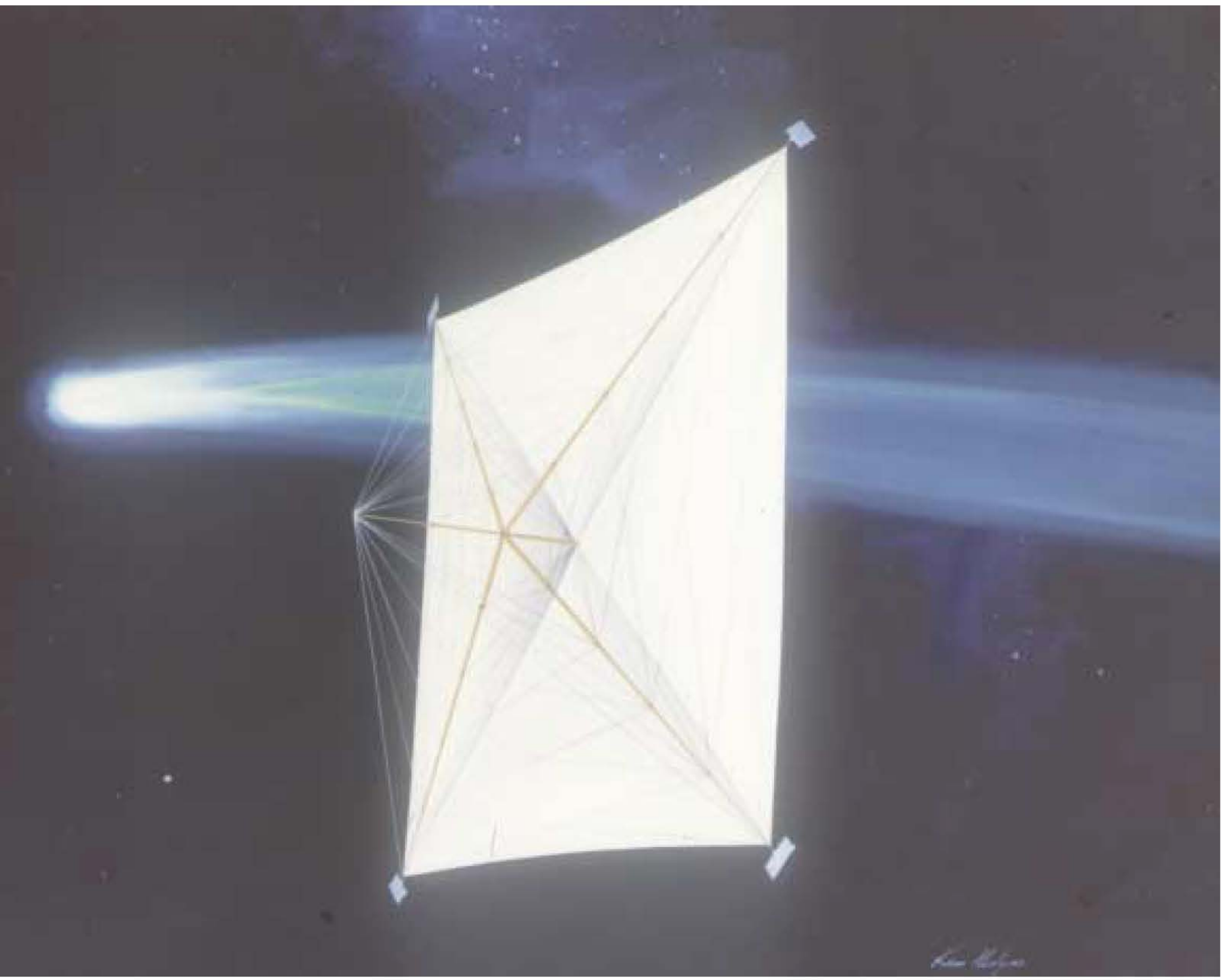
Kepler observed in 1619 that a comet's tail faces away from the sun, and concluded that the cause was outward pressure due to sunlight—a force that might be harnessed with appropriately designed sails.



Solar Sailing: The Next Space Craze?

by Joel Grossman

A proposed solar-sail mission to fly alongside Halley's comet in 1986 may have been ahead of its time. It was killed by NASA in 1977, partly on the grounds that the technology was unproven. But the idea keeps coming back—sails don't need to carry their own fuel, making them very attractive to mission planners. And now the hardware is starting to catch up with the hype. Rendering by Ken Hodges.

With a name like solar sailing, the technology sounds like it could be Southern California's next beach-sport craze. But the Jet Propulsion Laboratory (JPL), which is managed for NASA by Caltech, is planning to leave the Pacific Ocean far behind. Plans on the drawing board run the gamut from communications satellites hovering over Earth's poles, held in position by solar sails, to spacecraft hoisting giant, ultrathin sails for journeys exploring interstellar space.

Perhaps the grandest mission of all will be an interstellar probe. Its destination: Alpha Centauri, the sun's nearest neighboring star, approximately four and a half light-years away. Lasers as powerful as 10,000 suns, focused on the craft from Earth-orbiting satellites, could one day accelerate such a probe to one-tenth the speed of light. At that clip, it would reach Alpha Centauri within the professional lifetime of a scientist, arriving there in 40 to 50 years.

But that's going to be a while. JPL scientists estimate that a more near-term precursor spacecraft powered only by sunlight could cover the 25 trillion miles, or 273,000 astronomical units (AUs; an AU is 93 million miles, or 150 million kilometers, the average distance between Earth and the sun), at a speed of 15 AUs per year. This is equivalent to flying from Los Angeles to New York City in 63 seconds, about nine times faster than the orbital speed of the Space Shuttle. At 160,000 miles per hour, the solar-sail probe would be speeding through space five times faster than the 3-AU-per-year speed of Voyager 1, a conventionally propelled spacecraft launched in 1977 that is currently our most distant space probe. An interstellar precursor mission launched in 2010, the earliest projected date, would overtake the then-41-year-old Voyager 1 in 2018. It would take 100 millennia for Voyager 1 to reach Alpha Centauri, but only 20 millennia for the sailcraft.

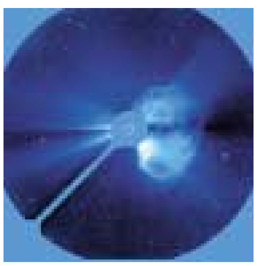
"We are *hoping* for a demonstration mission by 2005, with an interstellar precursor mission launch in the period 2010 to 2015," said Sarah Gavit, associate manager for JPL's Interstellar Program and preproject manager of the Interstellar Probe Mission until January 2001. "There are many other technologies that need development for interstellar or even near-interstellar travel. For example, communications, autonomy, etc. Sails are getting ready for flight demos, while some of these other technologies are still a ways off." Adds Chuck Garner, senior engineer in JPL's gossamer systems group, propulsion and thermal engineering section, "The sailcraft will be at very great distances from Earth, and therefore must operate and navigate itself without the aid of ground controllers. And communications hardware must be developed that can transmit data over enormous distances, utilizing very little power and requiring very little mass." To deal with these parallel technology needs, JPL created a Solar Sail Program to develop the solar sails, and a separate Interstellar Program is developing the other technologies.

Meanwhile, the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service, the Department of Energy, the Air Force, the Department of Defense (DoD), and the Space Environment Center in Boulder, Colorado, are eyeing solar-sail technology for more immediate practical applications. These include monitoring the sun for magnetic storms that can knock out communication and Global Positioning System (GPS) satellites, and play havoc with such earthbound things as electrical power grids and cell phones. This would require an orbit around the sun on a path that keeps the spacecraft directly between the sun and Earth at all times. However, this disobeys Kepler's laws of orbital mechanics, and such a satellite would need to carry a massive amount of propellant to fight the tendency to move out of the desired orbit. But propellantless propulsion via solar sails could keep satellites in such orbits—or in stationary orbits over Earth's poles, which are similarly non-Keplerian. Earlier

Right: Kepler's law says that objects in smaller orbits travel faster, so within, say, a month, a sun-orbiting early-warning spacecraft would be out of line with Earth.

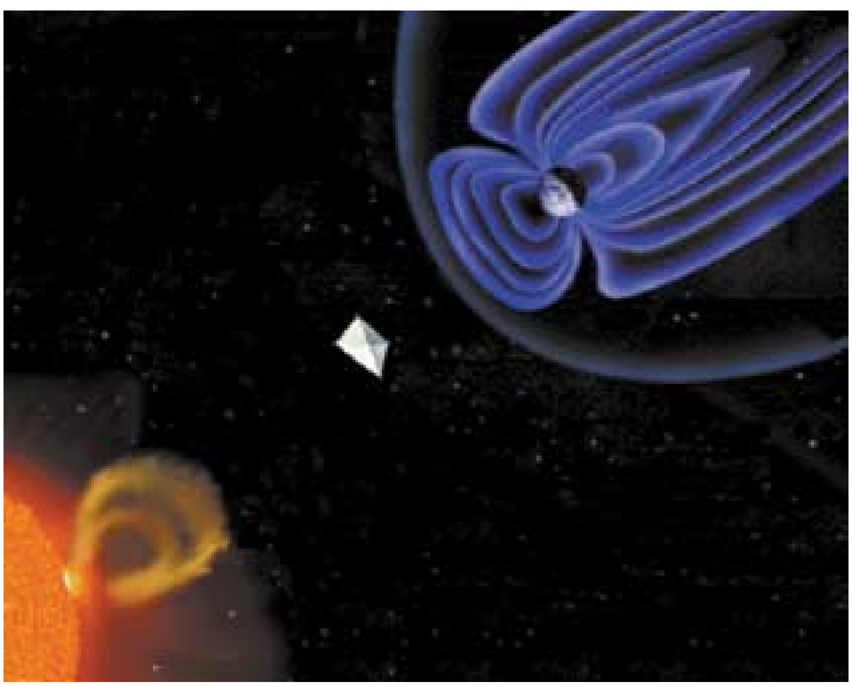
Below: A large coronal mass ejection, or solar storm, on April 20, 1998 as seen by the Large Angle and Spectrometric Coronagraph aboard SOHO. The central disk covers the sun, but the white circle in the disk's middle shows the sun's size (about 1,400,000 kilometers in diameter) and position.

Bottom: Geostorm on station.



warnings of inclement space weather would allow utilities more time to boost power reserves, provide wireless users time to prepare for transmission failures, and in extreme cases allow satellites time to go into "sleep" mode until the storm passed. And satellites permanently hovering over the North Pole would for the first time allow continuous monitoring of areas now only intermittently sampled by orbiting satellites. This round-the-clock surveillance of, for example, polar ice and the aurora borealis, or northern lights, could spur advances in meteorology, climatology, and oceanography. Other applications include search and rescue support, communications, and data relay over the poles.

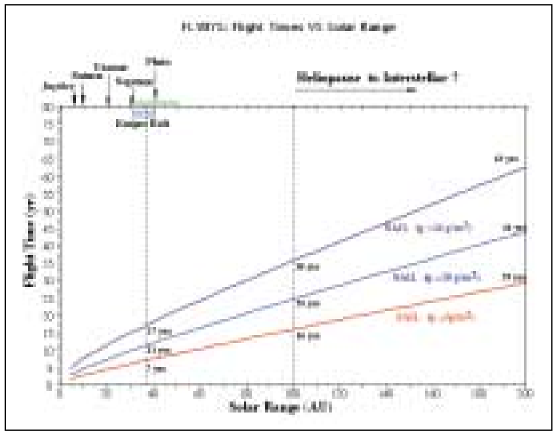
After early input from JPL, both NOAA and the DoD are planning a joint mission known as Geostorm, which will monitor space weather and the solar wind—a steady sun-produced stream of ions, electrons, and neutral atoms that is perhaps best known for interacting with the ionosphere to create the northern lights. The best space-storm warnings currently come from NASA's Advanced Composition Explorer (ACE), which along with the joint NASA/European Space Agency (ESA) SOlar and Heliospheric Observatory (SOHO) is "parked" about 0.99 AU from the sun, at the point where the gravitational forces of the sun and Earth balance each other. (This is called the first sun-Earth Lagrangian point, or L1.) However, Geostorm will be maintained in a similar position 0.98 AU from the sun, doubling the warning time for potentially disruptive storms from one to two hours. The photon pressure on a solar sail 67 meters on a side will counteract the sun's "extra" gravity to keep Geostorm sunward of L1. Another mission known as the Solar Polar Imager would further bolster scientific knowledge of the solar wind and geomagnetic storms via an orbit that passes over the sun's still largely unexplored north and south poles—an orbit that's hard to achieve conventionally because of the enormous amount of propellant required to leave the equatorial plane in which the planets move.



And solar sails could be a boon to planetary exploration. Mercury could be better studied from a sun-synchronous orbit about the planet, for example, which a solar sail would make feasible. Solar sails could also be useful for asteroid rendezvous, and for reducing the travel time needed to explore the outer planets and their many moons—a particular benefit in the case of sample-return missions. And the cost of transporting large amounts of cargo and equipment between Earth and, for instance, Mars to establish a permanent human presence could be so dramatically reduced that it would become practical financially.

Some attribute the idea of hoisting sails in outer space to the aforementioned Johannes Kepler, who

Estimated flight times to the outer solar system and beyond for a 500-kilogram solar-sail payload launched from a Delta II rocket. (For comparison, the 815-kilogram Voyager 2 took 12 years to reach Neptune after launch on a much larger Titan Centaur. Without the gravity assists from Jupiter, Saturn, and Uranus, it would have taken 30 years.) The sail's density per unit area is denoted by "g," and the green bar represents the range traversed by Pluto's wandering orbit. The Kuiper belt is a zone of icy material that managed to elude the outer planets during their formation.



four centuries ago wrote fellow astronomer Galileo a letter mentioning space travel using a "ship or sails adapted to the heavenly breezes." Kepler observed in 1619 that a comet's tail faces away from the sun, and concluded that the cause was outward pressure due to sunlight—a force that might be harnessed with appropriately designed sails. At the time, the corpuscular theory of light was in vogue, which turns out to be qualitatively consistent with today's quantum-mechanical view that light, in some cases, acts as a particle instead of a wave.

Scientific understanding moved closer to the mathematical basis for designing a working solar sail in 1873, when physicist James Clerk Maxwell, who is associated with the wave theory of light, predicted the existence of radiation pressure as a consequence of his unified theory of electromagnetic fields. Radiation pressure was independently shown to exist in 1876 by Adolfo Bartoli, who derived it mathematically from the second law of thermodynamics. Radiometers, invented by Sir William Crookes, were initially, albeit mistakenly, used to demonstrate the existence of radiation pressure in 1873—a classroom demonstration that is still done today.

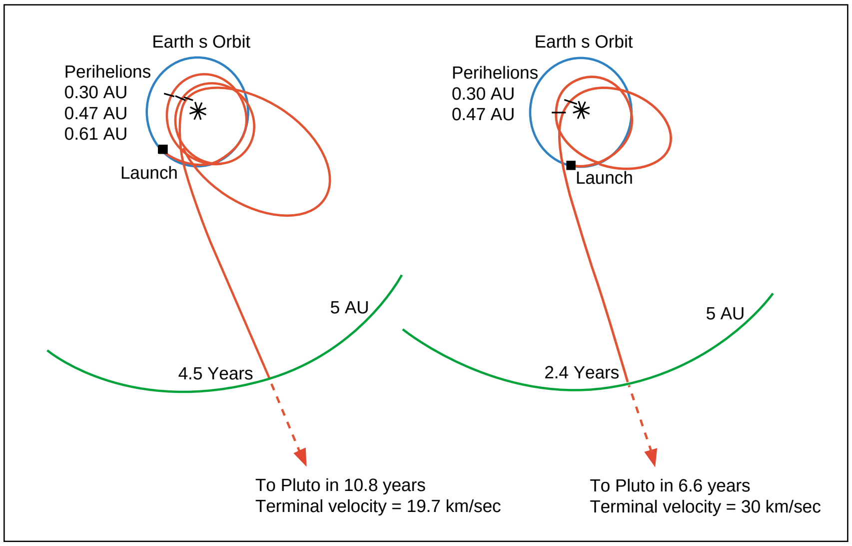
In fact, the force driving a radiometer is due to thermal-molecular forces, and is several orders of magnitude greater than radiation pressure. This type of levitation has recently been demonstrated by Energy Science Laboratories, Inc. (ESLI) of San Diego, under contract to JPL. "These experiments are part of a project to produce a spacecraft that can be launched from your backyard to the stars, using an assortment of different kinds of physics derived from photon interactions," says Henry Harris, chief scientist for space solar power at JPL and task manager of the project. This type of levitation only works where there's an atmosphere—but not too much of one!—so the scheme actually has four components. The fragile sail would be gently lofted on a carbon-fiber balloon to a sufficient height for the thermal-molecular effect to work. Then, when the air peters out, the sail continues to rise as the photon beam heats its underside enough that atoms in a special coating begin to evaporate off it, creating thrust. And upon reaching Earth orbit, it kicks over to purely photonic propulsion. Harris's team has demonstrated each of these four technologies individually, but putting them all together will take an enormous amount of additional work.

A carbon disk made by ESLI levitates in the light from a 100-watt bulb.

What is now accepted as the first true experimental verification of the existence of radiation pressure came from Russian physicist Pyotr Lebedev's elegant torsion balance experiments at the University of Moscow in 1900. Independent verification came from Ernest Nichols and G. F. Hull at Dartmouth College in 1901. But the modern concept of light as photons—massless packets of energy capable of producing momentum transfer, or radiation pressure—did not evolve until the early 20th century as Max Planck, Albert Einstein, and others grappled with thermal radiation and the then-puzzling nature of the photoelectric effect.

Indeed, as Colin McInnes notes in his book, *Solar Sailing: Technology, Dynamics and Mission Applications*, the term "photon" was not even coined until 1925. By this time, Einstein had won the Nobel Prize for explaining the photoelectric effect, and the equation $E = mc^2$ had become part of the modern lexicon (and *Time* magazine cover material!). The amount of momentum transferred from a photon to a solar sail is derived by combining quantum mechanics and Einstein's theory of special relativity. Both McInnes and former JPL employee Jerome Wright in his earlier book, *Space Sailing*, detail the mathematics needed to calculate radiation pressure, plot trajectories and orbits, and begin designing a solar sail, starting with Planck's law and Einstein's mass-energy equivalence.

Perhaps not surprisingly, science-fiction writers



A comparison of two sun-diver trajectories to Pluto. "Perihelion" refers to a point of closest approach to the sun. The three-loop trajectory at left is for a 270-square-meter sail with a density per unit area of 10 grams per square meter, and provides an initial acceleration of 0.5 millimeters per second per second. The faster flight at right assumes a 380-square-meter sail with half the areal density and twice the initial acceleration.

of the late 19th and early 20th centuries were also transfixed by light, and were penning tales of spacecraft propelled by mirrors. That is the principle of the solar sail: a photon reflecting off a shiny surface gives that surface a push equal to twice the photon's momentum. (The surface gets one dose of momentum in slowing the photon down and stopping it, and another one in accelerating it back in the opposite direction as it is reflected.) The catch is that because photons have no mass, and thus very little momentum, the mirror has to be featherlight in order to be moved significantly. The first really practical writings on solar sails are attributed to Konstantin Tsiolkovsky, the self-taught father of astronautics in the Soviet Union, and his Latvian colleague, Fridrickh Tsander, a liquid-propulsion rocket pioneer. In the early 1920s, the pair (their work appears to have been independent) wrote up their notions of very large, ultrathin mirrors propelled to "cosmic velocities" by the pressure of sunlight, a design concept still current.

After Tsiolkovsky and Tsander, solar sailing faded into oblivion for almost three decades, during which liquid-fueled rockets became the rage. The first American solar-sailing proposal, in the May 1951 issue of *Astounding Science Fiction*, appeared under the byline Russell Sanders—a pseudonym adopted by aeronautical engineer Carl Wiley to guard his professional reputation. The Sanders/Wiley article proposed using solar sails instead of rocket propulsion for interplanetary travel, and detailed what is now the usually accepted plan—to start the journey by spiraling in close to the sun to gain maximum momentum where the photon concentration is highest.

During the next decade the matter became a serious scientific subject, and Richard Garwin of Columbia University coined the term "solar sailing" in a 1958 article in the journal *Jet Propulsion*. Several studies in the next few years showed that solar sailing could theoretically equal or exceed the velocities attainable via chemical or ion propulsion for a number of missions. And, for fixed sail angles relative to the sun, solar-sail orbits were calculated to be logarithmic spirals. (If the spacecraft is inbound toward the sun, this is the exact equivalent of a moth's death spiral around a porch light, and for the same reason—the light is kept at a constant angle to the flight path.) But it was famed science-fiction writer Arthur C. Clarke's melodramatic 1963 short story, "The Wind from the Sun," that gave the idea its biggest push, capturing the public imagination and spreading the concept among sci-fi–reading engineers—who quickly figured out that the solar wind lacked the propulsive force of the sun's photon stream.

By the 1970s NASA was funding solar-sailing studies, and JPL's Wright came up with a trajectory for a solar-sail spacecraft to rendezvous with Halley's comet and watch it evolve as it neared the sun. Bruce Murray, who was then JPL's director and a Caltech professor of planetary science, elevated the idea to most-favored "purple pigeon" status. Two competing designs were produced: a three-axis-stabilized, square-shaped sail 800 meters on a side; and a "heliogyro" some 15 kilometers in diameter that sported 12 free-spinning, helicopter-like blades, designed with the help of helicopter engineers John Hedgepeth and Richard MacNeal. However, NASA dropped the project and its large payload in 1977, leaving Halley to conventionally propelled flybys (a much easier mission!) by spacecraft from the Soviet Union, Japan, and Europe. One reason the mission was shelved was that the deployment of a solar sail in outer space was considered a high risk. Indeed, a free-flying solar sail has not been deployed in space to this day.

Nevertheless, solar sailing had by then attracted an almost cultlike following, and several newly formed international organizations began promoting races to the moon and Mars, eerily reminiscent of Clarke's short story. JPL engineer Robert Staehle, who is now deputy manager of the Europa Orbiter Project, helped form the World Space Foundation in 1979 and attempted to obtain private funding for demonstration flights. Europeans formed the Union pour la Promotion de la Propulsion Photonique (U3P) in 1981, and along with the Solar Sail Union of Japan promoted a race to the moon. Solar-sail fever was still going strong in 1989, when the Christopher Columbus Quincentennial Jubilee Commission attempted to organize a race to Mars for 1992. Although they kept alive interest in solar sailing and encouraged designers to advance the art, the prize money and space-sailing contests never materialized.

The days of such promotions are over, at least for now, though other schemes worthy of the best of P. T. Barnum are taking their place. For example, Encounter2001.com, whose Web site also hosts ads for burials in space, is working with L'Garde, Inc., of Tustin, California, which specializes in inflatable space structures, on an interstellar spacecraft. Encounter2001 hopes for a live, members-only Webcast of its privately launched solar sail, which will double as a giant billboard and carry a payload of photos and greetings from customers who are expected to flock on line to pay by credit card as the launch date nears. For $24.95, you get a photo and a message; for another $25, you can send a "biological signature"—a sample of hair-follicle DNA.

Meanwhile, back at the lab, JPL's New Millennium Program (NMP), which solicits proposals to demonstrate new spaceflight technologies and funds the winners, has taken up the torch. NMP's Space Technology 7 (ST7) announcement in April 2001 is expected to include an opportunity for a full-flight solar-sail mission, says Hoppy Price, manager for solar-sail technology development in the NASA Technology Program Office at JPL. Price hopes to place a solar-sail satellite into a high equatorial orbit, deploy the sail, and then just let it fly around. The goals are twofold: first, to simply prove that it can be deployed; and second, to evaluate attitude-control issues, thrust performance, structural dynamics, and sail lifetime, and to prove out the control algorithms in the flight software. This will clear the way for "operational missions" like DoD and NOAA's Geostorm.

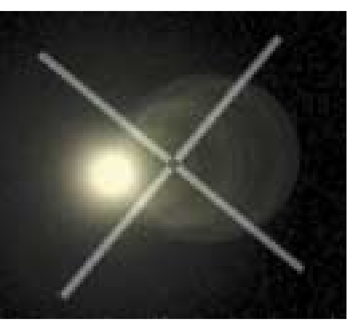
But the title of First Solar Sail in Space may go to the nonprofit Planetary Society, whose Pasadena headquarters is just a mile or so from the Caltech campus. As *E&S* was going to press, the society announced that it had contracted with Russia's Babakin Space Center to build a 600-square-meter, windmill-shaped sail 30 meters in diameter. The sail's deployment mechanism, which uses inflatable booms, will be tested on a subor-

Above: The World Space Foundation displayed a prototype solar sail on the floor of the Pasadena Convention Center at the Planetary Society's first Planetfest in 1981. Right: A panel of the Planetary Society's current solar sail, which is being assembled near Moscow. The Mylar sail is a relatively thick five microns, about one-fifth the thickness of a trash bag; April's suborbital flight test will include two such panels. And in a peace dividend from the end of the Cold War, both the suborbital test and the completed spacecraft will be launched in converted intercontinental ballistic missiles fired from a Russian nuclear sub in the Barents Sea. Far right: The completed spacecraft will carry two cameras and several instruments and, although just a point of light as seen from Earth, will shine as brightly as the full moon.

bital flight in April, as will a pioneering inflatable reentry shield the Russians have developed. The spacecraft itself is slated to be launched to an initial altitude of 850 kilometers between October and December 2001 to attempt the first solar-sail flight. "It's the Wright Brothers analogy," says Louis Friedman, the Planetary Society's cofounder and executive director. "This first sail won't fly to a distant location, but we hope it will demonstrate the concept." (Incidentally, Friedman led the Halley's comet solar-sail project at JPL.) This commercial venture, named Cosmos 1, is being privately funded by Cosmos Studios, a new-media company started by Ann Druyan, wife of the late Carl Sagan, who cofounded the Planetary Society with Friedman and Caltech's Bruce Murray; and Joe Firmage, an Internet entrepreneur.

Deploying a solar sail in space is fraught with structural-engineering complexities. The packaging is particularly tricky, as the stowed sail's exposed area may expand over a hundredfold as it unfurls. Risks inherent in unpacking solar sails in space include the sudden venting of air trapped in the folds of the sail, with enough force to tear it; tangles; rips in the fabric; electrical arcs or other discharges; and electrostatic forces—static cling, in other words—that may hold the folded sail together. "The folded-up sail is essentially a big capacitor," says Price. "We do not know how it will behave in space." Grounding can be designed-in to minimize some of the electrical-discharge risk, but it is "a bit hard to analyze on the ground." Thus, actual launches are needed to see how it works. Wrinkle management in the packing and unfurling is vital, because wrinkles can cause multiple reflections and intense hot spots that might damage the sail, and wrinkles will also decrease the sail's reflective performance. The sail's wrinkle potential will probably vary with the manufacturing process; wrinkle-management options being explored include special sail-fabrication machines that fold the sail wrinkle-free on a big table as it is built, and methods of pulling out the sail with enough tension to remove the wrinkles.

A number of sail shapes are likely to prove viable, including squares, hexagons, and other polygons, as well as disks and hoops. Carnegie Mellon University is reviving the heliogyro, albeit a more modest one with four blades 30 meters long and a meter wide. JPL is starting out with a simple design made up of four triangular panels. "It looks like a big kite with four booms coming out from the center," says Price. The four booms will deploy themselves straight out from the central hub to unfurl the sail.

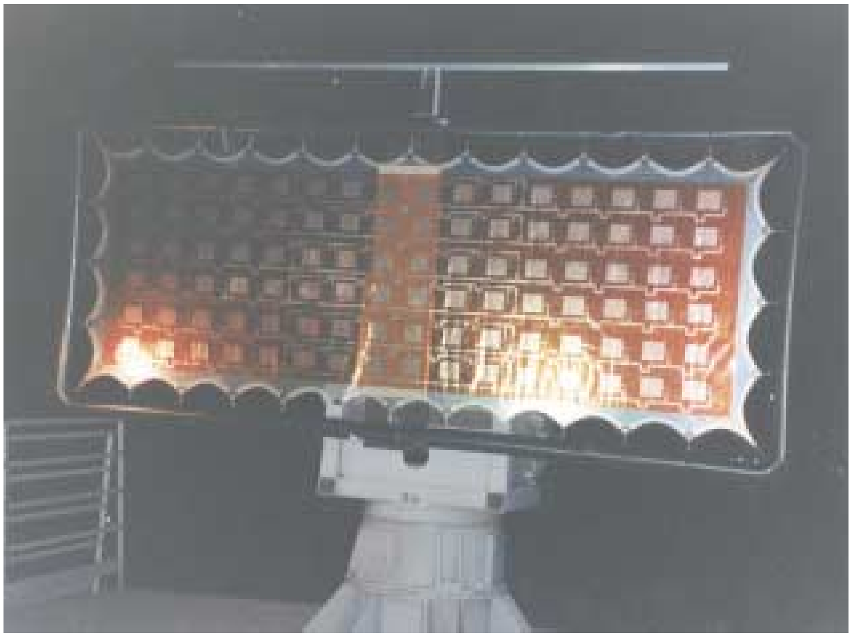


Above: The Carnegie-Mellon heliogyro. Right: The DLR's lens-shaped boom will be used in ESA's solar-sail program, which is planning a test flight in a year or so.

Houfei Fang, a member of the technical staff in JPL's gossamer systems group, holds two five-meter-long, three-inch-diameter STR booms. (One of them is rolled up on a six-and-a-half-inch diameter mandrel, as seen in the inset.) The boom weighs a kilogram, and can take a maximum axial force of 75 kilograms.

Several types of booms are being considered. One option is carbon-fiber booms, developed by the German Aerospace Center (DLR), that are lens-shaped in cross section. They lie flat when rolled up on a spool, but pop open as they unroll, becoming quite stiff. (The prototype sail built by the World Space Foundation in 1981 used similar tubes made of much heavier stainless steel.) Another novel design, recently patented by JPL, uses commercial-grade stainless steel carpenters' measuring tapes (from Sears!) as stiffeners. Called a Spring-Tape Reinforced (STR) aluminum laminate boom, it also rolls up flat, but has a circular cross section when deployed. Also under consideration are carbon or fiberglass rods in the form of a cross-braced, three-sided truss. When twisted, the truss coils up to stow compactly into a cylinder the size of a small trash can.

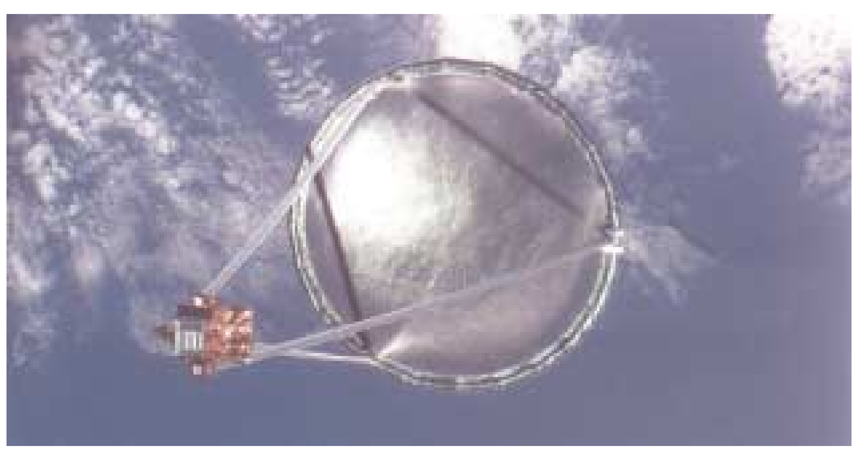
Inflatable booms that blow up like long, skinny balloons have the potential to unfurl a tightly rolled sail from its container, and, if properly stiffened—perhaps by being perfused with an epoxy that cures into a very hard plastic when



exposed to ultraviolet light—could then function as rigid struts to keep the sail taut. The deployment of an inflatable antenna in orbit has been demonstrated. The Spartan 207/Inflatable Antenna Experiment, which flew in May 1996 on space shuttle *Endeavour*, deployed a 14-meter antenna for several hours. "The demonstration was a success, and we learned a lot from it, but the process of inflation was not well controlled," says Price, which means the technology needs more testing in space.

JPL and its industrial and academic partners are currently developing inflatable structures for a variety of applications, including solar arrays, radar and communications antennas, telescopes, and all kinds of instruments. So solar sails will benefit from research directed toward projects like the construction of lightweight, inflatable space telescopes with minimal steel and glass, such as JPL's proposed Advanced Radio Interferometry between Space and Earth (ARISE) mission. ARISE is designed to look at the disks of gas and dust that surround black holes, zooming in on them with a resolution 5,000 times better than that of the Hubble Space Telescope.

The overall size of the inflatable synthetic aperture radar array above is 1.7 by 3.7 meters, yet it rolls up into the two scrolls at right for stowage. The antenna, which is a flat sheet, acts like a traditional parabolic dish antenna thanks to a tiny copper dogleg incorporated into each reflective element that steers and focuses the radar beam—the brainchild of John Huang, a principal engineer in JPL's Spacecraft Telecommunications Equipment Section.



Right: The 14-meter Spartan 207/Inflatable Antenna Experiment in flight.

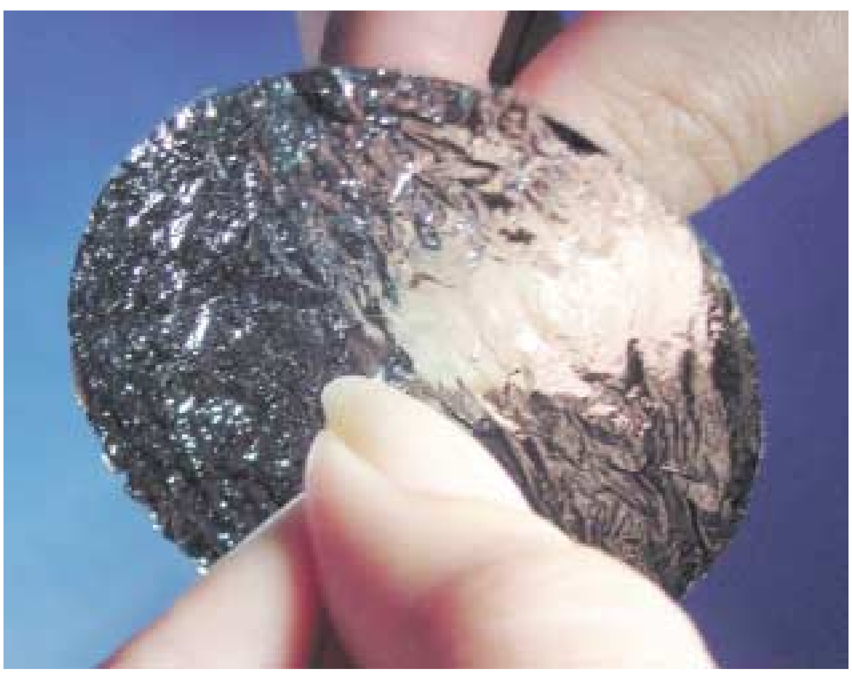
The Russians have twice attempted to deploy large, sail-like mirrors in space. The wheel-like mirrors, named Znamya ("Banner"), were spun on motor-driven axles to keep their shape through centrifugal force. A 20-meter-diameter version was successfully tested by Vladimir Syromiatnikov and colleagues at Energia in 1993, using a *Progress* resupply vehicle that had just undocked from the *Mir* space station. However, a 25-meter version failed in 1999, when it tangled on an antenna jutting out from the *Progress* spacecraft that was deploying it. The antenna had been used in the docking maneuver, and was supposed to have been retracted before sail deployment. A mission-operations software error was to blame.

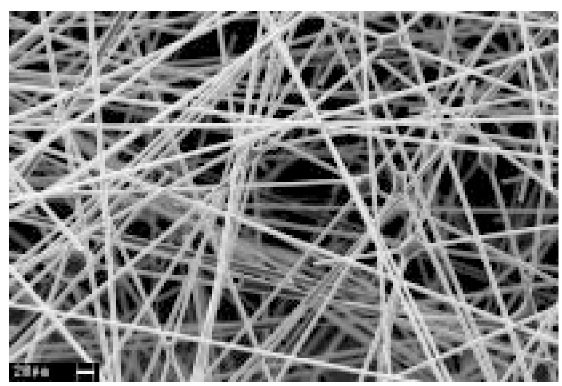
Once a sail is deployed, steering it and controlling its attitude (i.e., pitch, yaw, and roll) become paramount concerns. Thrusters could be used for steering, but the whole idea behind sails is to avoid the weight of propellant and the possibility of running out of it. One approach is to shift the spacecraft's mass relative to the sail's center of pressure by moving the spacecraft's electronics package around on the end of a long boom. Alternatively, the spacecraft could be steered like a sailboat by moving the center of pressure relative to the center of mass by use of adjustable vanes or flaps on the outer corners of the sail. "We expect to see different, competing ideas on how to control attitude," says Price.

Thin plastics like Mylar and Kapton are the major near-term candidates for solar-sail fabrication, as they're lightweight and are commercially available in wide rolls. Mylar can only be used for short-duration missions, as it is rapidly degraded by ultraviolet light. Kapton is chemically inert, has high radiation resistance, adheres well to metal films and adhesives, and does not degrade until 670 kelvins (K)—the melting temperature of glass, and well above the 520–570 K range considered safe for long-term solar-sail operation.

However, even moderate solar-sail performance requires films on the order of 2 microns (millionths of a meter) thick, which tear very easily and are not routinely fabricated in rolls. Kapton film is typically produced in rolls 7.6 microns thick. Though small-scale etching tests have gotten the thickness down to 0.4 microns, lifting and handling such ultrathin material without tearing—much less folding, packing, and deploying it in space!—is going to be quite a challenge. Suitable Mylar films are easier to come by commercially, and can be had as thin as 0.9 microns. Possible ways to strengthen these films include special backings, such as crisscrossed Kevlar fibers.

Mylar or Kapton needs to be coated with a material like aluminum, which has a reflectivity of close to 0.9 (1.0 being perfect), in order to make it an efficient photon reflector. Even so, some photons will be absorbed and the sail will heat up, especially on missions that go close to the sun. Coating the sail's back side with a substance like chromium, which has an emissivity of order 0.64, is one way to shed heat from absorbed photons and extend the sail's life. (Both metals would be added to the sail by vapor deposition under high vacuum, a common industrial process.) And advanced thermal-control technologies such as micromachined, whisker-like quarter-wave radiators, which act as antennas at infrared wavelengths, would be useful for close approaches to the sun. A typical recent design has 0.1 microns of aluminum vapor deposited on 2 microns of Kapton substrate and 0.0125 microns of chromium





Above: In this microphotograph of ESLI's carbon-fiber mesh, the scale bar is 20 microns long. The fibers are seven microns in diameter, or about one-tenth that of a human hair. The bulk material comes in sheets one millimeter thick, and typically has a density of about seven grams per square meter.

Right: A five-centimeter molybdenum-coated sail sample.

on the rear side, along with grounding straps to guard against electrical discharges between the front and rear surfaces that could cause the sail to tear, and rip stops to limit tearing should it start.

Since the substrate is mainly needed to allow handling, packing, and deployment of the sail, another strategy involves vaporizing the substrate after deployment. This would leave a sail composed of a thin reflective metal film, with rip stops and thick strips of unvaporized substrate left in strategic places to act as reinforcement. Small-scale experiments dating back decades show that it is possible to create metal films 0.05 microns thick, though at some point the film becomes too thin and starts letting a significant amount of light through. One scheme to make metal films lighter without degrading their optical properties involves perforating the films with holes smaller than the wavelength(s) of the light being used for propulsion. Technology to make these small holes already exists in the semiconductor industry.

Since space is a hard vacuum, one could even fabricate the sail in orbit, using a small vapor-deposition unit that would be discarded when the job was done. Direct heating would evaporate, say, powdered aluminum, and the metal would condense onto a sail-shaped substrate. After cooling, the metal film could be separated from the substrate. The technology for manufacturing thin metal films already exists, as do methods for controlling their thickness.

Two years ago there was movement toward graphite fibers for sails, and even more recently toward stronger and possibly thinner single-crystal carbon fibers. Timothy Knowles, president of ESLI (the company that did the thermal-molecular demonstration mentioned earlier), invented a mesh of randomly oriented, crisscrossing graphite fibers called a microtruss. The material, which rather resembles a scrubbing pad, is ultralight, yet stiff and strong. When rolled up or folded into accordion pleats, it springs back into a flat sheet upon release, greatly simplifying deployment. This carbon mesh also takes the heat much better than plastics do, which is vital for laser propulsion. If you want to get to Alpha Centauri within your own lifetime, you need to slam so many photons into the sail that even a near-perfect reflector will start to disintegrate from the accumulated heat it can't reradiate.

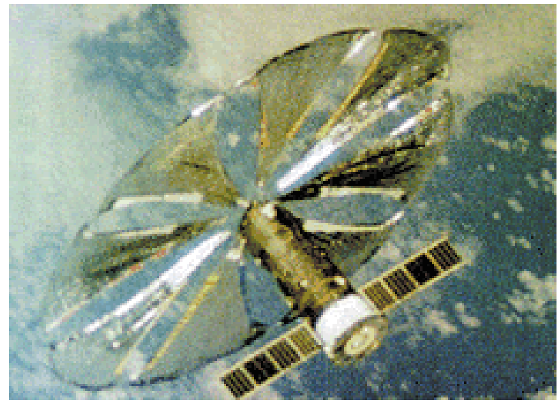
The world's first demonstration of photonic thrust with a real-world laser-sail material. Laser light first illuminates, then moves a five-centimeter specimen of ESLI's molybdenum-coated microtruss mounted on a magnetically suspended pendulum. The 150-kilowatt continuous CO_2 laser is part of the Laser-Hardened Materials Evaluation Laboratory II, run by the Anteon Corporation under contract to the Air Force at the Wright-Patterson Air Force Base.

In December 1999, JPL funded Leik Myrabo, a mechanical engineering professor at Rensselaer Polytechnic Institute in Troy, New York, to mount a disk-shaped sample of ESLI's microtruss on a sensitive pendulum apparatus, stick it in a high-vacuum chamber, and zap it with photons from a high-powered laser at the Wright-Patterson Air Force Base in Dayton, Ohio. The mesh was coated with a thin layer of molybdenum on one side to maximize its reflectance in the infrared, where the laser operates. The hope was that photonic thrust would deflect the pendulum from the vertical by a measurable amount. The thrust supplied by the laser could then be calculated very accurately by careful measurement of the angle of deflection. However, it was anticipated that the up-to-10-second laser blast would heat the sail enough to cause atoms to evaporate from its surface, giving the pendulum a "kick" as they left. This kind of thrust—the third step in Henry Harris's "backyard launch" scheme—could easily be mistaken for photonic thrust. So the samples were weighed before and after each run, and any thrust due to mass loss was calculated. The research, presented last July at NASA's 36th annual Joint Propulsion Conference in Huntsville, Alabama, showed that the pendulum deflected "from 2.4 to 11.4 degrees, measured as a function of incident laser powers from 7.9 to 13.9 kW. Laser photon thrust ranged from 3.0 to 13.8 dynes," according to the project report published by the American Institute of Aeronautics and Astronautics. The researchers also found that heating the sail to about 2600 K caused ablation, or mass loss, to occur, and those runs produced up to 50 percent more thrust than the theoretical maximum available from photon power alone. "It was amazing what those sails took," says Myrabo. "They were just incredible."

In December 2000 another round of tests was done, in which the sail was propelled up a vertical molybdenum wire. This is considerably more demanding. The pendulum tests translated into a spacecraft acceleration of 0.16 *g*, with one *g* being the force Earth's gravity exerts on you as you sit in your armchair reading this. In order to levitate the sail, it needs to be hit with an upward force in excess of one *g*. The same size microtruss samples were used again, but they were heavier this time because an eyelet to ride the guide wire had to be inserted into them and glued into place. So the sail really had to be zapped hard in order to lift it—in fact, some of the specimens wound up fusing to the wire. Nevertheless, says Harris, "we believe we have demonstrated 1-*g* photonic acceleration at 2600 K. Motion analysis [of the videotapes and high-speed movie footage taken of the runs} is currently under way to confirm this. We have also demonstrated small-scale deployment and are beginning stability and control analysis. Theoretical analysis suggests that with further development we may be able to achieve 100 *g* acceleration, which would enable achieving one-tenth the speed of light in approximately eight hours." (Such acceleration would require a sail with one-tenth the areal density and a laser with ten times more power—not unreasonable goals.)

"We have basically demonstrated that it is doable," says Neville Marzwell (MS '71, PhD '73), technology manager for the Technology and Applications Programs Directorate at JPL, though "there are many technological gaps." Sail fabric is getting stronger, and better able to withstand high pressures and temperatures, and Marzwell expects to eventually get to the point where the sail is reinforced with carbon fibers in the form of microdiamonds. Marzwell envisions laser or microwave beams blasting diamond-studded sails to Alpha Centauri with little need for photons from the sun. However, the same sturdy sailcloth would also be useful for "sun diver" missions, like those envisioned by Carl Wiley in his 1951 *Astounding Science Fiction* article, where sails tack in close to the sun to gain maximum momentum.

A parallel program studying microwaves instead of lasers is going on in-house at JPL, using a high-vacuum chamber in the Advanced Propulsion Laboratory, which had previously tested the ion drive for Deep Space 1. The lab also contains a high-power microwave test facility that was adapted for the purpose. Microwaves have several potential advantages as a propulsion beam. Microwave transmitters have been around a lot longer than lasers, and very large, high-power arrays are currently much cheaper to build. (The latter is an important consideration, as a microwave array needs to be considerably larger to support a sail of the same diameter, in order to compensate for the longer wavelength of the microwaves.) And if the sail is designed to absorb some of the microwaves, its interaction with a circularly polarized beam will set it spinning. The torque increases with the beam's wavelength, so the spinning effect works much better with microwaves than it does with lasers. The easiest way to keep a spacecraft on a steady course is to set it spinning perpendicularly to the direction of flight, like a rifle bullet or a well-thrown football. Controlling the sail's spin rate and angle by manipulating the beam's axis of



The Znamya 20-meter mirror used spin to deploy itself and maintain its shape.

polarization would clearly be superior to the heavy laser gyros and thrusters used on today's spacecraft. And the spin could be used to deploy the sail, or to keep it rigid without the use of structural stiffeners, as the Russians did with Znamya. The microwave program is using uncoated samples of ESLI's microtruss, which absorbs about 10 percent of the incoming microwave radiation. The sails were levitated on a guide wire, and in April 2000 the first flights were made. It is still unclear, however, how much of the thrust was photonic, and pendulum experiments are now under way to attempt to resolve this. The spin experiments were less ambiguous—the sail spun at exactly the rate predicted for 10 percent absorption, and when the beam's polarization was reversed, the sail spun in the other direction.

Either way, Marzwell envisions embedding the scrubbing pad with nanocomputers 10 microns square (about one-tenth the thickness of a hair), and instruments to match. A micropump could send captured interstellar material to a nanospectrometer for analysis, for example, while tiny cameras and dust-mote-sized vibration detectors helped navigate the spacecraft and monitor its health. Parallel programs are looking at the technologies, like nanobatteries, needed to make these tiny devices work. "You can't develop a sail without developing the instruments," says Marzwell. In essence, the spacecraft becomes the sail—there's no need for a separate hull dangling below it to carry the payload. This is a major departure from today's paradigm, where 80 to 90 percent of the weight on most missions is fuel and the instrument package seems almost an afterthought. Similarly, a metallic mesh could be embedded into Mylar, which would be evaporated in orbit to leave the

The spacecraft becomes the sail—there's no need for a separate hull dangling below it to carry the payload. This is a major departure from today's paradigm, where 80 to 90 percent of the weight on most missions is fuel and the instrument package seems almost an afterthought.

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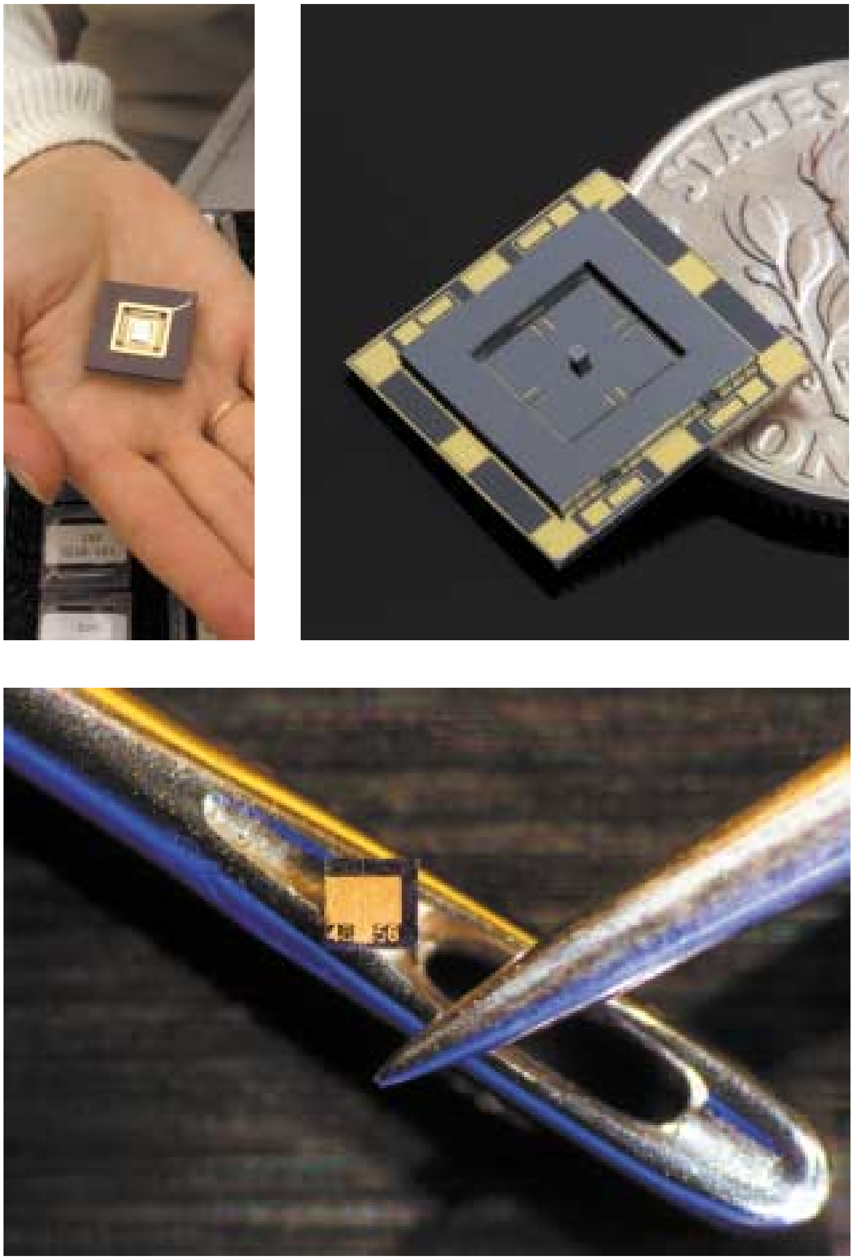
mesh and its instruments.

Choosing the sail's geometry is a complex problem, involving such variables as how the energy couples with the sail material, and the mechanical and elastic properties of the sail. "Shape is crucial because of the need to control the center of mass and center of gravity," says Marzwell, who believes that a conical, sombrero-like geometry will eventually replace flat sails to obtain maximum photon capture. Such a sail would ride the beam more stably—if the sail's pointy center started to slip off the center of the beam, the asymmetric pressure on the side of the cone would tend to move the sail back into alignment.

Building the laser or microwave facility needed for these missions will be no small feat. Harris's group estimates that the 40-year trip to Alpha Centauri would require a phased laser array 1,000 kilometers in diameter. (Planetary missions can get by with something more modest—a 15-meter array could send a 50-meter-diameter sail carrying a 10-kilogram payload to Mars in 10 days, he says in an article in *Scientific American*.) People are working on those issues, too, but that's another story….

While JPL, the ESA, and the Planetary Society prepare for their first deployment tests with Kapton and Mylar, the advanced concepts and technology people prepare for a more distant, diamond future as they analyze the electrodynamic coupling between high-energy beams and sails varying in shape from thin sheets to balloons. Hopefully, this research will lead beyond missions delivering better space weather reports to explorations of interstellar space that will tell us how the stars, the rocky planets, and perhaps life itself evolved in the universe. □



These solid-state instruments, which could potentially be embedded into an interstellar sail, have been developed by JPL's Center for Space Microelectronics Technology. Top, left: Of course, you've got to have cameras, as well as star sensors for navigation. This is a complementary metal-oxide semiconductor active pixel sensor. It requires one-hundredth the power of a CCD camera, is lighter, and is less susceptible to radiation damage in space. Top, right: A microgyro jointly developed by JPL and Hughes for spacecraft attitude control. Bottom: A tunable diode laser, which can be set like a radio transmitter to emit any given frequency within its range, allowing it to look for molecules of a specific gas.

Joel Grossman is a freelance writer based in Santa Monica, California. He last wrote about solar sailing for the Los Angeles Times Magazine *on August 20, 2000. He also wrote a piece about Professor of Electrical Engineering Yu-Chong Tai's bat-sized flying robot, which appeared in the* Los Angeles Times Magazine *on December 10, 2000.*

For Further Reading

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Scientific American, February 1999