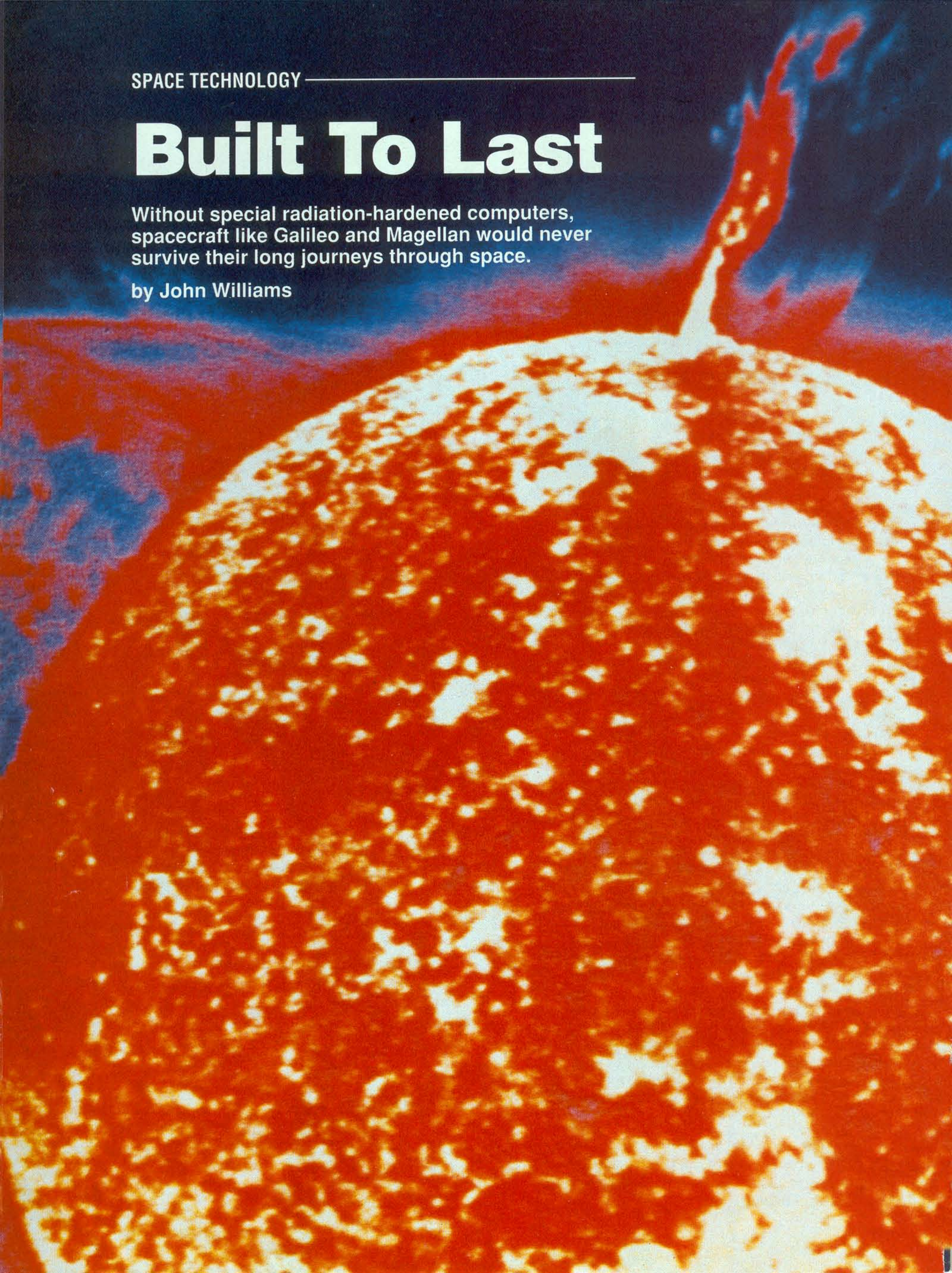
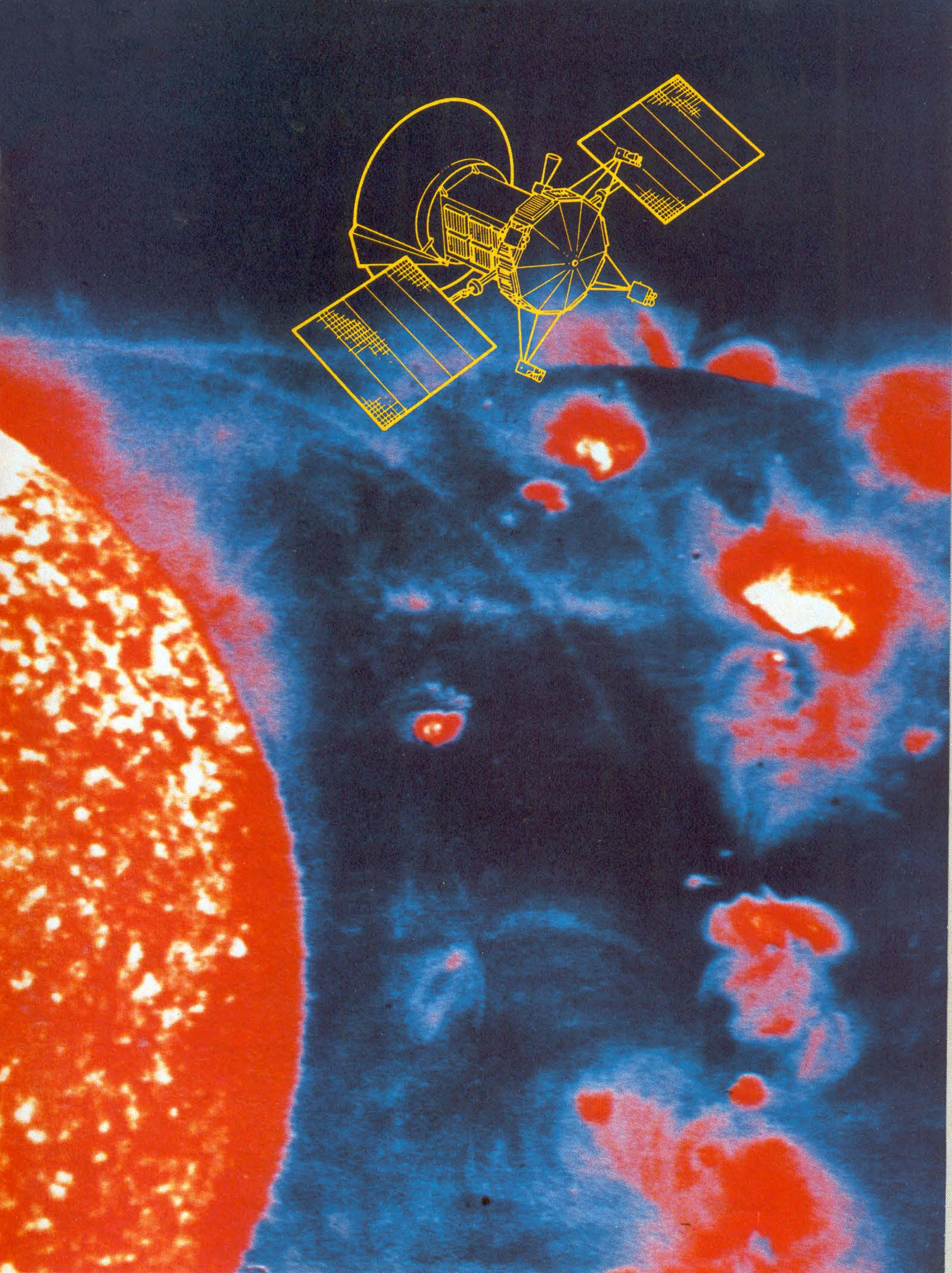
SPACE TECHNOLOGY

Built To Last

Without special radiation-hardened computers, spacecraft like Galileo and Magellan would never survive their long journeys through space.

by John Williams





Space can corrode an interplanetary probe as insidiously as salt and water do your car. Atomic oxygen eats away at spacecraft coverings, high-energy particles degrade solar panels, and dust covers everything. Even the most hardy spacecraft can be destroyed in a high-speed collision with a particle no bigger than a pea.

To survive the rigors of a years-long journey through the solar system, the components of a probe like *Voyager* or *Galileo* must be hardened to withstand high radiation, particle impacts, and temperature extremes. Since it is inaccessible for servicing, the probe must operate flawlessly under such conditions, often for many years. Ruthless testing of spacecraft parts, especially the computer components, is essential if the mission is to have any guarantee of success.

Such a guarantee does not come cheaply. As an example, you can buy one megabyte worth of memory for your home computer today for about $100. But harden that one megabyte for the space environment and the cost skyrockets to about $1 million.

A *Magellan* Memory Glitch

The most serious threat to a craft traveling through space often comes from radiation and high-energy particles knocking out the silicon memories of spacecraft computers.

Magellan, NASA's $550 million mission to map the surface of Venus, may have been hit with just such a problem. On August 16, six days after *Magellan* entered Venus orbit, ground controllers mysteriously lost contact with the spacecraft. Contact was regained after a tense thirteen hours, but another signal blackout occurred on August 21. The spacecraft systems appeared to be healthy, so engineers initially turned their suspicions to external causes: sparks from static electricity, higher-the-expected radiation around Venus, or possible hits from cosmic ray particles. Either culprit could zap a memory chip in the spacecraft's electronics, causing an on-board computer to run amok.

It's possible that the exact causes of the signal losses may never be known. NASA engineers are preparing to counter any further problems that develop during *Magellan's* 9-month mission. For example, mission engineers have programmed *Magellan's* computers with additional commands that will keep *Magellan* safe and sound during any future signal blackouts that might occur. In addition, engineers are able to write around any damaged memory cells they find.

The incidents at Venus demonstrate the concern mission planners have about radiation and high-energy particles. Hits from charged particles can create a "single event upset," or SEU, and it represents one of the most serious problems for today's advanced spacecraft.

Bullets from the Sun

In March 1989 one of the largest flares recorded since the beginning of the space age erupted on the surface of the Sun. On Earth, even observers as far south as Florida were treated to an aurora as the charged solar wind slammed into the magnetic field and spilled over the polar regions. Over the course of 1989, three intense solar flares interfered with telephone transmissions, FM radio broadcasts, and shortwave and satellite communications, and in some instances actually disrupted commercial power grids. Not since February 1956 had the Sun been so active.

In 1989 both the *Magellan* and the *Galileo* probes set sail into this storm of solar particles. It is during a time of intense solar flares that scientists most expect to see problems from particle bombardments. But particle upsets can also occur when a probe flies through a planet's radiation belts. *Voyager 1* experienced 42 single event upsets during its flyby of Jupiter. In one case the central computer was reset, causing the spacecraft clock to lag several milliseconds. Although that's not much time by earthly standards, milliseconds count in the precise maneuvering, imaging, and experimentation executed near Jupiter and its moons.

SEUs occur when computer circuits undergo what is called a "bit flip." In the binary computer language a spacecraft uses, a circuit is either on (a one) or it's off (a zero). In a bit flip, a one flips to a zero, or a zero changes to a one. Computers receive and send information in a string of ones and zeros, so an unwanted flip from one state to the other in a memory chip can seriously alter a message.

The culprits are heavy ions — either solar cosmic rays blown from the stormy Sun or galactic cosmic rays zipping in from more distant parts of the universe. The subatomic particles are extremely fast and penetrate with energies of as much as two to three *trillion* electron volts per particle. That's quite a punch. At this energy level, the particles can pass straight through the outer shield of the craft and into the delicate circuitry below, triggering a bit flip.

"SEUs are probably the most severe problem facing today's spacecraft," says Ron Draper, project manager of the joint *Comet Rendezvous and Asteroid Flyby* (*CRAF*) and *Cassini* project at the Jet Propulsion Laboratory (JPL). "Some data can be lost or the mission can be destroyed if the wrong command is sent to, say, the computer in charge of attitude and articulation." This computer, just one of many on board, keeps the spacecraft's systems pointed at the Sun for power, at Earth for communication, and at the stars for navigation. The computer also gives commands to point the scan platform, which carries cameras and science instruments. "A bit flip could cause us to point in the wrong direction," Draper says. "Conceivably, if there weren't backups to help correct the problem, the probe could die because it's pointed away from the Earth or the Sun." It almost happened to *Magellan*.

Bullet-Proofing a Probe

To reduce the risk of damage from SEUs, spacecraft designers have several options. One brute force method is to place metal shielding around critical electronic parts. However, physical shielding is not always enough. On a spacecraft, about 35 inches of aluminum would be needed to stop the more energetic particles, leaving little room for the basics of the spacecraft. So, short of building the shielding out of asteroids, the best method for constructing SEU-resistant computers lies in making the electronics themselves capable of withstanding bombardment, a process called hardening. (See "Designing Superchips.")

If neither option of shielding nor hardening is possible, engineers must write computer programs both to compensate for a possible upset in the spacecraft and to take care of the spacecraft until scientists on Earth correct the problem. If these computer routines were not included, scientists could very well end up with a dead spacecraft. Redundant components are also included, in case the other precautions don't work.

As an example, after spending $25,000 for initial tests, JPL estimated *Galileo's* attitude control system would experience 340 upsets from cosmic rays during the originally planned 27-month journey to Jupiter and 0.6 upsets during the critical 12-hour Jovian orbit insertion maneuver. *Galileo* mission scientists believed the computer could not react quickly enough to an upset with only self-correcting software, so they set out to harden the parts against radiation effects. Two years later the redesigned computer system was expected to have no more than one upset during the trip to Jupiter with an almost nonexistent chance of an SEU upon its arrival. "In almost all cases we were able to shield the parts of *Galileo* to appropriate levels," says John Zipse, an engineer with the *Galileo* mission.

"We were carefully watching *Galileo* right after launch during a large solar flare and watching the counter in the attitude control system to see if it failed," Zipse says. "We were looking for any instance of single event upsets, and we didn't have any. We tolerated what was a very high SEU environment without any problems. It was a good acid test right out of the gate." In fact, mission scientists are confident that *Galileo* will be nearly impervious to SEUs, both from the Sun en route and at its destination around Jupiter.

Danger: Radiation

SEUs are just one hazard a probe like *Galileo* faces. Heavy ions that cause SEUs can be encountered at any point during a mission, but near a planet with a strong magnetic field a spacecraft can also be immersed in electromagnetic radiation like x rays and gamma rays. At Jupiter, for example, *Voyager* found radiation levels that were much more intense than scientists had expected.

"When that realization hit home," Zipse says, "we did a systematic study of every part of the *Galileo* spacecraft, to decide if it would tolerate that kind of radiation. And you really need to appreciate the levels of radiation we are talking about here. When you get a chest x ray at the doctor's office, we're talking about a few millirads — not a lot of radiation. At Jupiter, it's hundreds of thousands of rads."

Radiation of this strength causes a slow degradation of spacecraft electronics. Long-term exposure to an intense dose of x rays or gamma rays adds a permanent trapped electrical charge to the silicon oxide of the transistors, changing the way they turn on and off. The result is a decrease in a computer's speed and an increase in its power requirements.

The environment at each of the planets is different, so each mission has its own requirements for instruments, size, speed of the computer, and the computer's radiation hardness. Draper says that while the radiation expected for the upcoming *CRAF* and *Cassini* probes will be pretty benign — around 15 kilorads — *Voyager* had a 75-kilorad requirement and *Galileo* is designed for a 150-kilorad environment. He adds that the computer chips used on *Galileo, CRAF,* and *Cassini* can withstand doses of up to one thousand kilorads over an entire mission.

Sometimes circuits can recover from a strong dose of radiation and return to their normal states. At other times, however, the component gets worse even after the radiation is no longer present.

This problem arose during testing of parts for the *Galileo* probe, according to Jim Coss, acting group supervisor of JPL's radiation effects testing group. Scientists were testing random access memories, or RAMs, which normally needed a minimum of 2 volts to operate. After being irradiated, however, their power requirement rose to 3 volts. After a part sat around on the test bench for a while, it had degraded so much that it required almost the entire 10-volt power supply to be turned on. Some components degrade so much that there simply is not enough power available to turn them on. With *Galileo*, the problem was remedied by adding shielding and radiation-hardened chips.

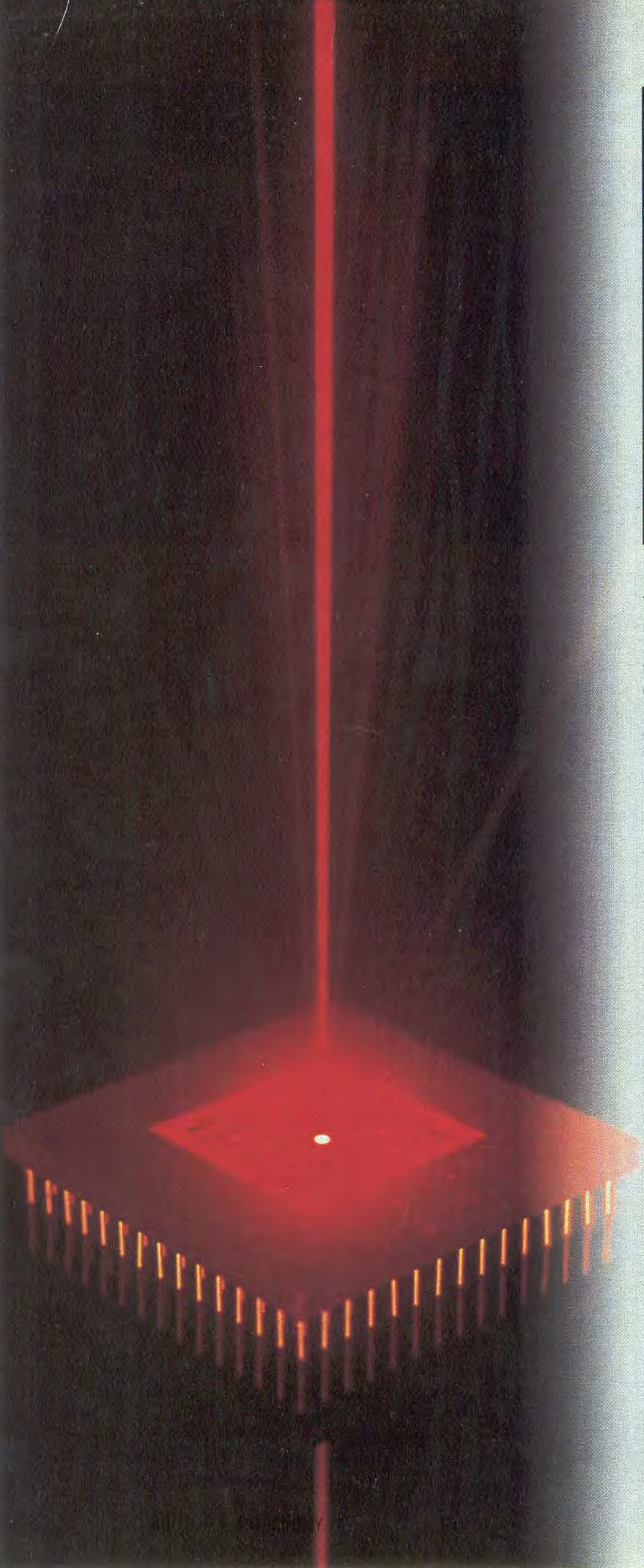
Simulating Space

Cosmic ray particles and radiation don't cause much of a problem here on Earth because our atmosphere shields the surface very effectively. So to simulate a space environment on Earth, scientists take the cover off the computer part and bombard it with high-energy particles from a particle accelerator to test for SEU resistance. By hitting the component with different kinds of particles, engineers can find its threshold.

Several kinds of particles are used in SEU tests. Collisions with krypton ions are considered the best test because krypton ions are heavier than iron, the heaviest particles a spacecraft is likely to see. Under such strenuous tests SEU problems can be found immediately. Either the part flips or it doesn't. A good chip for *CRAF* and *Cassini*, according to Coss, will not flip when hit with a hail of krypton ions. That standard was developed during the testing of parts for *Galileo*.

In testing spacecraft, engineers must simulate not only the environment the probe will encounter but also the length of the exposure. For *Galileo*, components need to survive 9 years or 80,000 hours. If you include all the time for delays and testing, the parts will need to function for nearly twenty years.

Since they can't wait seven to ten years while a part sits during testing, engineers take a sample of the computer system and perform accelerated life tests.



With *Galileo,* the sample parts were stress tested for 2,000 hours at 125 degrees Celsius. Subjecting the parts to temperatures higher than those expected on the actual mission speeds up their wear. This allows engineers to predict the life of the components flown in space. *Galileo's* parts operated for 350,000 hours of simulated time. During that time JPL engineers detected no significant failures.

In addition to using higher temperatures, engineers also accelerate test times by exposing components to much higher dose-rates of radiation. A typical space environment would deliver less than one millirad per second to a spacecraft. In the laboratory a cobalt-60 source blasts the part with 100 rads per second while an x-ray source can deliver a 1,000-rad-per-second dose. By combining high radiation with high temperatures, engineers can simulate some seven years of space exposure in only a few minutes.

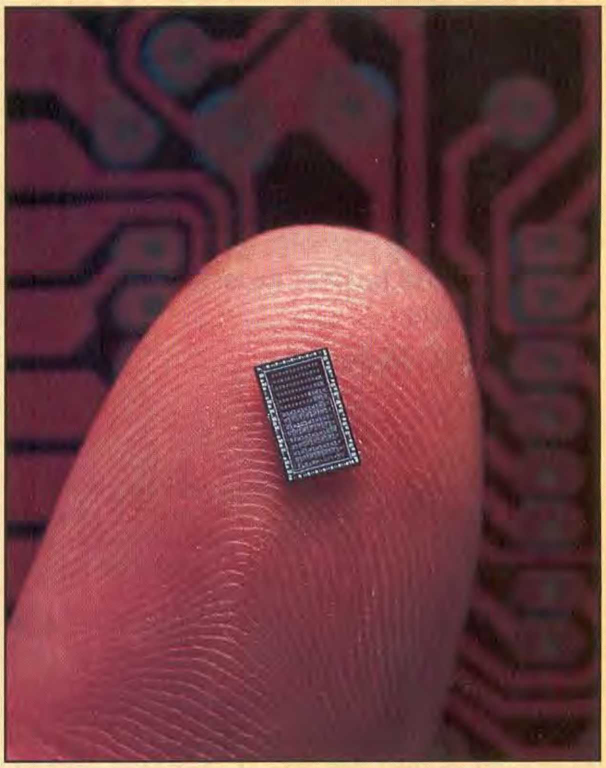
Is Newer Better?

Voyager's on-board computers consisted of about 100,000 transistors. *Galileo* is a bit more sophisticated, with the equivalent of a million transistors. Spacecraft like *CRAF* and *Cassini* will be made up of chips with tens of millions of tiny transistors.

Despite the growing sophistication of spacecraft electronics, NASA's philosophy has always been to use proven technology. In some cases this has resulted in the computer systems of space probes lagging behind their desktop counterparts by 10 years or more. Computer buffs are quick to point out that home and school computers have more computational ability and speed than most computers currently in space. According to Coss, "*Galileo* in reality is the most advanced bird we've launched, but if you look at its basic technology, it is 10 years old."

What the computer buffs don't realize is that the problems NASA has to contend with in building spacecraft are very different from those faced by designers of computers for the consumer market. NASA has to factor in the development and testing of hardware capable of surviving in space, the long spacecraft

Designing Superchips



Better computer chips have evolved since *Galileo* was designed, so the next generation of space probes will use the latest family of hardened electronics. The SA3300 chip, still under development at Sandia National Laboratories in Albuquerque, New Mexico, will combine speed, memory capacity, and radiation hardness.

The SA3300 is a version of a National Semiconductor chip, the 32C016, that has been available since 1986. According to Fred Sexton and R. Keith Treece, both Sandia staff members, the SA3300 functions exactly the same as the commercial part but has been hardened to withstand the high-energy particle- and radiation-filled space environments.

In the SA3300 each tiny transistor is about 10 by 1.25 microns across, about the size of a bacterium. The dot over the letter "i" could hold about a thousand of the 70,000 transistors making up the SA3300. At this tiny size, information stored in the computer circuits is easily scrambled by the spurious charges produced when a high-energy particle crashes through the chip.

To overcome the chip's sensitivity to SEUs, engineers have added capacitance or resistance to the circuits. A capacitor allows the spurious charge to dissipate more quickly, while resistors can slow that particular circuit down just enough — only a couple hundred trillionths of a second — so it will ignore the transient charge as the particle passes through.

To protect it against unwanted electrical charges from intense radiation, the SA3300's 200-angstrom-thick (20 billionths of a meter) oxide layer uses a special design at critical junctions to help dissipate charge buildup.

Both the *Mars Observer* mission and the *CRAF* and *Cassini* probes will use the data-handling abilities of this faster, more advanced chip.

development cycle, and launch delays. All these mean that the very latest technology often cannot be incorporated into the latest space probe. Design specifications have to be fixed years before launch.

But launch delays can sometimes help engineers bring spacecraft up to date. *Galileo* was approved in 1977 to be launched in 1982. The date slipped to 1984 and then to 1986 before the *Challenger* accident pushed the mission back even further. During that time scientists learned that Jupiter's environment was more harsh than expected. As a result, newer radiation-resistant chips were installed. The *Galileo* that was finally launched in 1989 was quite different from the craft that would have been launched in 1982.

But even if spacecraft engineers were able to use the latest and most sophisticated computer chips, the increase in performance might not be worth the risk. As Coss points out, "I don't know how well some of the stuff we're looking at now for future missions would survive."

The problem is that as the missions become more complex, the demands on the performance of the circuitry become greater. For example, the *Voyager* missions provided more information on the outer planets than had ever been written. But *Magellan* will provide even larger volumes of data, this time about one planet, Venus, while *Galileo* will flood Earth with more information than all previous planetary missions combined. To accomplish such a workload, engineers are turning to smaller, more powerful chips. But will they be as reliable?

"In our constant search for devices that are faster and more complex, and which draw less current," said Coss, "we are making them smaller and smaller. This makes them more sensitive to radiation." Seeking state-of-the-art performance without sacrificing proven reliability is a constant tradeoff. But by being conservative in their designs, and by taking the time to build space-ready hardware, the technical wizards that brought us the successes of *Voyager* and *Viking* will ensure that the super-smart spacecraft of tomorrow will survive the hazards of flight. □

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