the X-34. It will test two-stage-to-orbit technologies, including a new type of reusable ceramic tile, starting this year.

Looking beyond X-33 and X-34 technology, the agency recently beefed up work on hypersonic jet engines, which had taken a back seat since the National Aerospace Plane program was canceled in November 1994. Variants on jet engines called scramjets—which breathe air like conventional jets but can operate at speeds over Mach 6—could help bring the goal of single stage to orbit within reach. Several unpiloted scramjets, designated X-43, will fly at speeds of up to Mach 10 and then crash-land in the Pacific Ocean, starting in the year 2000 [*see box on page 62*].

The difficulty faced by such efforts, explains NASA's Gary E. Payton, is in slowing the incoming air enough so that fuel can be burned in it for thrust without generating excess heat. In principle, it can be done with a shock wave created at the air inlet. But the process wastes a lot of energy.

One potentially pathbreaking launch technology is an air-breathing engine that also operates as a rocket both when at low velocities and when the air becomes too thin to be worth taking in. At that altitude, a vehicle heading for space would most likely be traveling at about Mach 10. Such rocket-based combined-cycle engines have yet to advance beyond tests in wind tunnels, and they have to be de-

Light Sails

by Henry M. Harris

Science-fiction dreams of worlds beyond our own solar system have taken on a more realistic aspect since astronomers discovered that the universe contains planets in unexpectedly large numbers. Studying those distant planets might show how special Earth really is and tell us more about our place in the universe. This perspective is prompting the National Aeronautics and Space Administration to turn its gaze toward the stars.

Gazing is one thing, but for actual exploration the engineering reality is harsh. It would take tens of thousands of years to reach even the nearest stars with today's technologies. In 1998 I coordinated for NASA a survey of propulsion concepts that might enable an exploratory vehicle to travel to another star fast enough to accomplish its mission within 40 years, the professional lifetime of a scientist. We came up with only three that now seem plausible: fusion [*see box on page 72*], antimatter and beamed energy. Of these, only beamed energy is understood sufficiently to be part of any realistic near-term research program.

SLIM FILMS

It is easy to see why beamed energy is attractive. When you take your car on a long trip, you rely on gas stations for fuel and on mechanics to keep it running. Current spacecraft, in contrast, have to transport all the fuel they will need and must operate without human intervention. But could the engine somehow be kept on Earth, along with the fuel? Besides making in-flight repairs possible, the arrangement would make the spacecraft less massive and therefore easier to accelerate.

Beamed energy might offer a way. Engineering analyses suggest that the best approach for long-duration spaceflight is to shine a powerful optical laser at a large, thin "sail." This idea was first proposed by Robert L. Forward as long ago as 1984. Lasers can project energy over vast distances, and the large area of a sail allows it to receive a lot of energy in relation to its mass. Other types of beamed energy, such as microwaves, could also be used. Some investigators have even considered beaming charged particles at a spacecraft. The particles, on reaching the craft, would pass through a superconducting magnetic loop, thereby creating a Lorentz force that would provide thrust. But for now, laser light aimed at sails seems to be the most practical option.

When a photon from a laser hits a sail, one of two things can happen. It can collide elastically with the electromagnetic field surrounding the atoms in the sail and be reflected. Alternatively, the photon can simply be absorbed by the sail material, a process that heats the sail a minuscule amount. Both processes impart an acceleration, but reflection imparts twice as much as absorption. Thus, the most efficient sail is a reflective one.

The acceleration that a laser provides is proportional to the force it transmits to the sail and inversely proportional to the spacecraft's mass. Like other propulsion methods, then, light sails are limited in their performance by the thermal properties and the strength of materials—as well as by our ability to design low-mass structures. The sail designs that have been proposed consist of a polished, thin metal film, most with some kind of backing for structural strength.

The power that can be transmitted is constrained by heating of the sail: as the metal surface gets hotter, it becomes less reflective. The temperature a sail attains can be lowered, and so its acceleration increased, by coating its reverse side with materials that efficiently radiate heat.

To reach very high velocities, a spacecraft must sustain its acceleration. The ultimate velocity achievable by a light sail is determined by how long the Earth-bound laser can illuminate its target efficiently. Laser light has an important property known as coherence. It means that the energy it can impart is undiminished by distance, up to a critical value known as the diffraction distance. Beyond it, the power delivered quickly becomes insignificant.

The diffraction distance of a laser, and thus the ultimate velocity of a spacecraft it powers, is governed by the size of the laser's aperture. Very powerful lasers would probably consist of hundreds of smaller ones ganged together in an array. The effective aperture size is roughly the diameter of the entire array. Maximum power is transferred when the array is packed as densely as possible. We have a tessellated design that approaches 100 percent packing density.

At the Jet Propulsion Laboratory in Pasadena, Calif., my team has studied the trade-offs in mission cost between the power of individual lasers and the size of an array. The aperture size required for an interstellar mission is enormous. A phased laser array we have designed to send a probe in 40 years to the nearby star Alpha Centauri would be 1,000 kilometers (621 miles) in diameter. Fortunately, planetary missions require much smaller apertures. A 46-gigawatt laser illuminating a 50-meter-diameter, gold-plated sail would require only a 15-meter aperture to send signed as part of the body of a craft to achieve adequate thrust. NASA recently awarded Boeing a cost-shared contract under its new Future-X program to develop an Advanced Technology Vehicle that will test a variety of hypersonic flight technologies. Payton says that "if things go well" flight tests of rocket-based combined-cycle engines could occur between 2004 and 2006.

As soon as a vehicle has left the atmosphere and reached orbital velocity—around Mach 25, or 18,000 miles per hour—the engineering challenges change completely. Large thrusts are no longer needed, because the craft is not fighting Earth's gravity and air resistance. Several new approaches are being explored, including, notably, the ion engine now flying on NASA's Deep Space 1 spacecraft. Ion engines work by accelerating charged atoms (ions) of a propellant with electrical grids charged to high voltage. As the ions leave the engine, they impart thrust. Xenon is the currently favored propellant.

Power on Deep Space 1 comes from solar panels, but theoretically any means of generating electricity could be used to drive an ion engine, which can produce almost 10 times more thrust per kilogram of propellant than chemical rockets can. As a result, even though ion engines generate only a few grams of force, they can in principle operate for years nonstop, allowing a spacecraft to reach extremely high velocities. Ion engines could feasibly

a 10-kilogram payload to Mars in 10 days. This system could send a probe to the boundary between the solar wind and the interstellar medium in three to four years.

Light-sail craft can be designed to follow a beam automatically, so steering can be done from Earth. A sail might even be built incorporating a reflective outer ring that could be detached on reaching the destination. The ring would continue onward as before and reflect laser light back onto the separated central part of the sail, thus propelling it back home.

A good deal of work relevant to light sails has already been done. The Department of Defense has developed high-powered lasers and precision-pointing capability as part of its research into ballistic-missile defenses and possible antisatellite weaponry. And saillike structures whose purpose is to reflect sunlight have already been tested. Russian scientists have flown a spinning 20-meter-diameter, polymer solar reflector, Znamya 2, as part of a scheme to provide extra winter illumination in northern Russian cities; a 25-meter-diameter version is scheduled for testing in February.

Closer to home, the U.S. National Oceanic and Atmospheric Administration is planning to launch within four years a spacecraft powered by a solar sail. The craft would hover at an orbitally unstable location between Earth and the sun, from where it could provide about an hour's advance warning of particles emanating from solar storms.

NASA is now evaluating plans to develop laser light sails as a possible low-cost alternative to conventional rockets. Missions being considered range from a demonstration of a 100-meter-diameter sail in Earth orbit to a journey through the shock wave at the edge of our planetary system.

In the immediate future, laboratory tests could measure the properties of candidate laser-sail materials for missions to Mars, the Kuiper belt and the interstellar medium. A military megawatt-class chemical laser at White Sands Missile Range in New Mexico may be used to illuminate sails deployed from spacecraft so that the resulting accelerations can be verified. And planned megawatt-class lasers that can run inexpensively off the power grid could within five years be able to boost light sails between orbits. I estimate that such lasers could power scientific missions to the moon within a decade.

We see in light sails a possible glimpse of the future, a vision of rapid, inexpensive access to the remote solar system and beyond. In time they could make travel to distant stars a reality.

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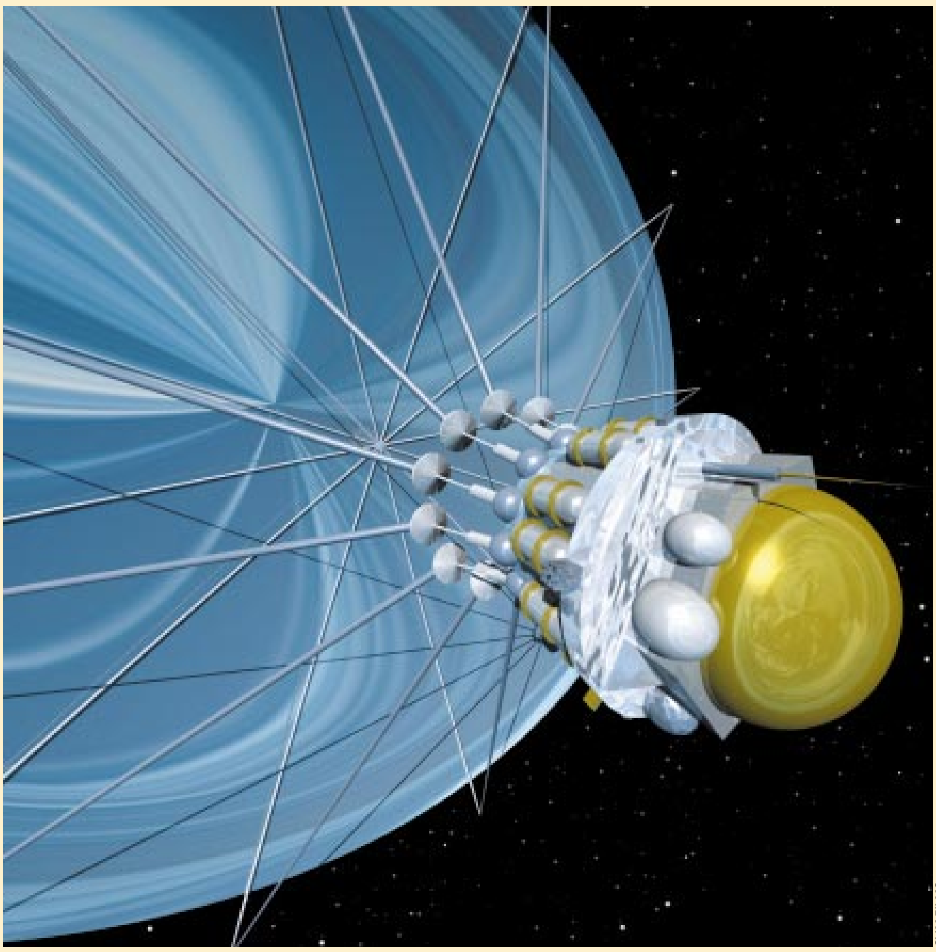

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THEORIZED LIGHT-SAIL craft (*far left*) driven from Earth by a laser could one day convey sensors to distant reaches of the solar system and even to other stars. The sail's reflective surface maximizes velocity. The low-mass structure might carry a light payload (*near left*).