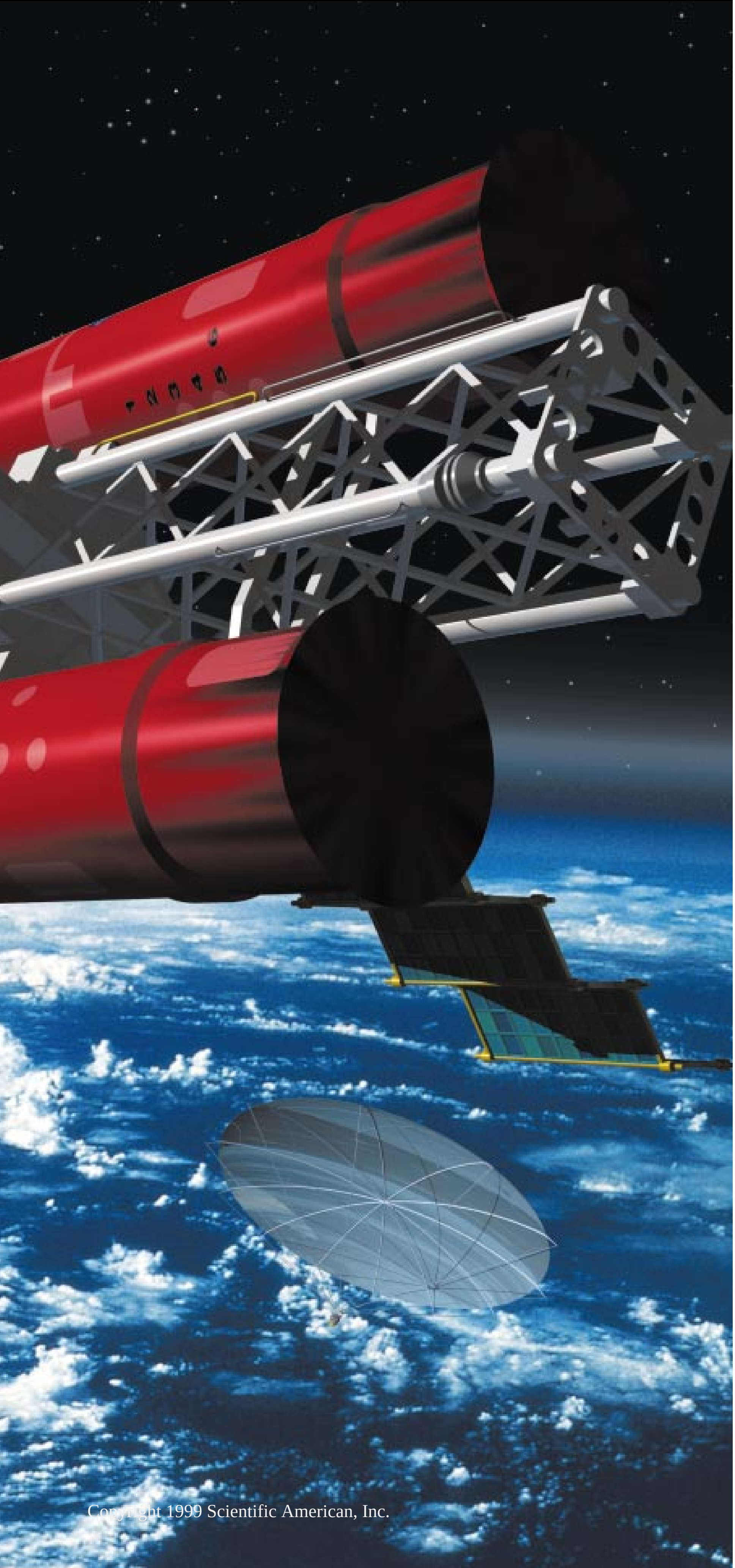
The Way to Go in Space

To go farther into space, humans will first have to figure out how to get there cheaply and more efficiently. Ideas are not in short supply



by Tim Beardsley, *staff writer*

The year 1996 marked a milestone in the history of space transportation. According to a study led by the accounting firm KPMG Peat Marwick, that was when worldwide commercial revenues in space for the first time surpassed governments' spending on space, totaling some $77 billion. Growth continues. Some 150 commercial, civil and military payloads were lofted into orbit in 1997, including 75 commercial payloads, a threefold increase over the number the year before. And the number of payloads reaching orbit in 1998 was set to come close to the 1997 total, according to analyst Jonathan McDowell of Harvard University. Market surveys indicate that commercial launches will multiply for the next several years at least: one estimate holds that 1,200 telecommunications satellites will be completed between 1998 and 2007. In short, a space gold rush is now under way that will leave last century's episode in California in the dust.

SLIM FILMS

SPACECRAFT DESIGNS decades from now may look very different from today's models. A solar-power station (*upper left*) beams microwaves down to a lightcraft (*lower left*) powered by magnetohydrodynamic forces; an old-style shuttle (*lower background*) has released a satellite that has been picked up by a rotating tether system (*upper right*). A single-stage-to-orbit rotary rocket craft deploys another satellite (*lower center*). Meanwhile a light-sail craft sets out for a remote destination (*lower right*).

Solar Orbit Transfer Vehicle

Approximate launch year: 2002
Approximate cost: $30 million
Power source: Solar thermal

COURTESY OF BOEING

SOLAR ORBIT TRANSFER VEHICLE is now being built by Boeing. This device utilizes a large reflector to focus the sun's rays onto a block of graphite, which is heated to 2,100 degrees Celsius and vaporizes stored liquid-hydrogen propellant to generate thrust. The vehicle gently lifts payloads from low-Earth orbits to higher orbits over a period of weeks. The light vehicle can launch satellites using smaller rockets than would otherwise be needed.

Space enthusiasts look to the day when ordinary people, as well as professional astronauts and members of Congress, can leave Earth behind and head for a space station resort, or maybe a base on the moon or Mars. The Space Transportation Association, an industry lobbying group, recently created a division devoted to promoting space tourism, which it sees as a viable way to spur economic development beyond Earth.

The great stumbling block in this road to the stars, however, is the sheer difficulty of getting anywhere in space. Merely achieving orbit is an expensive and risky proposition. Current space propulsion technologies make it a stretch to send probes to distant destinations within the solar system. Spacecraft have to follow multiyear, indirect trajectories that loop around several planets in order to gain velocity from gravity assists. Then the craft lack the energy to come back. Sending spacecraft to other solar systems would take many centuries.

Fortunately, engineers have no shortage of inventive plans for new propulsion systems that might someday expand human presence, literally or figuratively, beyond this planet. Some are radical refinements of current rocket or jet technologies. Others harness nuclear energies or would ride on powerful laser beams. Even the equivalents of "space elevators" for hoisting cargoes into orbit are on the drawing board.

"Reach low orbit and you're halfway to anywhere in the Solar System," science-fiction author Robert A. Heinlein memorably wrote. And virtually all analysts agree that inexpensive access to low-Earth orbit is a vital first step, because most scenarios for expanding humankind's reach depend on the orbital assembly of massive spacecraft or other equipment, involving multiple launches.

The need for better launch systems is already immediate, driven by private- and public-sector demand. Most commercial payloads are destined either for the now crowded geostationary orbit, where satellites jostle for elbow room 36,000 kilometers (22,300 miles) above the equator, or for low-Earth orbit, just a few hundred kilometers up. Low-Earth orbit is rapidly becoming a space enterprise zone, because satellites that close can transmit signals to desktop or even handheld receivers.

Scientific payloads are also taking off in a big way. More than 50 major observatories and explorations to other solar system bodies will lift off within the next decade. The rate of such launches is sure to grow as the National Aeronautics and Space Administration puts into practice its new emphasis on "faster, better, cheaper" craft: science missions now being developed cost a third of what a typical early-1990s mission did. Furthermore, over its expected 15-year lifetime the International Space Station will need dozens of deliveries of crew, fuel and other cargo, in addition to its 45 planned assembly flights. Scores of Earth-observing spacecraft will also zoom out of the atmosphere in coming years, ranging from secret spy satellites to weather satellites to high-tech platforms monitoring global change. The pressing demand for launches has even prompted Boeing's commercial space division to team up with RSC-Energia in Moscow and Kvaerner Maritime in Oslo to refurbish an oil rig and create a 34,000-ton displacement semisubmersible launch platform that will be towed to orbitally favorable launch sites.

After the Gold Rush

Even the most sobersided scientists would like to see many more research spacecraft monitoring Earth's environment and exploring the farther reaches of the solar system. The more visionary ones foresee a thriving space industry based on mining minerals from asteroids or planets and extracting gases from their atmospheres for energy and life support. K. R. Sridhar of the University of Arizona borrows the rhetoric of Mars enthusiasts when he says space pioneers will have to "live off the land": he has a developed an electrochemical cell that should be able to generate oxygen from the Martian atmosphere. Already one firm, SpaceDev, has talked about mining minerals from asteroids, earning a complaint from the Securities and Exchange Commission for its incautious enthusiasm. Some dreamers even devote themselves to finding ways of sending probes beyond the sun's domain into the vastness of interstellar space.

The clamor for a ticket to space is all the more remarkable in light of the extremely high cost of getting there. Conventional rockets, most developed by governments, cost around $20,000 per kilogram delivered to low-Earth orbit. The space shuttle, now operated privately by United Space Alliance, a joint venture of Boeing and Lockheed Martin, was intended to be an inexpensive ride to space, but its costs are no less than those of typical expendable rockets. In any event, the shuttle has been unavailable for commercial launches since the Challenger disaster in 1986. If a shuttle were outfitted today to take 50 passengers for a flight, they would have to pay $8.4 million a head for its operator to break even.

Getting into space is expensive today because boosters carry both the oxidizer and the fuel for their short ride and (with the exception of the partly reusable space shuttle) are abandoned to burn in the atmosphere after their few fiery minutes of glory. Engineers have long hoped to slash launch costs by building reusable craft that would need only refueling and some basic checks between flights, like today's commercial airliners. An energetic group of companies dedicated to reducing launch costs has sprung up in recent years, many of them populated with former NASA top brass. Most are adapting existing technology to gain a commercial edge for launching small payloads into low-Earth orbit.

Buck Rogers Rides Again

Nobody should underestimate the risks of building rockets, even ones based on conventional designs. The very first Boeing Delta 3, which was the first large booster developed privately in decades, exploded shortly after liftoff from Cape Canaveral last August, setting back Boeing's plans. A U.S. Air Force/Lockheed Martin Titan 4A had detonated over the cape two weeks earlier, and European Arianespace had a costly failure of a new launcher in 1996. In the U.S., disagreements over costs and demand have led to the cancellation of several government-sponsored efforts to develop new expendable rockets in the past decade.

The entrepreneurs are not easily deterred. One of the farthest along and best financed of this new breed is Kistler Aerospace in Kirkland, Wash., which is building the first two of five planned launchers that will employ Russian-built engines. The first stage of each vehicle would fly back to the launch site; the second would orbit Earth before returning. Both stages would descend by parachute and land on inflatable air bags. The company has raised $440 million and seeks hundreds of millions more; it says that despite world financial turmoil, flights should start this year. Privately financed Beal Aerospace Technologies in Texas is developing a three-stage launcher that is scheduled to fly in the third quarter of 2000. A reusable version may be developed later, says Beal vice president David Spoede.

Several firms plan to increase their advantage by using oxygen in the atmosphere, thereby reducing the amount of it that their rockets have to carry. This can be done most easily with a vehicle that

Roton Rotary Rocket | *Approximate launch year:* 2000 | *Approximate cost:* $100 million | *Power source:* Rotary rocket engine

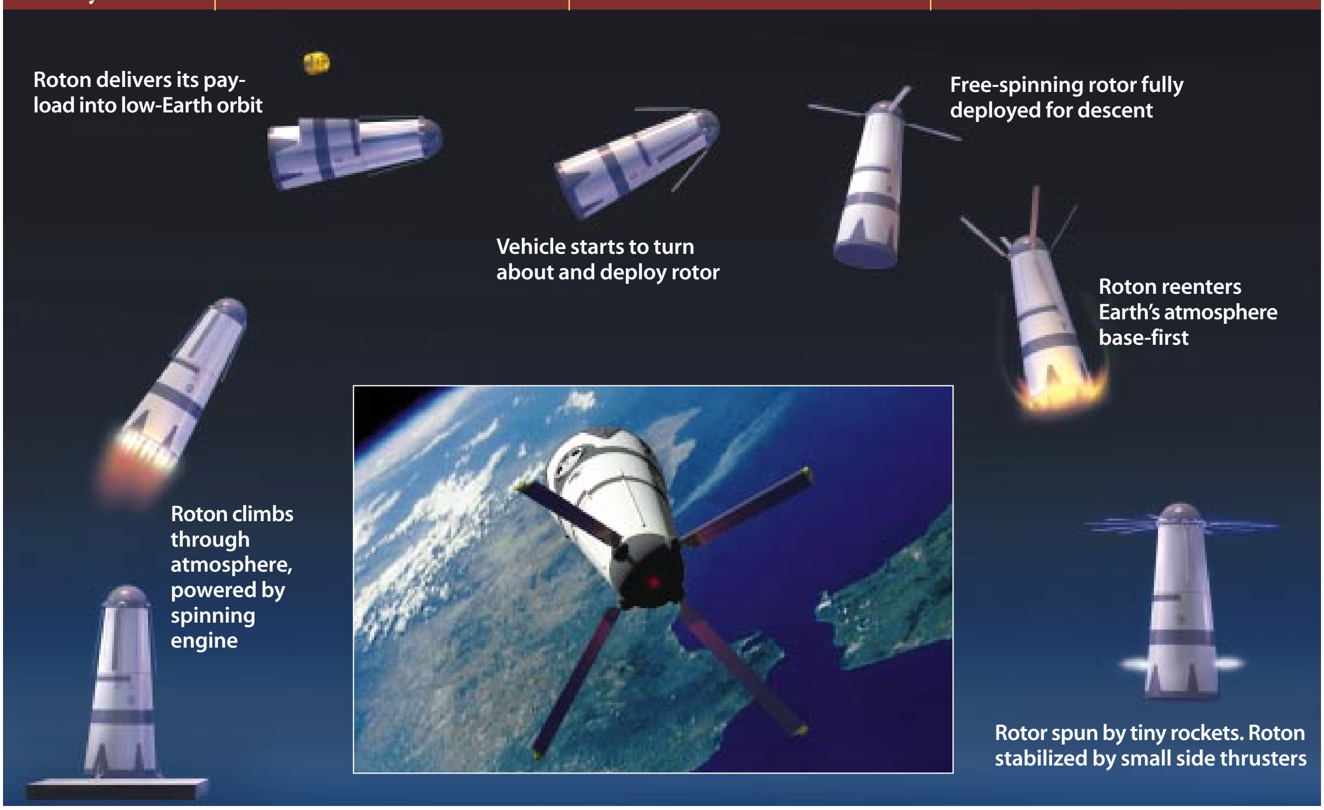


ILLUSTRATION BY ALFRED T. KAMAJIAN; INSET COURTESY OF ROTARY ROCKET COMPANY

ROTON VEHICLE is being constructed by Rotary Rocket in Redwood City, Calif. The craft takes off vertically, powered by a lightweight rotary rocket engine. After delivering a payload to low-Earth orbit, the craft comes about and unfolds helicopter blades. It reenters the atmosphere base-first. The helicopter blades rotate passively at first but are spun by small rockets on their tips for the vertical landing.

takes off and lands horizontally. Pioneer Rocketplane in Vandenberg, Calif., is developing a lightweight, two-seater vehicle powered by a rocket engine as well as conventional turbofan engines. The plane, with a payload and attached second stage in its small shuttle-style cargo bay, takes off from a runway with its turbofans and climbs to 6,100 meters (20,000 feet). There it meets a fuel tanker that supplies it with 64,000 kilograms (140,000 pounds) of liquid oxygen. After the two planes separate, the oxygen is used to fire up the smaller plane's rocket engine and take it to Mach 15 and 113 kilometers' altitude, at which point it can release its payload and second stage. A fail-safe mechanism for the cryogenic oxygen transfer is the main technical challenge, says the company's vice president for business development, Charles J. Lauer.

Kelly Space and Technology is also developing a horizontal takeoff plane for satellite launches, but one that can handle larger payloads, up to 32,000 kilograms. Kelly's Astroliner, which looks like a smaller version of the shuttle, has to be towed to 6,100 meters. At that altitude, its rocket engines are tested, and a decision is made either to zip up to 122,000

Air-Breathing Engines

by Charles R. McClinton

For years, engineers have dreamed of building an aircraft that could reach hypersonic speeds, greater than Mach 5, or five times the speed of sound. Propelled by a special type of air-breathing jet engine, a high-performance hypersonic craft might even be able to "fly" into orbit—a possibility first considered more than four decades ago. Recently, as the technology has matured and as the demand for more efficient Earth-to-orbit propulsion grows, scientists have begun seriously considering such systems for access to space.

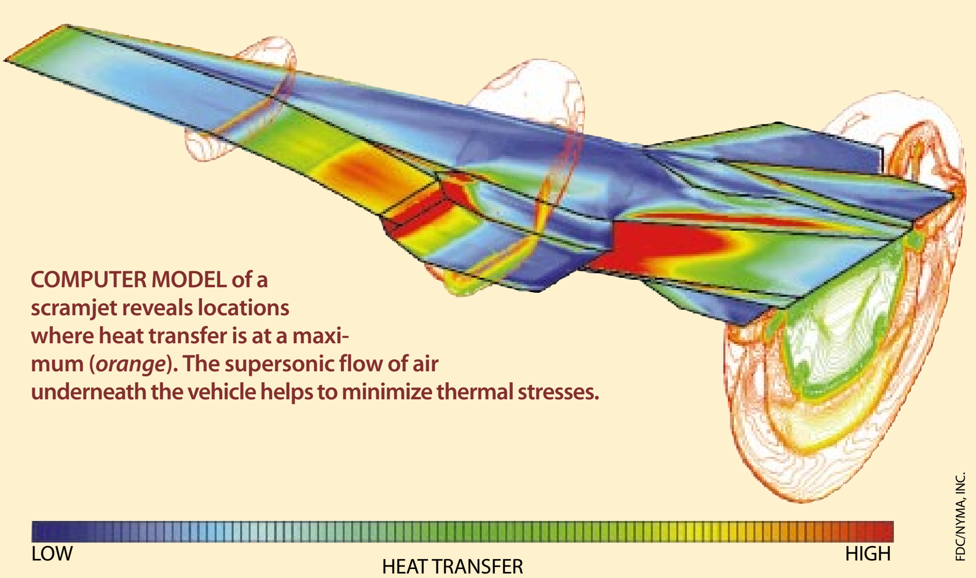
Air-breathing engines have several advantages over rockets. Because the former use oxygen from the atmosphere, they require less propellant—fuel, but no oxidizer—resulting in lighter, smaller and cheaper launch vehicles. To produce the same thrust, air-breathing engines require less than one seventh the propellant that rockets do. Furthermore, because air-breathing vehicles rely on aerodynamic forces rather than on rocket thrust, they have greater maneuverability, leading to higher safety: flights can be aborted, with the vehicle gliding back to Earth. Missions can also be more flexible.

But air-breathing engines for launch vehicles are relatively immature compared with rocket technology, which has continually evolved, with refinements and re-refinements, over the past 40 years. Hypersonic air-breathing propulsion is just now finally coming of age.

Of course, jet engines—which work by compressing atmospheric air, combining it with fuel, burning the mixture and expanding the combustion products to provide thrust—are nothing new. But turbojet engines, such as those found on commercial and fighter aircraft, are limited to Mach 3 or 4, above which the turbine and blades that compress the air suffer damage from overheating.

Fortunately, at such high supersonic speeds a turbine is not required if the engine is designed so that the air is "ram"-compressed. Such an engine has an air inlet that has been specially shaped to slow and compress the air when the vehicle is moving rapidly through the atmosphere. Because ramjets cannot work unless the vehicle is traveling at high speeds, they have been integrated in the same engine housing with turbojets, as in the French Griffon II experimental aircraft, which set a speed record of 1,640 kilometers per hour (1,020 miles per hour) around a course in 1959. Ramjets have also been combined with rockets in surface-to-air and air-to-surface missiles. But ramjets are limited to about Mach 6, above which the combustion chamber becomes so hot that the combustion products (water) decompose.

To obtain higher speeds, supersonic-combustion ramjets, or scramjets, reduce the compression of the airflow at the inlet so that it is not slowed nearly as much. Because the flow remains supersonic, its temperature does not increase as dramatically as it does in ramjets. Fuel is injected into the supersonic airflow, where it mixes and must burn within a millisecond. The upper speed limit of scramjets has yet to be determined, but theoretically it is above the range required for orbital velocity (Mach 20 to 25). But at such extreme speeds, the benefits of scramjets over rockets become small and possibly moot because of the resulting severe structural stresses.



COMPUTER MODEL of a scramjet reveals locations where heat transfer is at a maximum (*orange*). The supersonic flow of air underneath the vehicle helps to minimize thermal stresses.

Hypersonic air-breathing engines can operate with a variety of fuel sources, including both hydrogen and hydrocarbons. Liquid hydrogen, which powers the U.S. space shuttle, is the choice for space launch because it can be used to cool the engine and vehicle before being burned. Hydrocarbons cannot be utilized so efficiently and are limited to speeds less than about Mach 8.

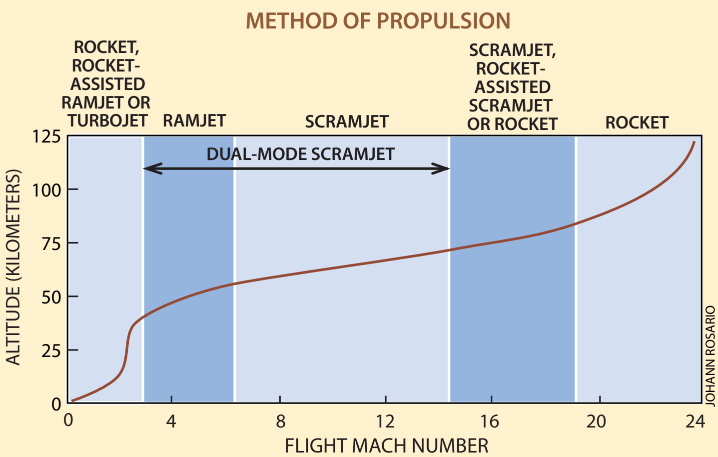
For a scramjet-powered craft, which must be designed to capture large quantities of air, the meters or to fly back to the launch site. The first two vehicles should cost close to $500 million, and Kelly is now lining up investors.

Other companies are being more technologically adventurous. One of the most intriguing is Rotary Rocket in Redwood City, Calif., which is building a crewed rocket that would take off and land vertically. The most innovative feature of the design, called the Roton, is its engine. Oxidizer and fuel are fed into 96 combustors inside a horizontal disk seven meters in diameter that is spun at 720 revolutions per minute before launch. Centrifugal force provides the pressure for combustion, thereby eliminating the need for massive, expensive turbo pumps and allowing the vehicle's single stage to go all the way to orbit. The Roton descends with the aid of foldaway helicopter blades that are spun by tiny rockets on their tips, like a Catherine wheel. Rotary Rocket says it will be able to deliver payloads to low-Earth orbit for a tenth of today's typical launch price. The first orbital flight is scheduled for 2000; the company has already tested individual combustors, and atmospheric flights are supposed to take place this year. The de-

distinction between engine and vehicle blurs. The oncoming flow is deflected mainly by the underside of the craft, which increases the pressure of the diverted air. Generally, the change is great enough to cause a pressure discontinuity, called a shock wave, which originates at the ship's nose and then propagates through the atmosphere. Most of the compressed air between the bottom of the vehicle and the shock wave is directed into the engine. The air gets hotter as its flow is slowed and as fuel is burned in the combustion region. The end product of the reaction expands through both an internal and an external nozzle, generating thrust. The high pressures on the underside of the vehicle also provide lift.

To broaden the scramjet's operating range, engineers have designed vehicles that can fly in either scram or ram mode. The dual-mode operation can be achieved either by constructing a combustor of variable geometry or by shifting the fuel flow between injectors at different locations.

Because neither scramjets nor ramjets can operate efficiently when they are traveling below Mach 2 or 3, a third type of propulsion (perhaps turbojet or rocket) is required for takeoff. So-called rocket-based combined-cycle engines, which could be used in a space vehicle, rely on a rocket that is integrated within the scramjet combustor to provide thrust from takeoff through subsonic, low-supersonic and then ramjet speeds. Ramjet operation is then followed by scramjet propulsion to at least Mach 10 or 12, after which the rocket is utilized again to supplement the scramjet thrust. Above Mach 18, the rocket by itself propels the vehicle into orbit and enables it to maneuver in space. The National Aeronautics and Space Administration is currently testing several variations of such a system.



SCRAMJETS (*top*) are designed to capture large quantities of air underneath the craft for burning with a fuel source, such as liquid hydrogen. Dual-mode scramjet engines could be combined with rockets (*graph*) in a vehicle that would, in essence, "fly" into space.

First, though, much work remains to validate scramjets. Sophisticated computational fluid-dynamic and engineering design methods have made it possible to develop a launch vehicle that has a scramjet built into its structure. Challenges remaining include developing lightweight, high-temperature materials, ensuring rapid and efficient fuel mixing and combustion, and minimizing the buildup of undesirable heat.

In the 1970s the NASA Langley Research Center demonstrated basic scramjet technology with models of hypersonic vehicles and a wind tunnel. Additional ground tests of prototype engines have been performed elsewhere in the U.S. as well as in England, France, Germany, Russia, Japan and Australia, with other related research under way in countries such as China, Italy and India. Today scientists routinely conduct ground tests of scramjet engines at simulated speeds up to Mach 15. In flight tests the Russians have demonstrated ramjet operation of a dual-mode scramjet up to Mach 6.4.

To date, though, no vehicle has flown under scramjet power. But this ultimate test is nearing reality. Through its Hyper-X research program at Langley and Dryden Flight Research Center, NASA is currently building the X-43A, a 3.6-meter-long aircraft that will demonstrate scramjet flight at Mach 7 and Mach 10 within the next three years. If all goes well, the tests will pave the way for future uses of scramjet propulsion, possibly in a vehicle designed for hypersonic flight into space.

CHARLES R. McCLINTON, technology manager of the Hyper-X Program at the NASA Langley Research Center in Hampton, Va., has been intrigued and captivated by the technical challenges of hypersonic air-breathing propulsion since the 1960s.

sign "has got a lot of challenges," observes Mark R. Oderman, managing director of CSP Associates in Cambridge, Mass., who has surveyed new rocket technologies. Oderman says the Roton has many features "that imply high levels of technical or financial risk."

Space Access in Palmdale, Calif., is designing an altogether different but equally daring craft. Its heavy space plane would take off and land horizontally under the power of a proprietary engine design called an ejector ramjet. This novel engine, which has been tested on the ground, will propel the craft from a standstill to Mach 6, according to Space Access's Ronald K. Rosepink—a performance well beyond anything in service today. Rosepink says the engine is almost 10 times more efficient than existing engines.

At Mach 6, the plane will fire up two

Space Tethers

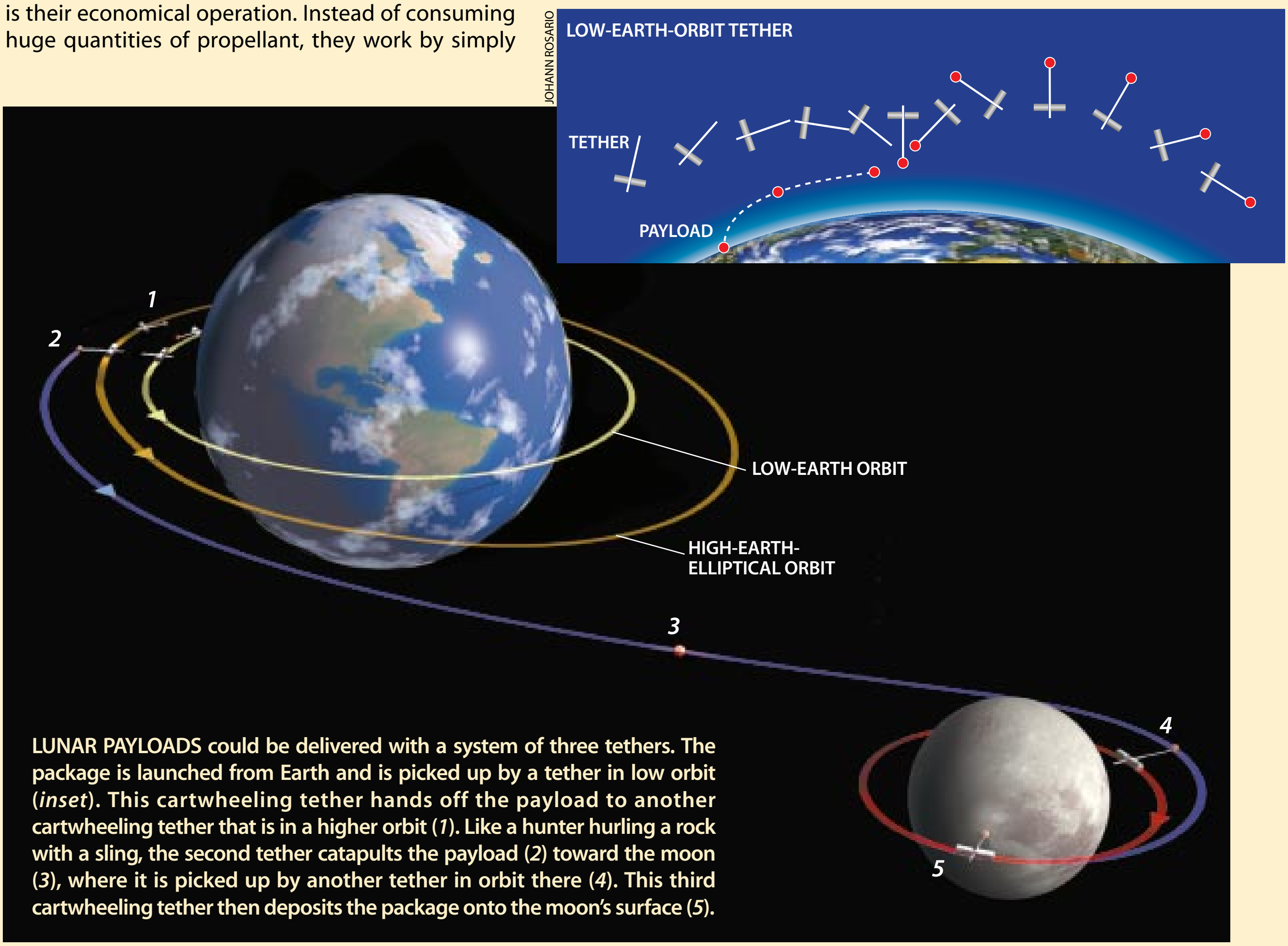
by Robert L. Forward and Robert P. Hoyt

When humans begin to inhabit the moon and planets other than Earth, they may not use the modern technology of rockets. Instead space travel and settlement may depend on an ancient technology invented long before recorded history—string.

How can mere string propel objects through space? Consider two scenarios. First, a thick strand connecting two satellites can enable one to "throw" the other into a different orbit, much like a hunter casting a stone with a sling. Such a concept could be adapted for transporting payloads to the moon and beyond. Second, if the string is a conductive wire, electricity flowing through it will interact with Earth's magnetic field to generate propulsive forces. The great advantage of both types of tethers—momentum transfer and electrodynamic—is their economical operation. Instead of consuming huge quantities of propellant, they work by simply draining a little momentum from a body already in orbit or by using electrical energy supplied from solar panels.

To date, 17 space missions have involved tethers. Most of these missions have been successful, but the general public has heard mainly about two failures. In 1992 a satellite built by the Italian Space Agency was to be released upward, away from Earth, from the space shuttle *Atlantis* at the end of a long tether made of insulated copper wire. But the spool mechanism jammed, halting the experiment.

Four years later the National Aeronautics and Space Administration tried again. In that mission, as the tether approached its full 20-kilometer (12-mile) length, the motion of the shuttle through Earth's magnetic field generated 3,500 volts in the tether.



LUNAR PAYLOADS could be delivered with a system of three tethers. The package is launched from Earth and is picked up by a tether in low orbit (*inset*). This cartwheeling tether hands off the payload to another cartwheeling tether that is in a higher orbit (*1*). Like a hunter hurling a rock with a sling, the second tether catapults the payload (*2*) toward the moon (*3*), where it is picked up by another tether in orbit there (*4*). This third cartwheeling tether then deposits the package onto the moon's surface (*5*).

JOHANN ROSARIO

ALFRED T. KAMAJIAN

liquid-hydrogen-fueled rockets. At Mach 9, its nose will open like the jaws of a crocodile to release the second and third stages plus the payload. All the stages have wings and will fly back and land horizontally at the launch strip. Space Access's plane will handle payloads of around 14,000 kilograms, as big as those carried by the shuttle. Commercial service could start in 2003, Rosepink claims.

The most prominent launch vehicle in development, the X-33, is under construction at Lockheed Martin's Skunk Works in Palmdale, Calif., as part of a joint industry-NASA effort to reduce launch costs 10-fold. The X-33 is a roughly half-size experimental craft intended to test a type of rocket engine known as a linear aerospike, as well as various other technologies. On paper the linear aerospike can power a fully reusable, vertical takeoff

Electronic devices on the shuttle and the Italian satellite provided an electrical conduit to the ionosphere, allowing ampere-level currents to flow through the tether. The experiment demonstrated that such electrodynamic tethers can convert shuttle momentum into kilowatts of electrical power, and vice versa.

Unfortunately, a flaw in the insulation allowed a high-power electric arc to jump from the tether to the deployment boom, and the arc burned through the tether. But although the break aborted the electrodynamic part of the project, it inadvertently triggered a spectacular display of momentum transfer. At the time, the Italian satellite was 20 kilometers above the shuttle and was being pulled along faster than the orbital speed for that higher altitude. Consequently, when the tether broke, the excess momentum made the satellite soar to seven times the tether length, or 140 kilometers, above the shuttle.

Other work has had greater success. In 1993, to test an idea proposed by Joseph A. Carroll of Tether Applications in San Diego, a payload attached to a 20-kilometer tether was deployed downward from a large satellite. Because the speed of the payload was then slower than that required for an object at that reduced orbital altitude, cutting the tether at the right moment caused the package to descend toward a predetermined point on Earth's surface. Tether Applications is now developing a reentry capsule and tether that the International Space Station could use to send urgent deliveries to Earth, including scientific payloads that cannot wait for the next shuttle pickup.

In a related mission in 1994, a payload was left hanging at the end of a 20-kilometer tether to see how long the connection—as thick as a kite string—would survive collisions with micrometeors and space debris. The expected lifetime of the tether, which could readily be cut by a particle the size of a sand grain traveling at high speed, was a meager 12 days. As things turned out, it was severed after only four.

The experiment demonstrated the need to make tethers out of many lines, separated so that they cannot all be cut by the same particle yet joined periodically so that when one line fails, the others take up the load. With that in mind, the Naval Research Laboratory (NRL) and the National Reconnaissance Office (NRO) fabricated a 2.5-millimeter-diameter hollow braid of Spectra fiber (a high-strength polymer used in fishing lines) loosely packed with yarn. A four-kilometer length linking two satellites that was launched in June 1996 has remained orbiting in space uncut for almost three years.

In a follow-up experiment last October, NRL and NRO tested a tether with a different design: a thin plastic tape three centimeters wide with strong fiber strands running along its length. The six-kilometer tether should survive for many years in space, but the tape makes it heavy. Our company, Tethers Unlimited in Clinton, Wash., is working with Culzean Fabrics and Flemings Textiles, both in Kilmarnock, Scotland, to fabricate multiline tethers with an open, fishnetlike pattern that will weigh less and should last in space for many decades.

Other tether demonstrations are scheduled. The Michigan Technic Corporation in Holland, Mich., has plans in 2000 for a shuttle to release two science packages joined by a two-kilometer tether.

In addition, the NASA Marshall Space Flight Center is investigating the use of electrodynamic tethers for propellantless space propulsion. In mid-2000 a mission will demonstrate that a conducting tether can lower the orbit of a Delta 2 upper stage. At Tethers Unlimited, we are developing a commercial version of the NASA concept: a small package that would be attached to a satellite or upper stage before launch. When the spacecraft completed its mission or malfunctioned, the conducting tether would unfurl and drag against Earth's magnetic field, causing the craft to lose altitude rapidly until it burned up in the upper atmosphere. We will test such a tether de-orbit device in late 2000 on an upper stage built by the Lavochkin Association of Russia.

NASA is also considering such electrodynamic tethers for upward propulsion. In the system, solar panels would supply a flow of electricity through the tether to push against Earth's magnetic field. The resulting force could haul payloads around Earth indefinitely. This approach might be used to keep the International Space Station in orbit without refueling.

How far can tethers take humankind in the future? We and others have analyzed a system of rapidly cartwheeling, orbiting tethers up to hundreds of kilometers long for delivering payloads to the moon and ever farther. The idea is simple—think of Tarzan swinging from one vine to the next. First, a low-Earth-orbit tether picks up a payload from a reusable launch vehicle and hands the delivery to another tether in a more distant elliptical-Earth orbit. The second tether then tosses the object to the moon, where it is caught by a Lunavator tether in orbit there.

The Lunavator would be cartwheeling around the moon at just the right velocity so that, after catching the payload, it could gently deposit the object onto the lunar surface a half-rotation later. Simultaneously, the tether could pick up a return load. No propellant would be required if the amount of mass being delivered and picked up were balanced. Such a transportation mechanism could become a highway to the moon that might make frequent lunar travel commonplace.

Obviously, there are many technological challenges that must be overcome before such a system becomes a reality, but its potential for opening up an economical expressway in space is tremendous. Perhaps someday there will be numerous cartwheeling tethers around many of the planets and their moons, carrying the hustle and bustle of interplanetary commerce. And it all will have begun with a piece of string.

ROBERT L. FORWARD and ROBERT P. HOYT are the founders of Tethers Unlimited, a start-up aerospace company based in Clinton, Wash., that specializes in developing space tether systems for commercial applications.

vehicle to orbit with a single stage of engines that would automatically adapt to changing atmospheric pressure. But the X-33, which will not itself achieve orbit, pushes the limits of current construction techniques. And some observers now doubt whether it will be able to provide NASA with enough information for a promised year 2000 decision on whether the agency should continue to rely on current shuttles until after 2020 or instead phase out those expensive workhorses around 2012.

Difficulties in building the engines have delayed the first flight of the X-33 by six months, until the end of this year. And Daniel R. Mulville, NASA's chief engineer, maintains that a further "year or two" of development will most likely be needed after flight tests are completed in late 2000 before a decision on building a full-

Highways of Light

by Leik N. Myrabo

Today's spacecraft carry their source of power. The cost of space travel could be drastically reduced by leaving the fuel and massive components behind and beaming high-intensity laser light or microwave energy to the vehicles. Experiments sponsored over the past year by the National Aeronautics and Space Administration and the U.S. Air Force have demonstrated what I call a lightcraft, which rides along a pulsed infrared laser beam from the ground. Reflective surfaces in the craft focus the beam into a ring, where it heats air to a temperature nearly five times hotter than the surface of the sun, causing the air to expand explosively for thrust.

Using an army 10-kilowatt carbon dioxide laser pulsing 28 times per second, Franklin B. Mead of the U.S. Air Force Research Laboratory and I have successfully propelled spin-stabilized miniature lightcraft measuring 10 to 15 centimeters (four to six inches) in diameter to altitudes of up to 30 meters (99 feet) in roughly three seconds. We have funding to increase the laser power to 100 kilowatts, which will enable flights up to a 30-kilometer altitude. Although today's models weigh less than 50 grams (two ounces), our five-year goal is to accelerate a one-kilogram microsatellite into low-Earth orbit using a custom-built, one-megawatt ground-based laser—expending just a few hundred dollars' worth of electricity.


LEIK N. MYRABO

MINIATURE LIGHTCRAFT demonstration vehicle has already flown to a height of 30 meters in tests, powered by a 10-kilowatt laser. Larger designs should be able to accelerate to orbit.

Current lightcraft demonstration vehicles are made of ordinary aircraft-grade aluminum and consist of a forward aeroshell, or covering, an annular (ring-shaped) cowl and an aft part consisting of an optic and expansion nozzle. During atmospheric flight, the forward section compresses the air and directs it to the engine inlet. The annular cowl takes the brunt of the thrust. The aft section serves as a parabolic collection mirror that concentrates the infrared laser light into an annular focus, while providing another surface against which the hot-air exhaust can press. The design offers automatic steering: if the craft starts to move outside the beam, the thrust inclines and pushes the vehicle back.

A one-kilogram lightcraft will accelerate this way to about Mach 5 and reach 30 kilometers' altitude, then switch to onboard liquid hydrogen for propellant as air becomes scarce. One kilogram of hydrogen should suffice to take the craft to orbit. A version 1.4 meters in diameter should be able to orbit microsatellites of up to 100 kilograms by riding a 100-megawatt laser beam. Because the beams we use are pulsed, this power might be achieved fairly easily by combining the output from a group of lasers. Such lasers could launch communications satellites and de-orbit them when their electronics become obsolete.

Lightcraft with different geometries can move toward their energy source rather than away from it—or even sideways. These variant vehicles have potential for moving cargo economically around the planet. Lightcraft could also be powered by microwaves. Microwaves cannot achieve such high power densities as lasers, so the vehicles would have to be larger. But microwave sources are considerably less expensive and easier to scale to very high powers.

I have also designed more sophisticated beamed-energy craft, operating on a different principle, that could transport passengers. These craft would be better for carrying larger cargoes because they can produce thrust more efficiently.

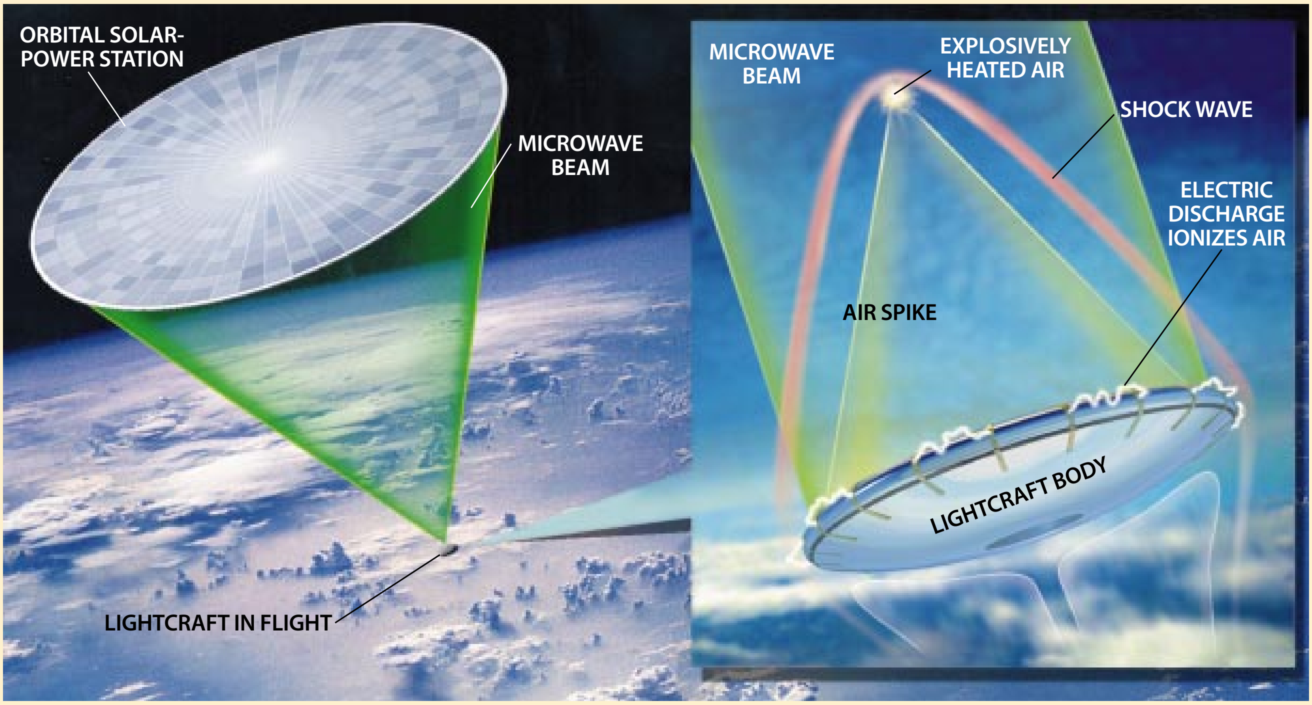
A mirror in the craft focuses some of the incoming beamed energy at a point one vehicle-diameter ahead of the vehicle. The intense heat creates an "air spike" that diverts oncoming air past the vehicle, decreasing drag and reducing the heating of the craft.

This craft taps some additional beamed energy to generate powerful electric fields around the rim, which ionizes air. It also uses superconducting magnets to create strong magnetic fields in that region. When ionized air moves through electric and magnetic fields in this configuration, magnetohydrodynamic forces come into play that accelerate the slipstream to create thrust.

By varying the amount of energy it reflects forward, the lightcraft can control the airflow around the vehicle. I demonstrated reduction of drag by an air spike in April 1995 in a hypersonic shock tunnel at Rensselaer Polytechnic Institute, though with an electrically heated plasma torch rather than with laser power. Tests aimed at generating magnetohydrodynamic thrust, using a 15-centimeter-diameter device, have just begun. A person-size lightcraft of this type driven by microwaves or by a 1,000-megawatt pulsed laser should be able to operate at altitudes up to 50 kilometers and to accelerate easily to orbital velocities.

Lightcraft could revolutionize transportation if they are driven from orbiting solar-power stations. But the cost of assembling the orbital infrastructure eventually must be reduced below a few hundred dollars per kilogram. It now costs about size single-stage-to-orbit vehicle. (Lockheed Martin, however, which calls its design the VentureStar, says it will be ready to commit by the end of 2000.) One problem: the world does not have a large enough autoclave to cure the VentureStar's all-composite liquid-hydrogen tank. More effort is also needed on the metallic tiles that will protect the craft from the heat of reentry.

The VentureStar was billed as a potential national launch system, notes Marcia S. Smith of the Congressional Research Service. Yet the timing could be awkward, as the first VentureStar would not carry humans. NASA has recently asked industry to study the options for carrying to orbit both human and nonhuman cargo early next century. Some potentially useful tricks are being explored with a smaller experimental vehicle known as



NASA AND TOM MOORE

ORBITING solar-power station (*upper left*) could beam microwave energy to an ascending lightcraft (*right*) powered by magnetohydrodynamic thrust. The lightcraft focuses the microwave energy to create an "air spike" that deflects oncoming air. Electrodes on the vehicle's rim ionize air and form part of the thrust-generating system.

$20,000 to put a kilogram of payload in orbit by means of the space shuttle, about 100 times too much.

I think we can bridge the gap by making the first orbital power station one that is specialized for enabling cheap access to space. Imagine a one-kilometer-diameter structure built like a giant bicycle wheel and orbiting at an altitude of 500 kilometers. Its mass would be about 1,010 metric tons, and it would slowly spin to gain gyroscopic stability. Besides the structural "spokes," the wheel would have a disk made from 55 large, pie-slice segments of 0.32-millimeter-thick silicon carbide. Completely covering one side of the silicon carbide would be 30 percent efficient, thin-film solar photovoltaic cells capable of supplying 320 megawatts of electricity. (Such devices are expected within a decade.) On the other side would be 13.2 billion miniature solid-state transmitters, each just 8.5 millimeters across and delivering 1.5 watts of microwave power.

Today's heavy-lift chemical rockets could loft this entire structure over about 55 launches, at an affordable cost of perhaps $5.5 billion. The station would be ringed by an energy storage device consisting of two superconducting cables, each with a mass of 100 metric tons, that could be charged up with counterflowing electric currents. (This arrangement would eliminate the titanic magnetic torque that would be produced by a single cable.)

During two orbits of Earth, the station would completely charge this system with 1,800 gigajoules of energy. It would then beam down 4.3 gigawatts of microwave power onto a lightcraft at a range of about 1,170 kilometers. Torquing forces produced by shifting small amounts of current from one cable to the other would crudely point the power station, but fine control would come from a beacon mounted on the lightcraft. It would send a signal that would coordinate the individual transmitters on the power station to create a spot 10 meters in diameter at the launch site. The vehicle could reach orbit in less than five minutes, subjecting occupants to no more than three g's of acceleration, about the same that shuttle astronauts experience. Or the solar-power station could unload all its energy in a 54-second burst that should offer a nearly vertical 20-g boost to geostationary orbit or even to escape velocity.

The first orbital solar-power station will pave the way for a whole industry of orbital stations, launched and assembled from specialized lightcraft. Within decades, a fleet of these will make feasible rapid, low-cost travel around the globe, to the moon and beyond.

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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.

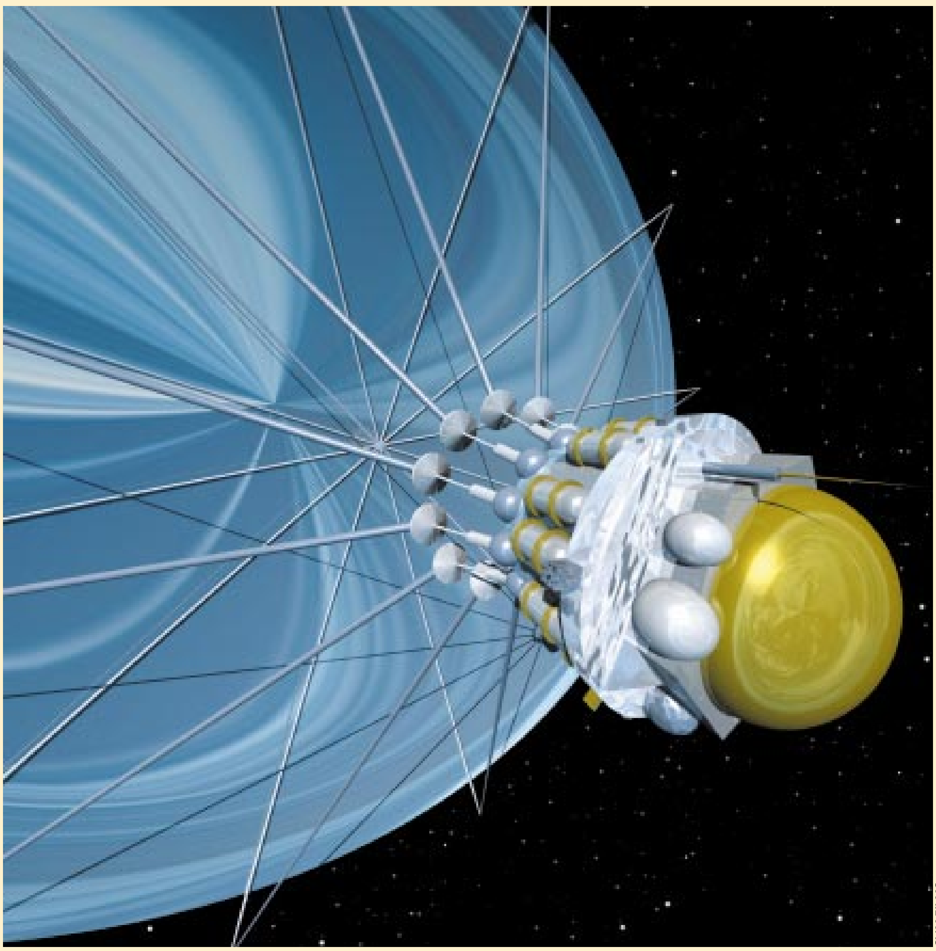
Closer to home, the U.S. National Oceanic and Atmospheric Administration is planning to launch within four years a spacecraft powered by a solar sail. The craft would hover at an orbitally unstable location between Earth and the sun, from where it could provide about an hour's advance warning of particles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

HENRY M. HARRIS is a physicist who studies interstellar exploration at the Jet Propulsion Laboratory in Pasadena, Calif. He has also designed space shuttle and other experiments. Harris has worked as a jazz musician and has written a novel about science and spirituality.


SLIM FILMS

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*).

Compact Nuclear Rockets

by James R. Powell

Someday, in exploring the outer planets of our solar system, humankind will want to do more than send diminutive probes that merely fly rapidly by them. In time, we will want to send spacecraft that go into orbit around these gaseous giants, land robots on their moons and even return rock and soil samples back to Earth. Eventually, we will want to send astronauts to their intriguing moons, on at least a couple of which liquid water—the fundamental requirement for life as we know it—is believed to be abundant.

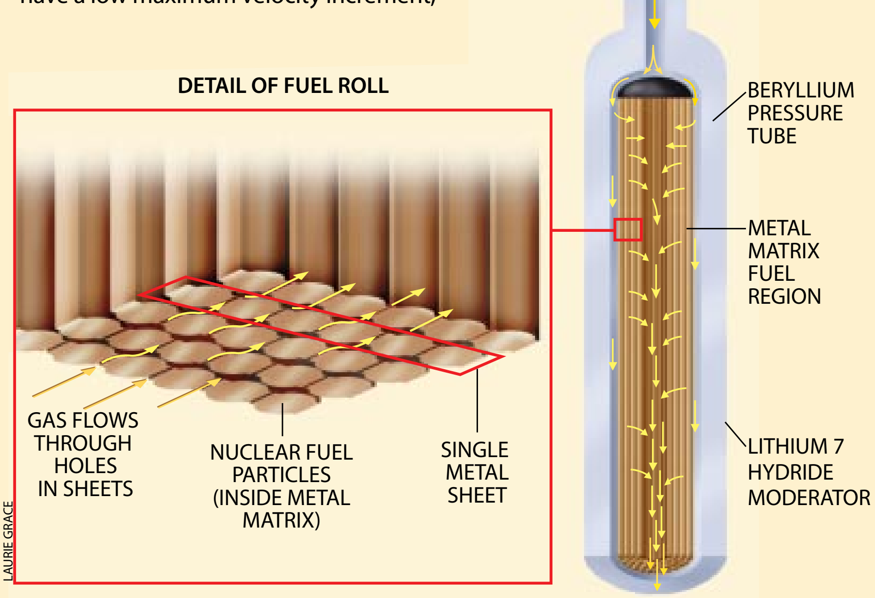
For missions such as these, we will need rockets powered by nuclear fission rather than chemical combustion. Chemical rockets have served us well. But the relatively low amount of energy that they can deliver for a given mass of fuel imposes severe restrictions on spacecraft. To reach the outer planets, for example, a chemically powered space vehicle must have very limited mass and make extensive use of planetary gravitational "assists," in which the craft maneuvers close enough to a planet for the planet's gravitational field to act like a slingshot, boosting the speed of the craft. To take advantage of these assists, mission planners must wait for "windows"—short periods within which a craft can be launched toward planets appropriately positioned to speed it on its way to more distant bodies.

In technical terms, chemical rockets have a low maximum velocity increment, which means that their exhaust velocities are not high enough to impart very high speeds to the rocket. The best chemical rockets, which are based on the reaction between hydrogen and oxygen, impart a maximum velocity increment of about 10 kilometers (six miles) a second to spacecraft departing from Earth orbit.

Nuclear rockets, in contrast, could impart a maximum velocity increment of up to about 22 kilometers a second. Such a high value would make possible a direct path to, say, Saturn, reducing travel time from about seven years to as little as three. A nuclear rocket such as this would be inherently safe and environmentally benign: contrary to popular belief, a nuclear rocket need not be strongly radioactive when launched. The spacecraft, with its nuclear thrusters, would be launched as a payload atop a conventional chemical rocket. Then, once the payload was in high-Earth orbit, above about 800 kilometers, the nuclear reactor would start up.

The technology required to build a rocket motor powered by nuclear fission is not far beyond current capabilities. In fact, my colleagues and I have designed a compact nuclear rocket engine, which we call Mitee (deriving the letters loosely from the words "miniature reactor engine"), that could be built in about six or seven years at a cost of $600 million to $800 million—actually quite modest in the context of space launches. In fact, the costs of developing the engine would be offset by savings in future launch costs. The reason is that nuclear spacecraft powered by the engine would not need to haul along a large mass of chemical propellant, meaning that launching it would not require a Titan IV vehicle costing $250 million to $325 million. Instead a lower-priced rocket, such as a Delta or an Atlas in the range of $50 million to $125 million, could be used.

In our design, the reactor's nuclear fuel would be in the form of perforated metal sheets in an annular roll, in a configuration similar to a jelly roll with a hollow center [*see illustration below*]. A jacket of lithium 7 hydride around the outside of the fuel roll would act as a moderator, reducing the speed of the neutrons emitted by the nuclear fission occurring inside the fuel. The coolant—liquid hydrogen—would flow from the outside of the roll inward, quickly turning into a gas as it heated up and flowed toward the center. The superheated gas, at about 2,700 degrees Celsius (4,900 degrees Fahrenheit), would flow at a high velocity along a channel at the center axis of the roll and then out through a small nozzle at the end.



FUEL ELEMENT would be one of 37 in a compact nuclear rocket engine. Liquid hydrogen flowing into the element would convert to a gas and flow through the nuclear fuel roll (*light brown*). Five of the roll's metal matrix sheet layers are shown in the detail at the left. The superheated gas would then shoot down a center channel and out the bottom of the element, providing thrust.

A key attraction of nuclear propulsion is that its propellant—hydrogen—is widely available in gaseous form in the giant planets of the outer solar system and in the water ice of distant moons and planets. Thus, because the nuclear fuel would be relatively long-lasting, a nuclear-powered craft could in theory tour the outer solar system for 10 or 15 years, replenishing its hydrogen propellant as necessary. A vehicle could fly for months in the atmospheres of Jupiter, Saturn, Uranus and Neptune, gathering detailed data on their composition, weather patterns and other characteristics. Alternatively, a craft could fly to Europa, Pluto or Titan to collect rock samples and also accumulate hydrogen, by electrolyzing water from melted ice, for the trip back to Earth.

Because its reactor would start up well away from Earth, a nuclear-powered spacecraft could actually be made safer than some deep-space probes that are powered by chemical thrusters. In the outer reaches of the solar system, the sun's rays are too feeble to provide energy for a spacecraft's instruments. So they generally run on plutonium 238 power sources, which are highly radioactive even during launch. In a probe with nuclear thrusters, on the other hand, the instruments would be run off the same reactor that provides thrust. Moreover, the amount of radioactive waste produced would be negligible—amounting to about a gram of fission products for a deep-space mission—and in any event the material would never come back to Earth.

Nuclear rockets are not new. Among the U.S. Department of Defense's projects in this area was the Space Nuclear Thermal Propulsion program in the late 1980s. Its goal was to develop a compact, lightweight nuclear engine for defense applications, such as launching heavy payloads into high-Earth orbit. The cornerstone of the design was a particle bed reactor (PBR), in which the fuel consisted of small, packed particles of uranium carbide coated with zirconium carbide. Although the PBR work ended before a full-scale nuclear engine was built, engineers did successfully build and operate low-power reactors based on the concept and demonstrated that high-power densities could be achieved.

Indeed, our Mitee engine owes much to the PBR effort, on which my colleagues and I worked for nearly a decade at Brookhaven National Laboratory. In addition to the same basic annular configuration of fuel elements, the Mitee also would use lightweight, thermally stable lithium 7 hydride as a moderator. To be conservative, however, we designed the Mitee's fuel assembly to have a power density of about 10 megawatts per liter instead of the PBR's 30.

It is an easily provable fact that with only chemical rockets, our ability to explore the outer planets and their moons is meager. In the near term, only nuclear rockets could give us the kind of power, reliability and flexibility that we would need to improve dramatically our understanding of the still largely mysterious worlds at the far edges of our solar system.

JAMES R. POWELL is president of Plus Ultra Technologies in Shoreham, N.Y., which conceived and designed the Mitee reactor for space propulsion. He worked for Brookhaven National Laboratory from 1956 to 1996 and was head of its reactor systems division. The author wishes to thank his co-workers George Maise and John Paniagua for their help in the preparation of this article.

make long-term exploratory missions to Uranus and Neptune that would return far more data than the simple flybys that Voyager 2 made in the 1980s, according to James S. Sovey of the NASA Lewis Research Center.

Other Thrusters

Ion engines are not the only futuristic space drive being considered for solar system exploration. Hall thrusters also accelerate ions, but without grids. They employ radial magnetic fields, in part, to direct the ions, and they can deliver larger thrusts: a 50-kilowatt version has been tested, and research models are as propellant-efficient as an ion engine, according to Robert S. Jankovsky of the NASA Lewis center. The devices are attractive for now mainly for near-Earth space applications, although that could change if performance improves. The U.S. government has already flown one on a classified payload, and Teledesic, which plans to offer a broadband, global telecommunications service, will use Hall thrusters on its fleet of satellites.

Photovoltaic cells are now used to power almost all satellites in near-Earth orbit. And their performance is expected to improve: NASA has developed advanced designs that incorporate myriad small lenses that focus sunlight on the photovoltaic material. Deep Space 1 is now testing this type.

But solar power can be used to provide thrust more directly. The U.S. Air Force has committed $48 million to a four-year program to develop a solar-powered final rocket stage that would move satellites from low-Earth orbit to geostationary orbit at a fraction of the cost of chemical rockets. The Solar Orbit Transfer Vehicle uses a lightweight mirror to direct the sun's light onto a graphite block, which reaches 2,100 degrees Celsius (3,800 degrees Fahrenheit) and vaporizes stored liquid hydrogen. The expanding gas provides the thrust.

An operational version would take three to eight weeks to boost a typical payload to geostationary orbit, but its light weight means that a satellite will be able to go on a smaller rocket than it would otherwise. The savings amount to tens of millions of dollars for each launch, notes deputy program manager Thomas L. Kessler of Boeing.

The sun, however, can only do so much, and it is difficult to exploit solar power for journeys to planets more distant than Jupiter. The Galileo mission to Jupiter and the Cassini mission to Saturn both employed radioisotope thermal generators, which utilize the heat generated by the decay of plutonium 238 to generate modest amounts of electricity. But this technique

Space Access		
	Approximate launch year:	2003
	Approximate cost:	$4 billion to $6 billion
	Power source:	Air-breathing engines, rockets

COURTESY OF SPACE ACCESS

HEAVY SPACE PLANE is being developed by Space Access in Palmdale, Calif. The craft will utilize innovative ejector ramjet engines to accelerate to Mach 6, then switch to rocket engines. Separated stages will individually fly back to the launch strip.

cannot readily be scaled up to provide larger amounts.

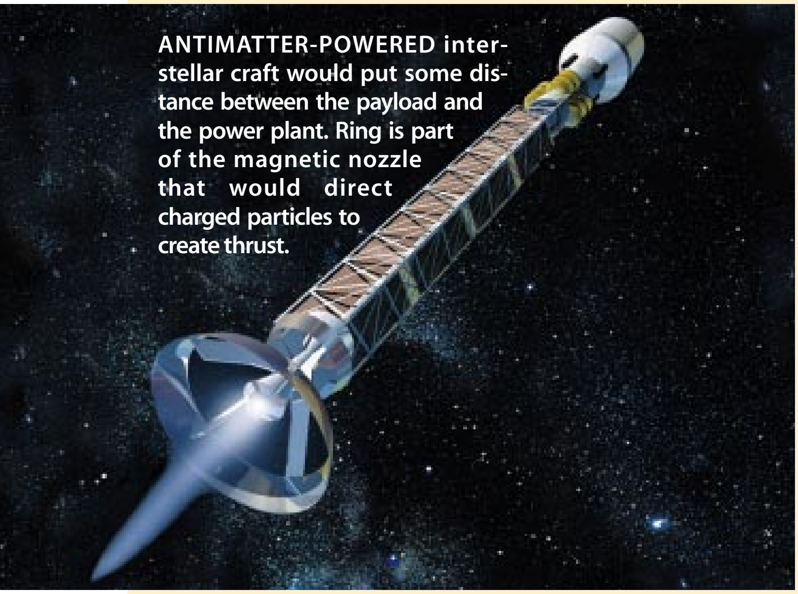
Many space buffs believe nuclear reactors designed to operate in space could be the answer. Because operating a reactor generates some radioactive waste, proponents of space nuclear power now envisage designs that would be launched on chemical rockets in an inactive state. They would be energized only after attaining a safe distance from Earth, so they would present no threat in the event of a launch accident. Some estimates indicate that a nuclear-powered journey to Mars might last just 100 days, about half the estimated trip time for a chemical rocket. A reactor could also be valuable to provide power to support a base on Mars,

Reaching for the Stars

by Stephanie D. Leifer

The notion of traveling to the stars is a concept compelling enough to recur in countless cultural artifacts, from Roman poetry to 20th-century popular music. So ingrained has the concept become that when novelists, poets or lyricists write of reaching for the stars, it is instantly understood as a kind of cultural shorthand for striving for the unattainable.

Although interstellar travel remains a glorious if futuristic dream, a small group of engineers and scientists is already exploring concepts and conducting experiments that may lead to technologies capable of propelling spacecraft to speeds high enough to travel far beyond the edge of our solar system. A propulsion system based on nuclear fusion could carry humans to the outer planets and could propel robotic spacecraft thousands of astronomical units into interstellar space (an astronomical unit, at 150 million kilometers, or 93 million miles, is the average distance from Earth to the sun). Such a system might be built in the next several decades. Eventually, even more powerful engines fueled by the mutual annihilation of matter and antimatter might carry spacecraft to nearby stars, the closest of which is Proxima Centauri, some 270,000 astronomical units distant.



ANTIMATTER-POWERED interstellar craft would put some distance between the payload and the power plant. Ring is part of the magnetic nozzle that would direct charged particles to create thrust.

BOB SAULS *John Frassanito & Associates*

The attraction of these exotic modes of propulsion lies in the fantastic amounts of energy they could release from a given mass of fuel. A fusion-based propulsion system, for example, could in theory produce about 100 trillion joules per kilogram of fuel—an energy density that is more than 10 million times greater than the corresponding figure for the chemical rockets that propel today's spacecraft. Matter-antimatter reactions would be even more difficult to exploit but would be capable of generating an astounding 20 quadrillion joules from a single kilogram of fuel—enough to supply the entire energy needs of the world for about 26 minutes.

In nuclear fusion, very light atoms are brought together at temperatures and pressures high enough, and for long enough, to fuse them into more massive atoms. The difference in mass between the reactants and the products of the reaction corresponds to the amount of energy released, according to Albert Einstein's famous formula $E = mc^2$.

The obstacles to exploiting fusion, much less antimatter, are daunting. Controlled fusion concepts, whether for rocket propulsion or terrestrial power generation, can be divided into two general classes. These categories indicate the technique used to confine the extremely hot, electrically charged gas, called a plasma, within which fusion occurs. In magnetic confinement fusion, strong magnetic fields contain the plasma. Inertial confinement fusion, on the other hand, relies on laser or ion beams to heat and compress a tiny pellet of fusion fuel.

In November 1997 researchers exploiting the magnetic confinement approach created a fusion reaction that produced 65 percent as much energy as was fed into it to initiate the reaction. This milestone was achieved in England at the Joint European Torus, a tokamak facility—a doughnut-shaped vessel in which the plasma is magnetically confined. A commercial fusion reactor would have to produce far more energy than went into it to start or maintain the reaction.

But even if commercial fusion power becomes a reality here on Earth, there will be several problems unique to developing fusion rockets. A key one will be directing the energetic charged particles created by the reaction to produce usable thrust. Other important challenges include acquiring and storing enough fusion fuel and maximizing the amount of power produced in relation to the mass of the spacecraft.

Since the late 1950s, scientists have proposed dozens of fusion rocket concepts. Although fusion produces enormous amounts of very energetic particles, the reaction will accelerate a spacecraft only if these particles can be directed so as to produce thrust. In fusion systems based on magnetic confinement, the strategy would be to feed in fuel to sustain the reaction while allowing a portion of the plasma to escape to generate thrust. Because the plasma would destroy any material vessel it touched, strong magnetic fields, generated by an assembly that researchers call a magnetic nozzle, would direct the charged particles out of the rocket.

In an engine based on the inertial confinement approach, high-power lasers or ion beams would ignite tiny fusion fuel capsules at a rate of perhaps 30 per second. A magnetic nozzle might also suffice to direct the plasma out of the engine to create thrust.

The particles created in a fusion reaction depend on the fuels used. The easiest reaction to initiate is between deuterium and tritium, two heavy isotopes of hydrogen whose atomic nuclei include one and two neutrons, respectively, besides a proton. The reaction products are neutrons and helium nuclei (also known as alpha particles). For thrust, the positively charged alpha particles are desirable, whereas the neutrons are not. Neutrons cannot be directed; they carry no charge. Their kinetic energy can be harnessed for propulsion, but not directly—to do so would involve stopping them says Samuel L. Venneri, NASA's chief technologist.

Reactors could be used for propulsion in various ways. One that generates thrust directly and operates for a short intense burst is described by James R. Powell on page 70. Such a design might make it possible to return rock samples to Earth from Pluto, Powell maintains. But there are other possibilities. A reactor could be designed to generate heat over long periods. Several different schemes then would be available to convert the heat to electricity to power ion drives, Hall thrusters or a new type of electric propulsion in early development known as a magnetoplasmodynamic thruster. "You can mix and match different reactor and thrust

in a material and making use of the heat generated by their capture. Neutron radiation also poses a danger to a human crew and would necessitate a large amount of shielding for piloted missions.

These facts lead to a key difficulty in fusion fuel selection. Although it is easiest to initiate fusion between deuterium and tritium, for many propulsion concepts it would be more desirable to use deuterium and the isotope helium 3 (two protons, one neutron). Fusion of these nuclei produces an alpha particle and a proton, both of which can be manipulated by magnetic fields.

The problem is that helium 3 is exceedingly rare on Earth. In addition, the deuterium–helium 3 reaction is more difficult to ignite than the deuterium-tritium reaction. But regardless of the fusion fuel selected, a spacecraft of thousands of tons—much of it fuel—would be necessary to carry humans to the outer reaches of the solar system or deep into interstellar space (for comparison, the International Space Station will have a mass of about 500 tons).

Even individually, the key obstacles to fusion propulsion—getting higher levels of power out of a controlled reaction, building effective containment devices and magnetic nozzles, and finding enough fuel—seem overwhelming. Still, for each of them, there is at least a glimmer of a future solution.

In the first place, there is every reason to believe that fusion reactors will go far beyond the break-even point, at which a reactor produces as much energy as is fed into it. Inertial confinement work in the U.S. is enjoying robust funding as part of the stockpile stewardship program, in which researchers are working on methods of assuring the safety and reliability of thermonuclear weapons without actually test-firing them. The research is centered at the National Ignition Facility, now under construction at Lawrence Livermore National Laboratory. The facility is expected to start up in 2001, with full laser energy of 1.8 million joules—for four billionths of a second—available in 2003. With that kind of power, researchers anticipate liberating up to 10 times the energy required to initiate the reaction.

There are indications, too, that the tokamak, which has dominated magnetic confinement research, may someday be supplanted by more compact technologies more amenable to rocket propulsion. In 1996 the Fusion Energy Sciences Advisory Committee of the U.S. Department of Energy endorsed investigation of such promising magnetic confinement schemes as reverse-field pinches, the field-reversed configuration and the spherical tokamak.

In the meantime, workers have begun preliminary work on magnetic nozzles. The largest research effort at present is a collaboration among the National Aeronautics and Space Administration, Ohio State University and Los Alamos National Laboratory. Researchers from the three organizations are using extremely high electric currents to create a plasma, which in the experiments stands in for a fusion plasma, and to study its interactions with a magnetic field.

Even the fusion fuel problem may be tractable. Although there is very little helium 3 on Earth, there are larger quantities of it in the lunar soil and in Jupiter's atmosphere as well. Also, other elements found on Earth, such as boron, may figure in alternative fusion reactions that are difficult to ignite but that yield alpha particles.

For all the promise of fusion propulsion, there is one known physical phenomenon—matter-antimatter annihilation—that releases far more energy for a given mass of reactants. A space propulsion system based on this principle would exploit the mutual annihilation of protons and antiprotons.

This annihilation results in a succession of reactions. The first of these is the production of pions—short-lived particles, some of which may be manipulated by magnetic fields to produce thrust. The pions resulting from matter-antimatter annihilation move at speeds close to that of light.

Here again, though, one of the key problems is scarcity: the number of antiprotons produced at high-energy particle accelerators all over the world adds up to only a few tens of nanograms a year. To carry humans on a rendezvous mission to the nearest star, Proxima Centauri, a matter-antimatter drive system would need tons of antiprotons. Trapping, storing and manipulating antiprotons present other major challenges because the particles annihilate on contact with ordinary protons.

Nevertheless, it may be possible to exploit, albeit to a lesser extent, antimatter's high energy content while requiring much smaller numbers of antiprotons—amounts that are most likely to be available in the next decade. Such a system would use antiprotons to trigger inertial confinement fusion. The antiprotons would penetrate the nuclei of heavy atoms, annihilating with protons and causing the heavy nuclei to fission. The energetic fission fragments would heat the fusion fuel, initiating the fusion reaction. The first steps toward determining the feasibility of such a propulsion system are already being taken under NASA sponsorship. One research activity is the design and construction, at Pennsylvania State University, of a device in which antiprotons could be trapped and transported.

DANA BERRY (*spaceship*); ROBERT O'DELL (*Orion nebula*)

HUMAN-PILOTED interstellar spaceship would have a rotating structure in front, to simulate gravity in four compartments.

At this very early stage, the challenges to building fusion—let alone antimatter—propulsion systems may seem insurmountable. Yet humankind has achieved the seemingly impossible in the past. The Apollo program and the Manhattan Project, among other large undertakings, demonstrated what can be accomplished when focused, concerted efforts and plenty of capital are brought to bear. With fusion and antimatter propulsion, the stakes could not be higher. For these will be the technologies with which humanity will finally and truly reach for the stars.

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concepts," observes Gary L. Bennett, NASA's former manager of advanced space propulsion systems. Yet strong public distaste for anything nuclear means that space reactors face enormous political obstacles, and NASA's effort in that area is now dormant.

Beam Me Up

Whether space nuclear power is eventually developed or not, inventive engineers and scientists are optimistic about the prospects for further solar system exploration. Ivan Bekey, a former top NASA official and now a consultant, believes that a sustained effort could reduce launch costs from $20,000 a kilogram to as low as $2 a kilogram over the next 40 years. Fully reusable single-stage-to-orbit launchers should achieve the first factor of 10 within a decade, he predicts.

Engines that combine hypersonic technology and rocket propulsion, together with new high-energy propellants, should achieve another factor of 10. (Reusable single-stage-to-orbit vehicles that could each fly 1,000 flights a year would be another way of bringing launch costs down to $200 per kilogram, Bekey estimates.) Bekey is impressed, too, with the potential of magnetically levitated catapults, devices that would suspend a rocket craft above a track like a maglev train. The track would have an upward curve at one end—built, perhaps, on the side of a mountain. The rocket-powered vehicle would accelerate along the track and leave it skyward at a 30- to 40-degree angle and about the speed of sound.

Beyond 20 years from now, Bekey envisages microwave-powered vehicles like the designs described by Leik N. Myrabo of Rensselaer Polytechnic Institute [*see box on page 66*]. These craft would create thrust by means of what are termed magnetohydrodynamic forces, which arise when a conductive fluid or gas moves through crossed electric and magnetic fields. The engineering obstacles are substantial—but many of those who have examined the principle believe it could be made to work. Because beamed energy means that neither oxidizer nor fuel has to be carried out of Earth's gravitational potential well, laser- or microwave-driven craft should reduce launch costs to $20 a kilogram, Bekey asserts.

Myrabo and others believe beamed-energy craft could be supported by a network of orbital solar-power stations. In principle, power stations in space have many advantages: for the part of their orbit when they are illuminated by the sun, they are assured of receiving plenty of photons. NASA, spurred by an enthusiastic Dana Rohrabacher, representative from California and chairman of the House of Representatives's subcommittee on space and aeronautics, is studying the idea for supplying power to users on the ground. But Venneri says that "in the past the economics have not been there" to support that application. Using inflatable structures in low-Earth orbit could bring costs down somewhat, he adds.

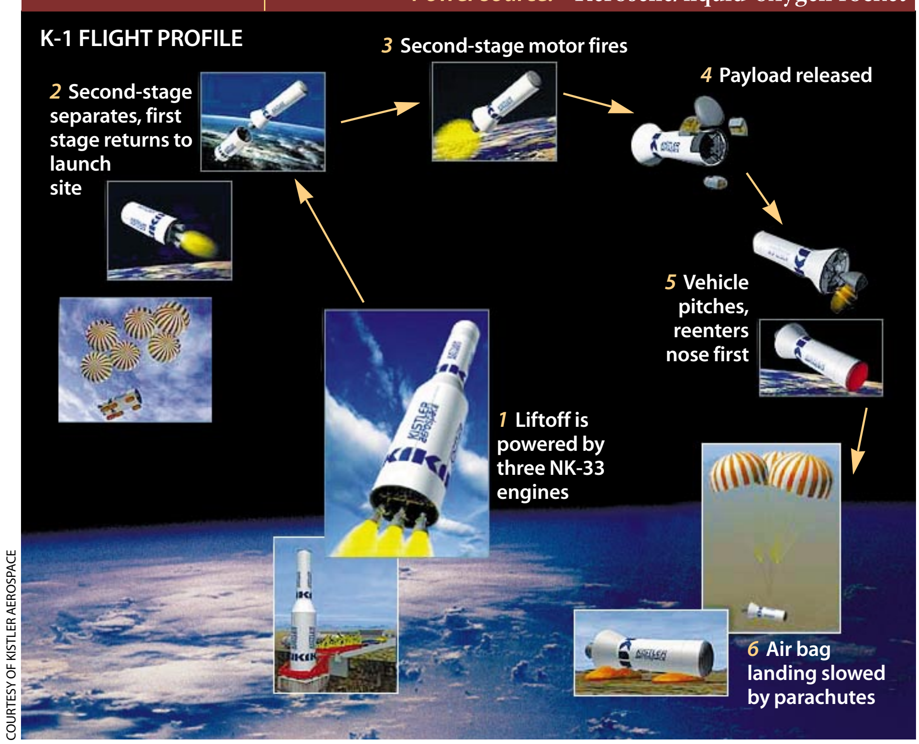
Orbital solar-power stations, which could resemble the alien saucers in the movie *Independence Day,* might however make more economic sense if their energy were used by craft in transit through Earth's atmospheric veil. That, at any rate, is Myrabo's contention.

Space enthusiasts are also gung-ho about the potential of tethers, long connecting cables that in orbit acquire astonishing properties nearly qualifying them as a means of propulsion. Their bizarre behavior arises because to stay in orbit, objects farther from Earth's center must maintain a slightly slower horizontal velocity than closer objects. As a result, when objects at different altitudes are connected by a tether more than a few hundred meters long, powerful forces keep it in tension.

Other physical principles, notably the conservation of angular momentum, can then operate on the tethered bodies. The upshot, via some counterintuitive mechanics, is that a tether can be used like a giant slingshot to transfer momentum efficiently between payloads and so quickly propel satellites between orbits. Electrically conducting versions can even be used to generate electricity or contribute lift [*see box on page 64*]. Yet predicting and controlling the dynamics of large, multibody systems in orbit remains a difficult challenge, Venneri cautions.

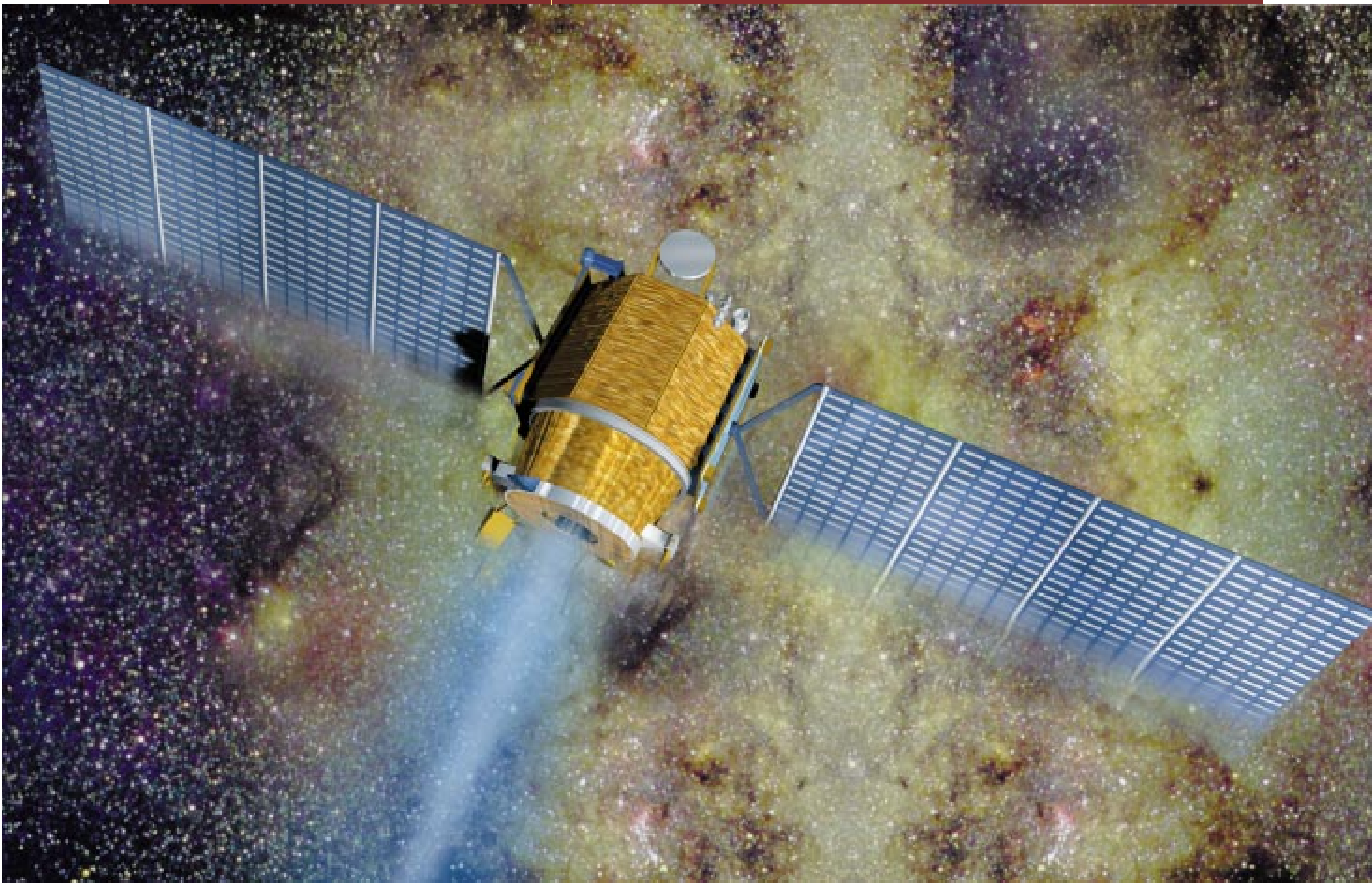
Tethers even open up the startling possibility of connecting the whole Earth to a satellite in geostationary orbit by a fixed line attached at a point on the planet's

Kistler Reusable Rocket		
	Approximate launch year:	1999
	Approximate cost:	Undisclosed
	Power source:	Kerosene/liquid-oxygen rocket



"WORLD'S FIRST FULLY REUSABLE LAUNCH VEHICLE" is how Kistler Aerospace in Kirkland, Wash., describes its K-1 rocket, scheduled to fly late this year. The two-stage rocket utilizes Russian-built engines that run on kerosene and liquid oxygen. The separated stages return to Earth by parachute.

Ion Propulsion System	Launch year:	1998
	Approximate cost:	$150 million
	Power source:	Photovoltaics



DON FOLEY

ION ENGINE is flying now on the Deep Space 1 spacecraft, which is scheduled to visit an asteroid. The system uses solar panels to generate electric fields that accelerate charged atoms of xenon. The engine can operate for weeks at a time and so reach high velocities.

equator. Climbing devices could then ascend the tether to reach any desired altitude up to 36,000 kilometers, with very little expenditure of energy.

Such a tether could not be built today, because the forces it would experience mean it would have to be made from a material far stronger for its weight than Kevlar, the polymer used for some small-scale tethers. But Bekey notes that buckytubes, which are microscopic fibers made of carbon atoms assembled into tubes just a few nanometers in diameter, might fit the bill. "When we learn how to grow them into long ropes and work and tie them, we'll be able to make a tether 600 times stronger than with current materials," he predicts, with airy confidence. That would be more than strong enough. A geostationary tether system could reduce launch costs to $2 a kilogram, Bekey says.

As if such schemes were not ambitious enough, long-term thinkers are even now studying concepts that might one day allow humans to send a spacecraft to another star. The most promising approach at present seems to be light sails [*see box on page 68*]. Such devices might well also be employed to move cargo around the solar system.

Tapping the huge theoretical power of fusion to propel spacecraft has its devotees, too. Although controlled production of useful energy from fusion has not yet been demonstrated even on Earth, hope springs eternal, and a fusion reactor in space would be able to provide enough energy to reach any solar system destination with ease [*see box on page 72*].

Other notions for propulsion technologies are even more far-out and have been floated as possible means for making interstellar journeys: quantum teleportation, wormholes and the elimination of momentum. These mind-boggling ideas seem to require entirely new understandings of physics; the steps for making them feasible cannot even be listed today. Even so, serious investigators continue to look for ways to turn each of these concepts into reality. If they work, they will change radically our ideas about the universe. And who is to say that any of them will prove forever impossible? SA

Further reading for this article is available at www.sciam.com/1999/0299issue/0299beardsleybox1.html on the World Wide Web. This article also appeared in Scientific American *in February 1999.*