the space shuttle.

Except that some people don't buy it. "We have essentially zero faith in the contention that the casks will hold the RTGs in case of an accident," says Orlando, Florida, activist Bruce Gagnon. After Three Mile Island, Chernobyl, and Challenger itself, such official reassurances ring pretty hollow, says Gagnon—so hollow that he and his allies soon hope to ask the federal court in Washington, D.C., for an injunction to stop the launch.

Gagnon, who is director of the Florida Coalition for Peace and Justice, a statewide alliance of 75 local peace groups, claims to see a rising ground swell of public concern in the state about "The Plutonium Shuttle." But in addition, he says, there is a second reason to be concerned about the Galileo and its RTGs: "this whole [Pentagon] plan to put weapons in space. We feel that this is an effort to break the ice for the 100 nuclear reactors that the military is going to need to launch for Star Wars."

What could they do about it? Well, besides possibly seeking an injunction, Gagnon says, "We hope to institute a nonviolent civil disobedience campaign to put people on the launch pad."

That may prove difficult. The shuttle launch pad is sealed off by fences, motion sensors, a regular security force, and the equivalent of a SWAT team. The Coast Guard keeps the offshore waters clear on launch day, and the Air Force patrols the sky. "Our policy is to allow anyone free access right up to the gates of the Kennedy Space Center," says NASA spokesman Charles Redmond. "That lets them have all the publicity they could want."

The injunction possibility is more worrisome for NASA. Agency officials say that it is hard to see what the grounds could be: NASA has filed an Environmental Impact Statement and has allowed for all the public comment required by law. Still, the agency's lawyers are briefed and ready. Says Redmond, "NASA is taking this extremely seriously." ■ **M.M.W.**

per second from the roughly tenfold larger distance of Jupiter.

Under normal circumstances, the backup antenna's glacial rate of communication would be adequate. But suppose something goes wrong with the spacecraft as it whips by Venus? JPL mission controllers would have to diagnose the problem through this extremely slow communications channel and then try to radio correction commands the same way—a process one engineer close to the project compares to groping your way through a dark room where your 3-year-old may or may not have scattered toys on the floor. You can do it—slowly. But it would certainly be easier and safer if you could increase the data rate and, in effect, turn up the lights.

"The low data rate is something we didn't want to do," says Ausman. But he remains a cautious optimist. "We have assessed the problem, and we believe we have sufficient visibility to always reconstruct what's going on in the spacecraft."

He admits that 40 bits per second is too low for the controllers to exercise and calibrate Galileo's attitude-control system, which is what maintains the pointing. But that will be done shortly after launch, when the available data rates are much higher, he says. "We can't think of any failure modes near Venus that would require us to recalibrate immediately."

So in the last analysis, does sending Galileo past Venus bring it too near the edge? Is the mission about to set a new NASA record for technical risk?

Well—probably not, says Ausman. "The design margins we built into the spacecraft at the outset have been almost miraculously maintained," he says. "We've been able to satisfy the fundamental thermal and power constraints unchanged throughout the mission." He maintains that he and his colleagues are comfortable with the mission as it stands.

In many ways, in fact, Galileo today is in better condition than it was in 1986. During the 3-year delay caused by the Challenger disaster, a number of the science instruments were upgraded. And several hardware glitches were found—at least two of which could have caused serious problems in flight if they had not been fixed. One involved cracked solder in the computer electronics and the other overheating in the attitude-control thrusters.

Still, everyone will be much happier once Galileo has looped back and made its first pass at Earth in December 1990. From then on it will remain outside Earth's orbit, where the sunlight is cooler—and where the high-gain antenna can at last be safely unfurled. ■ M. MITCHELL WALDROP

Gene Control Research Gets a Boost

Researchers clone the gene for a critical cog in the gene control machinery of higher organisms

FIVE RESEARCH TEAMS—four in the United States and one in Europe—are about to announce a significant advance in biologists' struggle to understand how the cells of higher organisms turn their genes on and off. They have discovered the gene that directs the synthesis of the TATA protein, one of the most elusive—and critical—components of the gene regulatory machinery. "The TATA protein is a key factor in gene transcription, the one that the other regulatory factors talk to," says Leonard Guarente, the leader of one of the U.S. teams.

How cells control their genes so that they manufacture the necessary proteins at just the right times is key to much of basic cell biology. This includes the orchestration of embryonic development as well as the adaptations that cells must make in everyday life as they respond to the environment. In addition, derangements in gene activities may contribute to the development of cancer and other diseases.

No wonder then that over the past several years molecular biologists have expended a great deal of time and energy trying to analyze the biochemical machinery that controls gene expression. They have been very successful in doing this in the bacteria, but in more complicated organisms the problem has proved to be a much more difficult nut to crack.

Researchers learned that genes in the higher organisms, like those in bacteria, are activated by proteins that bind to specific DNA sequences connected to the genes. But the molecular control machinery in the higher organisms proved to be very complex, involving several proteins that have to act together to turn on any given gene. On top of that, some of the crucial regulatory proteins could not be isolated.

The TATA protein, which is particularly critical because it is the first of the proteins to bind to a gene regulatory site—the sequence known as the TATA box—was one of those that could not be isolated, and its absence presented a major roadblock to researchers who wanted to understand the biochemical basis of gene control. The new achievement—the cloning of the yeast gene for the TATA protein—ought to break through that roadblock.

Guarente, who works at the Massachusetts Institute of Technology, and his former postdoc Steven Hahn, who is now at the Fred Hutchinson Cancer Research Center in Seattle, cloned the gene with Stephen Buratowski and Phillip Sharp, who are at MIT. The gene has also been cloned independently by Fred Winston's group at Harvard Medical School, by Robert Roeder's group at Rockefeller University, by Martin Schmidt and Arnold Berk at the University of California in Los Angeles, and by Pierre Chambon at the University of Strasbourg in France. The MIT and Harvard workers describe their results in the 22 September issue of *Cell*. The Roeder group's paper is scheduled to appear in the 28 September issue of *Nature* and that of the Berk group is in press at the *Proceedings of the National Academy of Sciences*. Chambon has also submitted a paper to the *Proceedings*.

The search for the factors that control gene activity in higher organisms began about 10 years ago when molecular biologists found that genes carry identifiable regulatory sequences that are needed for normal gene activation. One of the first regulatory sequences identified was the TATA box, which was so named because it contains the bases thymine and adenine in a roughly alternating sequence.

The researchers already knew that bacterial genes are turned on by the binding of specific proteins to their regulatory sequences. So the discovery of the TATA box ignited an intensive search for the proteins that might control genes in higher organisms by binding to that sequence.

Ironically, the efforts yielded an embarrassment of riches. Researchers found that four different regulatory proteins plus RNA polymerase II bind in and around the TATA box. The polymerase is the enzyme that gets gene expression under way by copying the DNA of genes into messenger RNAs, which make the proteins the cells need.

Then a few years ago, Roeder, Sharp, and Chambon brought some order out of the confusion by pinpointing the particular protein that actually recognizes the TATA sequence. Only after this protein, which is designated transcription factor IID