The PLANETARY REPORT

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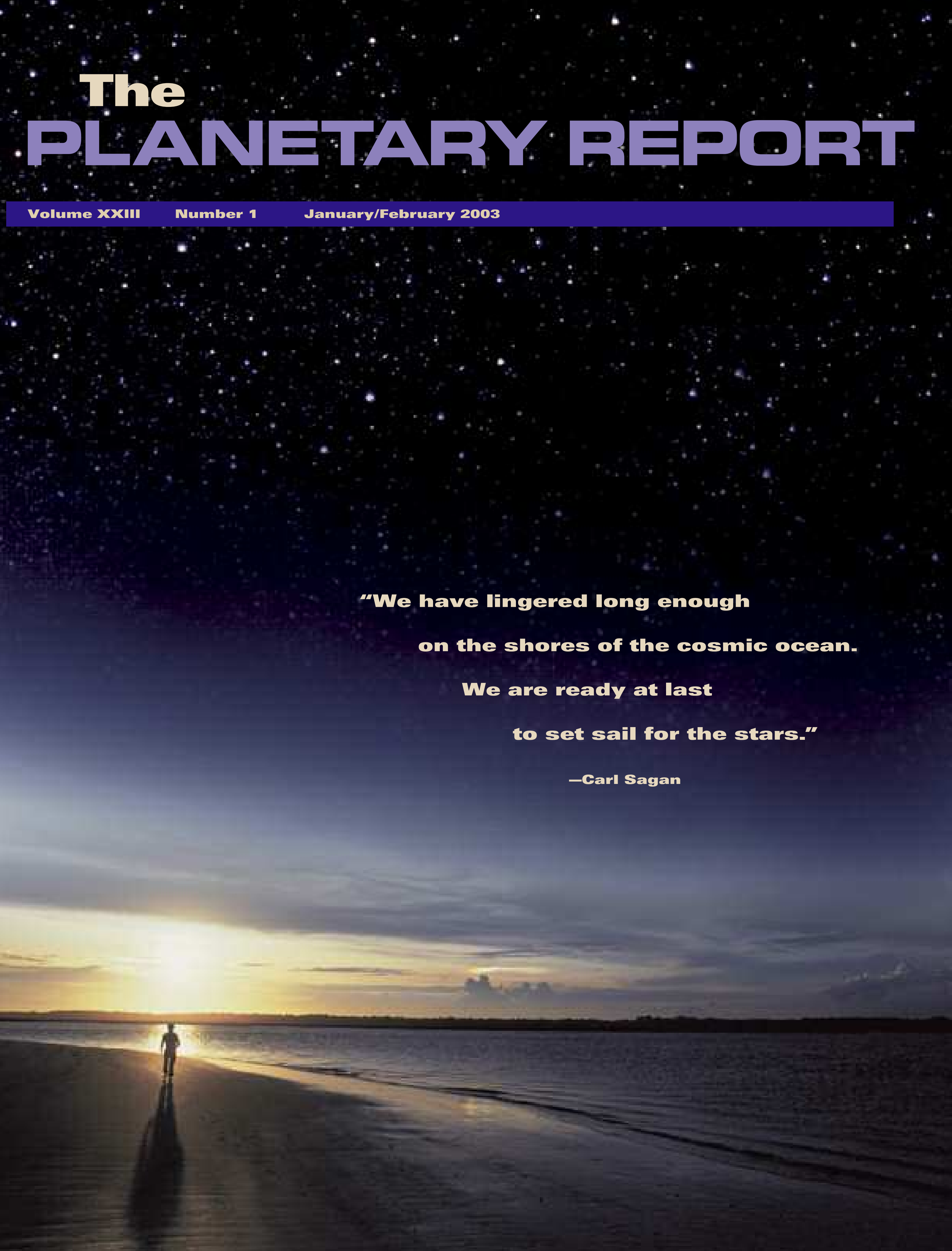

A PUBLICATION OF THE PLANETARY SOCIETY

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From The Editor

One great benefit of belonging to The Planetary Society is the contact with fascinating and sometimes audacious minds. In this issue, you will encounter minds that are not afraid to tackle in a concrete and realistic way a problem as difficult as travel between the stars.

Why is The Planetary Society interested in interstellar flight? Doesn't our mission tie us to exploring more solid bodies and technologies? Yes, but the science and engineering techniques learned in exploring other worlds can be extrapolated to take us even farther into space . . . and we must always dream.

In fact, a direct connection to interstellar flight lies in our solar sail project, *Cosmos 1*. In the near future, we hope to see the technology we are pioneering today help open up the solar system to even more exploration. Solar sailing may very well be the only technique based on current technology that has a chance of taking us to the stars.

For this issue, we have asked some of our bigger-thinking friends to share with Society members their own dreams—and carefully crafted proposals—for interstellar flight. Not every organization can pull together such a roster of thinkers. Fewer can say they are working toward fulfilling the dreams dared by such thinkers. You are a member of one of those intrepid few.

—Charlene M. Anderson

On the Cover:

Ever since our ancestors realized that the lights in the sky were other suns like our own—and that around those suns might orbit other worlds, perhaps like Earth—we've wanted to visit. It may not happen for centuries, but we're working on it. We'll get there.

Sunrise photo: © Clyde H. Smith, Peter Arnold Inc.
Photo montage: Barbara S. Smith

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Members' Dialogue

Historic Missions

Congratulations on your historical issue of *The Planetary Report* devoted to *Voyagers 1* and *2*. I read it, and read it again, with great pleasure.

How about a special issue on *Pioneers 10* and *11*? The *Voyagers* and *Pioneers* have been extremely important science missions and absolutely fundamental to the evolution of the science and history of humankind.

It is an honor to be a member of The Planetary Society!
—ULLISSES BREDER AMBROSIO,
Rio de Janeiro, Brazil

Yet More to Tell Them

In our July/August 2002 column, member James Walker asked the question "How does someone tell anyone else just why it is so important to understand not only the planet on which we live but also the solar system in which this planet lives, the galaxy in which this solar system lives, and the universe in which this galaxy lives?"

We asked our members for answers, in 25 words or less, and received many responses—more than we have room to print. Thanks very much to all of you who've written.
—Charlene M. Anderson, Associate Director

From ancient sages to Carl Sagan, we've learned we can't fully understand the Earthly here and now without resorting to the cosmic there and then.
—JIM VICKREY,
Troy, Alabama

The knowledge and understanding we gain will give us the wisdom, respect, and expertise to preserve it all for future generations.
—SHIRLEY A. HANSEN,
Las Vegas, Nevada

Our survival as a species may depend on being able to understand and predict cosmic disasters like asteroid collisions, superflares, and nearby supernovae.
—JIM SECOSKY,
Manchester, New York

The search in the universe for knowledge is the natural and inevitable consequence of the evolution of human life and intelligence.
—HAROLD ST. MELGAARD,
Humlebæk, Denmark

The Voyager Record

After recently watching a wonderful cable TV show about the *Voyager* mission, I reread the special *Voyager* issue of *The Planetary Report* (September/October 2002).

Of great concern to me was the statement by Timothy Ferris that few people have ever heard the Voyager record that flew aboard the spacecraft. He states that some years ago, a now-defunct record company released an "uneven" version, which is currently unavailable. I also have learned that the book *Murmurs of Earth* by Carl Sagan, which included a CD-ROM of the record, is out of print.

What's the deal here? World music is huge today. Why aren't people walking into Barnes & Noble bookstores and seeing this book, with the CD, filling the front racks? They would buy it. They would eat it up!

Somebody call the record companies! Call the producers! Call the lawyers! Call whoever it takes to get this thing done, no matter how daunting. It is crucial that our collective spirit be reawakened to exploration and discovery.

Plus, we always want to hear more cool music.
—KENNETH A. WIRT
Springfield, Missouri

A New Member

I am a person, like many, who was tremendously and profoundly influenced by Carl Sagan when I was young. I've spent many enjoyable hours reading *Cosmos* and awakening to the joy of scientific understanding. I know that one of Carl's main goals was to be able to share and spread the simple enjoyment of learning and scientific discovery to the "everyday" person.

After visiting your website this morning, I was surprised to find many individuals whom I admire, and whose work I've enjoyed, to be on The Planetary Society's Board of Directors and Advisory Council. I think it's high time I become a member.
—CURTIS RUTHERFORD,
Collinsville, Oklahoma

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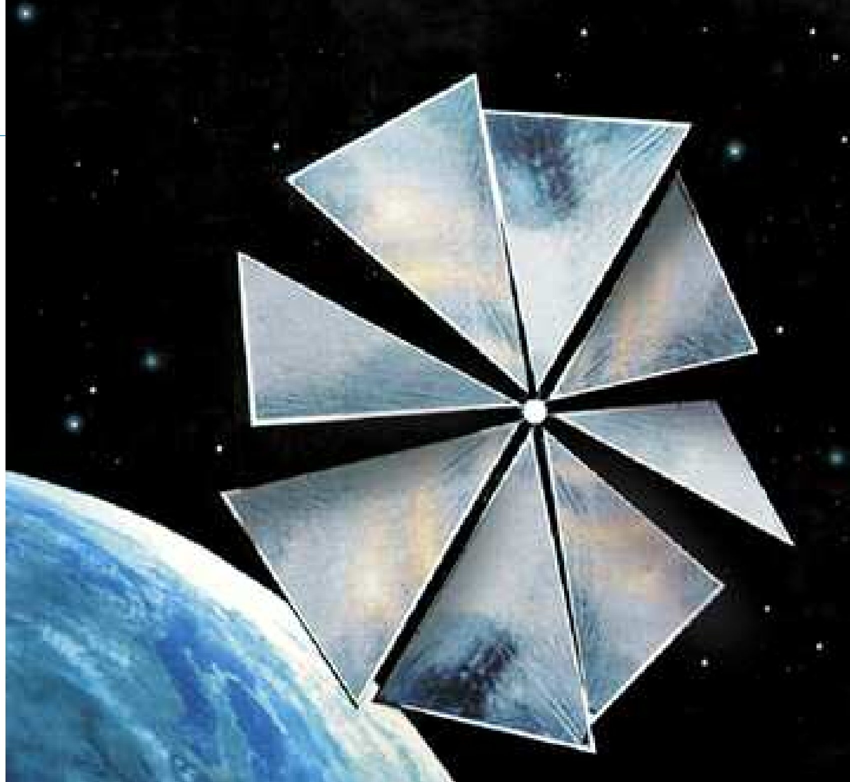
In Memory of
ROBERT L. FORWARD
1932–2002

To the STARS!

by Louis D. Friedman



When The Planetary Society launches* Cosmos 1 *into Earth orbit, we will have taken the first tiny step in humankind's long, long journey to the stars. *Illustration: Barbara S. Smith*

Space is big. The nearest star, Proxima Centauri, is roughly 4.3 light-years (41,000,000,000,000 kilometers or 25,000,000,000,000 miles) away; the fastest vehicle ever devised by humans, *Voyager 1*, is traveling approximately 61,900 kilometers (38,400 miles) per hour (less than 0.01 percent the speed of light). At that speed, it would take 76,000 years to reach the next stellar neighborhood. Interstellar flight is tough.

Science fiction is full of technologies for conquering distance and time: hyperdrive, warp speed, wormholes, matter-antimatter propulsion, faster-than-light information channels, and so on. However, these all remain speculative; no solid physics supports them. Nor have any flight engineers come up with a credible way to make interstellar flight practical on timescales conducive to human lifespans. Still, we can't shake the vision that someday we will travel from star to star.

This vision triggered my personal interest in solar sailing, which I have pursued for more than 25 years. During that time, several NASA studies and various independent and eminent physicists have concluded that light sailing is the only technology we know of today that can enable interstellar flight. As our members are aware, The Planetary Society is attempting to fly the first solar sail with our *Cosmos 1* project. In essence, we are taking humankind's first very tiny baby steps to the stars.

Hence, this special issue of *The Planetary Report* on interstellar flight. Freeman Dyson, Bob Forward, and Greg and Jim Benford—all pioneers in the field—have enthusiastically contributed to the issue. Bob Forward, suffering from a brain tumor, was unable to write a new article for us; instead, he suggested we reprint a feature he wrote for *The Planetary Report* several years ago. In September, as we were preparing this special issue, Bob passed away. A leading thinker about the real physics of interstellar flight, he invented the concept of beam sailing using lasers and microwaves, which made researchers consider that interstellar flight might be within our reach after all.

Still, I think we may be as far from interstellar flight as Leonardo da Vinci was from airplane flight. We can produce sketches, make suggestions, and even outline the principles. But we must pass through several generations of engineering and technology before we can even attempt it.

Freeman Dyson reminds us that solar sailing could create opportunities for us right here in our own solar system before we ever embark on our first interstellar journey. For example, we could develop an interplanetary transportation system that would open up frontiers throughout the solar system, taking us from the Sun to unknown, trans-Plutonian distances. This is a vision that The Planetary Society could truly make happen.

But that vision is still decades away. Right now, we are getting ready to launch *Cosmos 1*. Our spacecraft is built, and final assembly and testing are well under way. Even though we are getting close to launch, it remains hard for me to comprehend that The Planetary Society has actually developed and prepared a space mission, especially one so audacious. When the Society was founded more than two decades ago, we expected the government space agencies to be building and testing solar sails. They will someday, but they need to be prodded. That is a role we are well accustomed to playing.

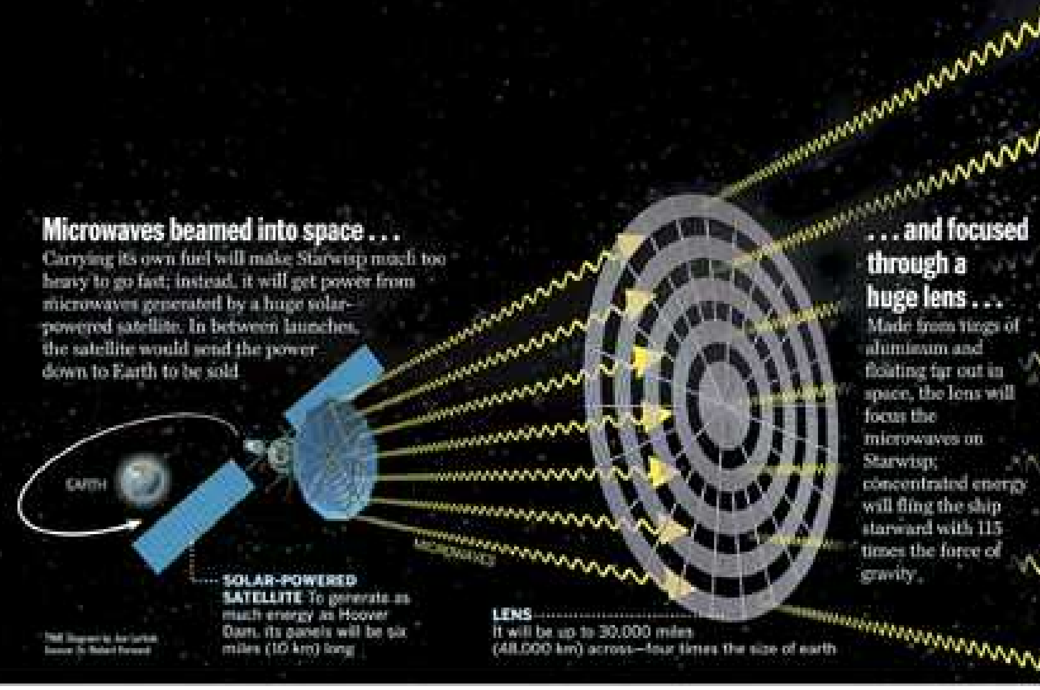
Bob Forward, Freeman Dyson, the Benford brothers, and many others, including Leonardo da Vinci, have inspired The Planetary Society and our sponsor, Cosmos Studios, with their dreams of flight to other worlds. We are making their vision a reality.

Louis D. Friedman is executive director of The Planetary Society.

Photo at left: Milky Way in Scorpius
© John Gleason and Steve Mandel

The Stars Our Destination?
THE FEASIBILITY OF INTERSTELLAR TRAVEL

by Robert L. Forward



It is difficult to go to the stars. They are far away, and the speed of light limits us to a slow crawl along the starlanes. Decades and centuries will pass before the stay-at-homes learn what the explorers have found. The energies required to launch a manned interstellar transport are enormous, for the mass to be accelerated is large and the cruise speed must be high. Yet even these energies are not out of the question once we move our technology out into nearby space, where the constantly flowing sunlight is a never-ending source of energy—greater than a kilowatt per square meter, a gigawatt per square kilometer. There are many ideas on methods for achieving interstellar transport. In time, one or more of these dreams will be translated into a real starship.

Is It Possible?

Many people (some of them quite well-known) have "proved" by "calculation" that interstellar flight is "impossible." Actually, in each case, all they have proved is that the initial assumptions they forced on the problem made it so difficult that they were unwilling to consider it further. Some examples of these "obvious" assumptions are that a self-contained rocket has to be used; to keep the humans inside the rocket comfortable, the rocket has to accelerate at a constant one-Earth gravity; all the energy needed to run the rocket has to be extracted out of Earth's resources; and the mission has to be completed in 10 years.

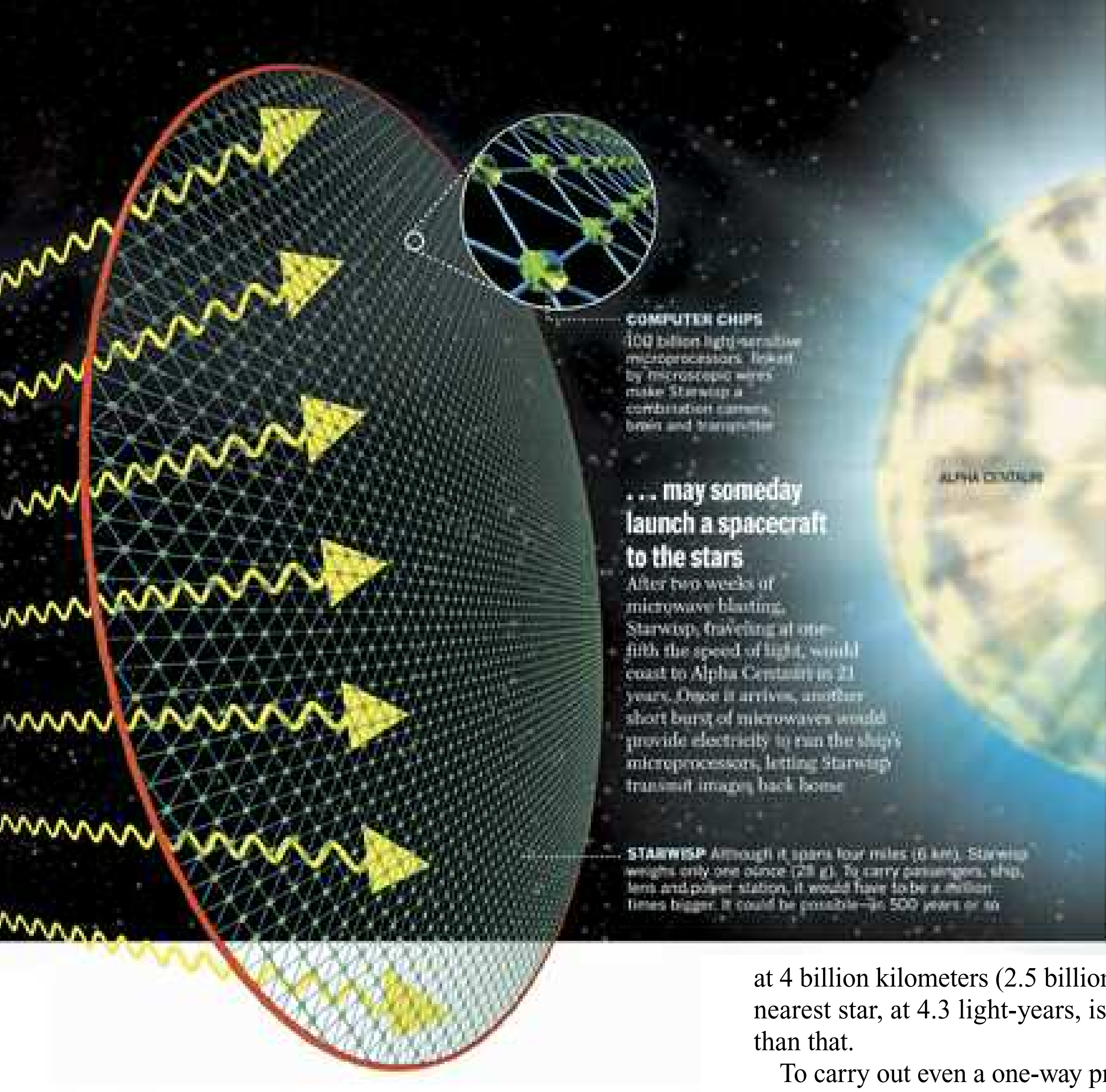
Rapid interstellar travel with simple rocket technology is not feasible. If standard rockets are used to propel a space vehicle, the vehicle will be limited in its terminal velocity to a small fraction of light speed. If the spacecraft has a human crew, it will have to be designed as a "worldship," where the crew lives for many generations during the long journey between the stars. To get to the stars in less than a human lifetime, interstellar vehicles must use some form of "rocketless rocketry," where the vehicle does not carry its energy source, reaction mass, or other parts of a conventional rocket. (In a chemical rocket, the propellant is the reaction mass; it contains the energy to expel itself through the nozzle.)

Interstellar travel at a constant one-Earth-gravity acceleration is not feasible. After the first year of acceleration, the vehicle is moving at 0.7 c (70 percent the speed of light). From then on, the energy used for propulsion doesn't make the vehicle go significantly faster (to the people at home paying for the mission). Instead, all that energy just adds to making the vehicle heavier and harder to push. A properly optimized interstellar mission accelerates up to some cruise velocity that depends on the mission and then coasts, cutting energy and fuel requirements by orders of magnitude.

Interstellar travel using only the resources of Earth is not feasible. The vehicles can be easily built with Earth resources (proposed interstellar unmanned probes might have masses from 20 grams to 100 tons, while manned exploration vehicles can go up to 100,000 tons). However, the reaction mass and especially the energy to drive the interstellar vehicles should be extracted from space.

Interstellar travel with round-trip times of 10 years is not feasible. Even light requires 8.6 years to get to the nearest star system and back. By admitting that interstellar missions

Reprinted from the September/October 1986 issue of *The Planetary Report*.



One of Robert Forward's legacies is the Starwisp, his concept for an interstellar space probe. Three years ago, Forward shared the details of a possible Starwisp design with Time *magazine. This diagram was used to illustrate "Will We Travel to the Stars?"—a short article by Freeman Dyson that appeared in* Time*'s April 10, 2000 issue.*

Diagram: Joe Lertola,

will require trip times of 30 to 50 years, the coast velocities needed to carry out a mission to the nearer stars drop from more than 0.9 c (90 percent the speed of light) to less than half the speed of light. This eliminates many problems, such as the erosional effects of the interstellar medium.

If one uses "obvious" but improper assumptions like those mentioned above, one can show that interstellar travel is not feasible. Yet, as we shall see, interstellar travel is feasible if instead the proper assumptions are made and the proven techniques are used.

The first travelers to the stars will be our robotic probes. They will be small and won't require amenities such as the food, air, and water that humans find necessary. The power levels to send the first flyby probes are within the present reach of the human species. If we started today, the first flyby interstellar probe could be on its way before the present millennium is out.

Interstellar Distances

It is not easy to comprehend the distances involved in interstellar travel. Of the billions of people living today on this globe, many have never traveled more than 40 kilometers (about 25 miles) from their place of birth. Of these billions, a dozen have traveled to the Moon, which at almost 400,000 kilometers (248,560 miles) distance is 10,000 times 40 kilometers away. Soon, one of our interplanetary probes will be passing Neptune, 10,000 times farther out at 4 billion kilometers (2.5 billion miles). However, the nearest star, at 4.3 light-years, is 10,000 times farther than that.

To carry out even a one-way probe mission to the nearest star, in the lifetime of the humans that launched it, will require a minimum velocity of 0.1 c (10 percent the speed of light). At that speed, it will take the probe 43 years to get there and 4.3 years for the information to get back to us. The nearest star is Proxima Centauri, part of a three-star system called Alpha Centauri. One of the stars is similar to our Sun.

Farther away are two other single stars similar to our Sun that are our best candidates for finding an Earth-like planet: Epsilon Eridani at 10.8 light-years and Tau Ceti at 11.8 light-years. To reach these stars in a reasonable time will require probe velocities of 0.3 c (30 percent the speed of light). At this speed, it will take nearly 40 years to get there, plus another 11 to 12 years for the information to return to Earth.

Yet, although we need to exceed 0.1 c to reach any star in a reasonable time, if we can attain a cruise velocity of 0.3 c, there are 17 star systems with 25 visible stars and probably hundreds of planets within 12 light-years. This many stars and planets within reach at 0.3 c should keep us busy exploring while our engineers work on faster starship designs.

Rocketless Rocketry

We need not use the rocket principle to build a starship. If we examine a generic rocket, we find that it consists of payload, structure, reaction mass, energy source, an engine to put the energy into the reaction mass, and a thruster that expels the reaction mass to provide thrust. In most rockets, the reaction mass and energy source are combined into the chemical fuel. The fuel is then burned in the engine and expelled through the thruster. Because a standard rocket has to carry its fuel along with it, its performance is significantly limited.

There is a whole class of spacecraft that does not have to carry along any energy source or reaction mass or even an engine and consists only of payload, structure, and a thruster. These spacecraft work by means of beamed power propulsion. In a beamed power propulsion system, the heavy parts of a rocket (reaction mass, energy source, and the engine) are all kept in the solar system.

Here, around the Sun, unlimited amounts of reaction mass are readily available, and an energy source (usually the abundant sunlight) and an engine can be maintained and even upgraded as a mission proceeds.

Starwisp: A Maser-Pushed Probe

Starwisp is a lightweight, high-speed interstellar flyby probe pushed by beamed microwaves. The basic structure is a wire-mesh sail with microcircuits at each intersection. The mesh sail is pushed at high acceleration using microwave power formed into a beam by a large segmented transmitter lens made of alternating sparse metal mesh rings and blank rings. The high acceleration allows Starwisp to reach a coast velocity near that of light while still close to the transmitting lens.

Upon arrival at the target star, the transmitter floods the star system with microwave energy. Using the wires as microwave antennae, the microcircuits on Starwisp collect energy to power their optical detectors and logic circuits to form images of the planets in the system. The direction of the incoming microwave beam is sensed at each point of the mesh, and that information is used to electronically transform the mesh into a microwave antenna that beams a signal back to Earth.

A minimal Starwisp would be a 1-kilometer (0.6-mile) mesh sail weighing 16 grams (0.6 ounces) and carrying 4 grams (0.1 ounce) of microcircuits. Starwisp would be accelerated at 115 gravities by a 10-gigawatt microwave beam, reaching one-fifth the speed of light in a few days. Upon arrival at Alpha Centauri 21 years later, Starwisp would collect enough microwave power to return a high-resolution color television picture during its fly-through of the system.

Because of the probe's very small mass, the beamed power level needed to drive a minimal Starwisp is about that planned for the microwave power output of a solar power satellite. Thus, if power satellites are constructed in the next few decades, they could be used during their checkout phase to launch one or more Starwisp probes to the nearer stars.

Once the Starwisp probes have found interesting planets, we can use another form of beamed power propulsion to visit these bodies. Although microwave beams can be used only to "push" a spacecraft away from the solar system, if we go to laser wavelengths, then it is possible to design a beamed power propulsion system that can use laser power sent from the solar system to make a return journey.

Laser-Pushed Lightsails

One of the best methods for traveling to the stars would use large sails of light-reflecting material pushed by the photon pressure from a large laser array in orbit around the Sun. With this technique, we can build a manned spacecraft that not only can travel at reasonable speeds to the nearest stars, but also can stop, then return its crew back to Earth within their lifetimes. It will be some time before our engineering capabilities in space will be up to building the laser system needed, but no new physics is involved, just a large-scale engineering extrapolation of known technologies.

The lasers would orbit Mercury to keep them from being blown away by the reaction from their light beams. They would use the abundant sunlight at Mercury's orbit to produce coherent laser light, which would be collected into a single coherent beam and sent out to a segmented transmitter lens floating between Saturn and Uranus. The transmitter lens consists of rings of 1-micron-thick plastic film alternating with empty rings. Because it is crude in construction, it only works well at one wavelength of light. We chose the laser wavelength to match the design wavelength of the lens. The lens would be 1,000 kilometers (about 620 miles) in diameter with a mass of 560,000 tons, about the mass of a solar power satellite. A lens this size can send a beam of laser light over 40 light-years before the beam starts to spread.

The lightsail carrying the payload would be 1,000 kilometers in diameter and made of thin aluminum film stretched over a supporting structure. The total mass would be 80,000 tons, including 3,000 tons for the crew, their habitat, their supplies, and their exploration vehicles. The lightsail would be accelerated at 0.3 gravities by 43,000 terawatts of laser power. (For comparison, Earth now produces only 1 terawatt of electrical power. We would certainly want to power the lasers by collecting sunlight from space with large reflectors rather than attempting to use Earth-based power sources.) At this acceleration, the lightsail will reach a velocity of half the speed of light in 1.6 years. The expedition will reach Epsilon Eridani in 20 years Earth time and 17 years crew time, and it will then be time to stop.

At 0.4 light-years from the target star, the 320-kilometer (about 200-mile) rendezvous portion of the sail is detached from the center of the lightsail and turned to face the large ring sail that remains. The laser light from the solar system reflects from the ring sail, which acts as a retro-directive mirror. The reflected light decelerates the smaller rendezvous sail and brings it to a halt in the Epsilon Eridani system.

Returning Home

After the crew explores the system for a few years (using their lightsail as a solar sail), it will be time to bring them back. To do this, a 100-kilometer-diameter (62-mile-diam-

In the future, this light sail could be used for an interstellar rendezvous. Laser light transmitted from our solar system would bounce off a ring sail 1,000 kilometers (about 620 miles) in diameter onto a rendezvous stage 320 kilometers (200 miles) wide, decelerating the sail to a stop in its target star system. *Painting: Seichi Kiyohara*

eter) return sail is separated from the center of the 320-kilometer rendezvous sail. The laser light from our solar system hits the ring-shaped remainder of the rendezvous sail and is reflected back on the return sail, sending it on its way back to the solar system. As the return sail approaches the solar system 20 Earth-years later, it is brought to a halt by a final burst of laser power. The members of the crew have been away 51 years (including 5 years of exploring), have aged 46 years, and are ready to retire and write their memoirs.

It is important to recognize that although interstellar unmanned probes and manned starships are possible, they will be difficult to build as well as expensive. The masses needed to produce any kind of interstellar transportation system and the power levels to operate it will require that we first have a large industrial base in space. A space station with 20 to 100 people in residence at one time is not enough. We will need many space stations, bases on the Moon, prospectors in the asteroid belt, and solar power stations for processing materials and powering factories. This is at least 20 to 50 years away.

A simple example is the amount of power needed to carry out an interstellar mission. No matter what propulsion method you can dream of, to accelerate a 1-ton interstellar probe up to one-third the speed of light even over a three-year period requires a power input of 50 gigawatts. Even at 50 percent efficiency, this requires a power input of 0.1 terawatt. (One gigawatt equals 1 billion watts; one terawatt equals 1 trillion watts.) This is one-tenth Earth's present output of electrical power. For a crewed vehicle weighing 10,000 tons, the power required is 1,000 terawatts. To obtain this power, we must be out in space where sunlight supplies more than 1 kilowatt per square meter and must have the manufacturing capability to build solar collectors 1,000 kilometers in diameter.

The masses required for such large structures are not trivial either. These solar collectors, thin aluminum and microwave lenses made of fine wire, will weigh between 50,000 and 100,000 tons, while laser lenses with 1-micrometer-thick plastic will reach 600,000 tons. For the microwave lens, this mass can be obtained from a nickel-iron asteroid 25 meters in diameter, while the aluminum can be obtained from a stony asteroid 100 meters across. The plastic will have to be made from carbonaceous chondrites perhaps 1 kilometer in diameter. These are modest-size asteroids, but all that mass has to be processed in a reasonable time, and that will take a very big factory.

New Industrial Revolution

But in 20 to 50 years, it is likely that there will be a new industrial revolution where robots take over all labor, leaving management to humans. Suddenly, labor costs may disappear; only capital, energy, and material costs would remain. Especially for such simple structures as solar collectors and segmented ring lenses, robots would be more than adequate construction workers.

Once we have constructed the space industrial base and once we have found the right asteroids, we can invest a little capital in a small crew of smelter and spinner robots and a solar collector to provide energy. We then go away, and return in a few years to find the asteroid gone and a wire-mesh microwave ring lens in its place. During the fabrication phase, the waste products from the smelting operation have been heated and expelled to provide thrust to move the entire system to the position and velocity desired (typically far from the Sun and not orbiting a planet).

What will this cost? A lot—but not as much as you might think if you attempted to do it with material hauled up on the expensive space shuttle and assembled by expensive human beings.

It is difficult to go to the stars, but it is not impossible. Many different technologies, all under intensive development for other purposes, if suitably modified and redirected can give the human species a flight system that will reach the nearest stars. All it really takes is the desire and the commitment to a few decades of hard space-engineering work. Our first interstellar probe could be heading to the stars within our lifetimes.

The late Robert L. Forward is remembered as one of the world's leading experts in exotic physics and future space travel. At the time of his passing in September 2002, Forward was owner and chief scientist for Forward Unlimited and chairman and chief scientist for its spin-off company, Tethers Unlimited Inc. In addition to more than 200 papers and articles, Forward published 11 "hard" science fiction novels.

Bridging the Gap: A DISCUSSION WITH FREEMAN DYSON

The "pellet stream" is another innovative concept for propelling a spacecraft though the solar system. A robotic "gun" in orbit around Jupiter shoots pellets at a lightweight spacecraft. The impacts of the pellets on the craft's sail fuel its journey. Nearby Ganymede sparkles with the lights of civilization in this futuristic scene.

Illustration: Michael Carroll

Going to another star is a terribly powerful idea, just as going to the Moon was originally. At some point in human history, there will be a leap across the great void—not just to the nearest star but to any star that might be interesting to explore.

Last September, renowned physicist, educator, and author Freeman Dyson joined Planetary Society Chairman of the Board Bruce Murray and Executive Director Louis Friedman at Society headquarters for an informal discussion about interstellar flight.

Bruce Murray: In the 1970s, when I was director at the Jet Propulsion Laboratory [JPL]—at the same time that *Voyager* set out on its wonderful journey—we seemed to be in a period where there were no limits. And yet I became very aware of a sudden end to this period. I couldn't foresee a way to push beyond the horizon.

Then, in October 1980, just after *Voyager*'s Saturn encounter, I organized an informal conference in Pasadena. The question I wanted to address was, how do we eventually go to another star? At that point, the only potentially doable system was some kind of giant sail powered by enormously powerful lasers located in the solar system but not on Earth. This seemed to be within the bounds of physical plausibility, which was pretty exciting.

Now, I'd like to ask you, Freeman, even with all that's happened in the last 20 years, is that still the conclusion?

Freeman Dyson: I think that's still true, although there is an alternative way—pellet stream propulsion—of voyaging to another star that could be somewhat more economical though more difficult to do. Instead of shooting at your sail with a laser beam, you shoot at it with pellets. The problem is how to catch the pellets, but in principle, the vehicle could be a lot smaller and more compact, so the system could in fact end up being more economical. It hasn't really been worked out in detail. But I would say the pellet stream is perhaps just as good a contender as the solar sail.

Bruce: Is the energy needed to collect and capture the pellets less than to collect photons with the sail?

Freeman: The energy isn't any less. A mass on the order of a ton traveling at half the speed of light takes a lot of energy no matter how you do it. The question is, just what is your efficiency? Although the pellet stream doesn't in the end use all that much less energy, it's a lot neater from an engineering point of view. Because the vehicle can be less massive, you save energy simply on the total mass. The problem with the laser sail is that the sail itself weighs so much, and you don't really want that.

Lou Friedman: What about the really advanced technology sail: some kind of wispy carbon structure, with just a few molecules of aluminum as the reflector? That wouldn't weigh very much.

Freeman: No, it wouldn't, but at 30 kilometers [about 20 miles] in diameter it adds up to quite a lot.

The question is, are you using light or are you using microwaves? If you're using light, then you must have a metal surface of some kind to reflect the light. If you're using microwaves, you can have a network that can be a lot lighter. In fact, we really don't know how light that can be.

Bob Forward's proposal, to make the network out of chicken wire and what he calls Starwisp, involves a really wispy kind of a sail driven by microwaves. That could be a great deal lighter.

Lou: Which would you bet on: light or microwaves?

Freeman: I don't know. I think it's foolish to make the choice. In all these technological questions, you have to try everything and find out what works.

Lou: JPL is starting microwave experiments right now. They've done some in the laboratory, and they've done a light-sail experiment. On our *Cosmos 1* mission, we'll try to pulse the sail with a microwave from the Deep Space Network and see if we can measure the acceleration. If we do that, Freeman, will it be the first interstellar propulsion experiment?

Freeman: Maybe, I don't know. But, of course, there's a lot of stuff between here and Alpha Centauri. And I think it's foolish to think that after you've explored the solar system, there's nothing else interesting until you get to Alpha Centauri.

In fact, there's a lot of stuff along the way. A fellow named Jack Baggaley in New Zealand is observing meteors with radar—a project called AMOR, which stands for Advanced Meteor Orbit Radar. He actually sees stuff arriving here on Earth from Beta Pictoris, which I find very delightful. So we're already getting interstellar stuff, and it's being measured and observed.

Beta Pictoris is a star with a huge disc of dust around it. The dust presumably is being thrown around by encounters with planets or other objects. So, before we reach the edge of the solar system, we'll probably see a lot of interlopers on the journey there—for example, comets and asteroids from Beta Pictoris. It's wrong to think of all that space as empty. There's all sorts of interesting stuff going on.

Bruce: Let me ask Lou a question: You're the only one of the three of us who has written a book about solar sailing. What was your conclusion in the book, and what is your conclusion now about solar sailing to another star?

Lou: My favorite line from my book is "Space is big." When I was writing that in the mid-1980s, I was quite negative on the whole notion of interstellar flight. At that time, I held the view that interstellar travel is to us what the airplane was to Leonardo da Vinci. We could think of it, sketch cartoons about it, but we were centuries away from being able to implement it.

I'm not intimidated by the size of the solar sail—even the idea that the sail has to be hundreds of kilometers or so. If I were, I wouldn't be doing what I'm doing. The thing that is intimidating to me is the power source.

Freeman: Well, that to me is the easiest part. The Sun is just a wonderful source of power once you get out there. That's something we more or less understand.

What we don't understand, of course, is the biology and how to provide for the comfort of human beings in quite different environments. That we don't know anything about. And that, to me, is far more interesting than the problem of solar power.

Lou: To me, the exciting aspect of solar sailing is the idea of lasers and microwaves. They may change our perspective, so maybe interstellar flight is not so unimaginably far away.

Freeman: Well, I don't consider 500 years a long time. Interstellar travel is not unimaginable at all. We'll be there before we know it. Five hundred years is a very short time in the history of the species.

Lou: Do you think we'll be putting the lasers in space or on the Moon?

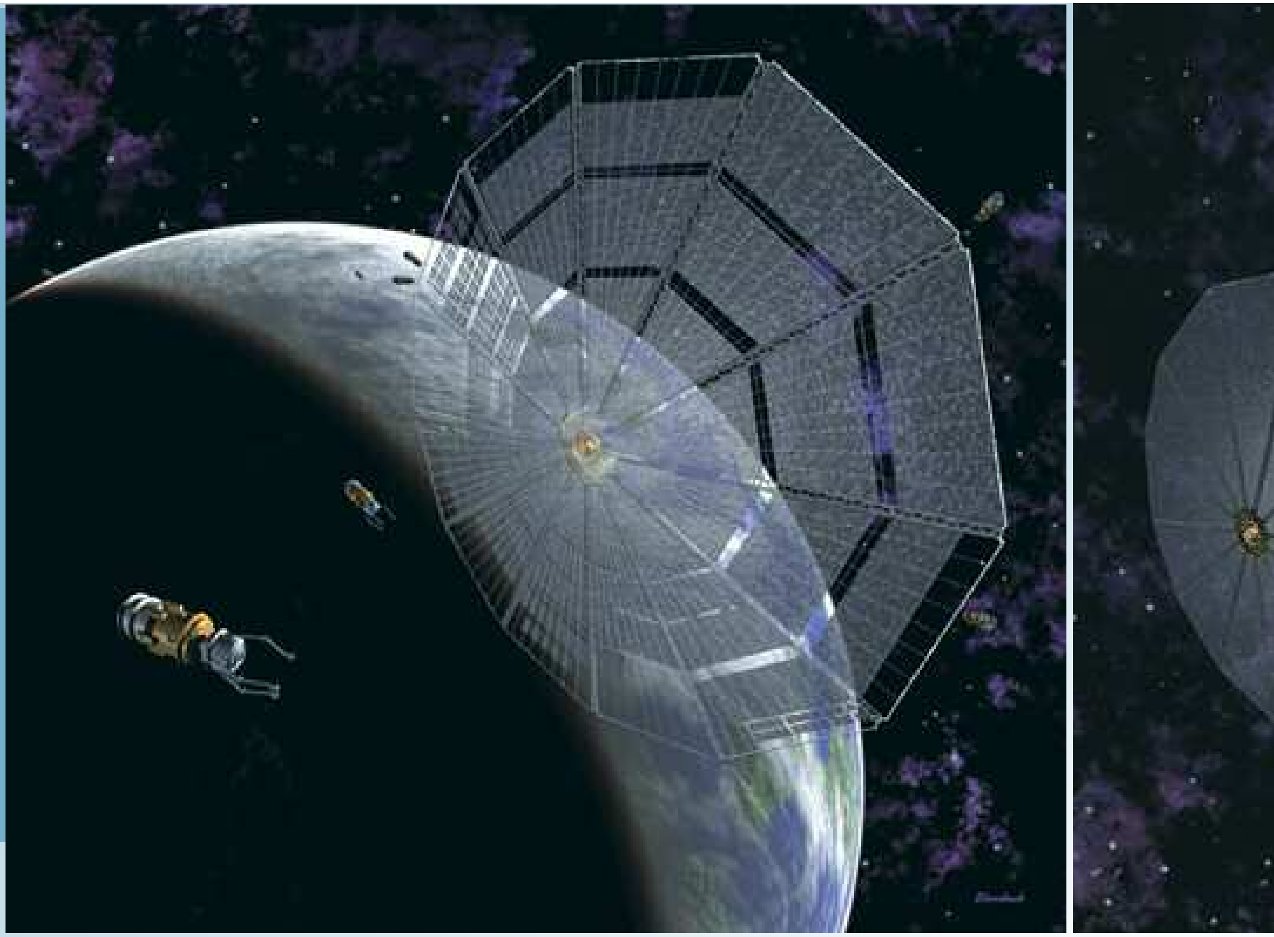
Freeman: I would say in space, but I think that's a matter of convenience. One of the problems with the Moon is day and night—14 days of night is inconvenient if you're talking about solar energy.

Lou: A nuclear-powered laser doesn't make much sense.

Freeman: It makes no sense at all. Nuclear power is fine for getting around the solar system. But it's no good if you're talking about really high speeds—you're only using 1 percent of the mass. That's no good at all.

With the power available from nuclear reactors, whether fission or fusion, you can comfortably reach speeds on the order of 100 kilometers [60 miles] a second or so—which allows you to go more or less anywhere you want in the solar system within a couple of years, maybe even quicker.

But if you're serious, you really want to travel at something like half the speed of light, which is tens of thousands of kilometers per second. So, the amounts of energy you need are enormously larger, and neither fission nor fusion



Large constructions—be they spacecraft or power stations—could be more efficiently built in space. Once these huge structures are out there, they can easily gather the abundant power generated by our Sun. Like two spiders building a web, these human-crewed spacecraft are slowly constructing a giant sail in Earth orbit. Bit by bit, they apply a fine film of metal to the sail's delicate carbon framework.

Illustration: Rick Sternbach

has that much energy. At the very most, if you consume the fuel at 100 percent efficiency and have no other machinery on board, you're using a little less than 1 percent of the mass.

Lou: Freeman, you said you weren't intimidated by lasers, and I'm not intimidated by the sail. However, we agree that the biology, the challenge of human space travel long distance, is very hard. One revolution that may make interstellar flight more practical is the information revolution. We might be able to build brains and communication power into the wispy structure of the sail itself. You wouldn't need to send humans at all.

Freeman: But people would like to go.

Bruce: Still, there may be 200 years' difference between sending robotic spacecraft and sending humans.

Freeman: Oh, certainly. It's the same with exploring the solar system. We've done that with robots very beautifully, making human pilots, from a scientific point of view, irrelevant. We'll send humans for the human adventure.

When I said it will take 500 years to go interstellar, I was thinking of humans. When you're talking about instruments only, then we could probably cut that in half.

Lou: Probably the biggest challenge will be to get a data rate that's kilobits per seconds; megabits would be better.

Bruce: *Mariner 4* was 8 bits per second. So, don't knock it. We learned a lot. Eight bits per second from Alpha Centauri would be wonderful.

Lou: Only if we can use Bob Forward's scheme of slowing down. Eight bits per second zooming through the Alpha Centauri system wouldn't be good. Forward came up with an idea for a detachable sail that, after positioning itself out in front, reflects the light back so it can be used as a brake system.

Freeman: I think you can probably do better using magnetic fields, but that we will learn in due time.

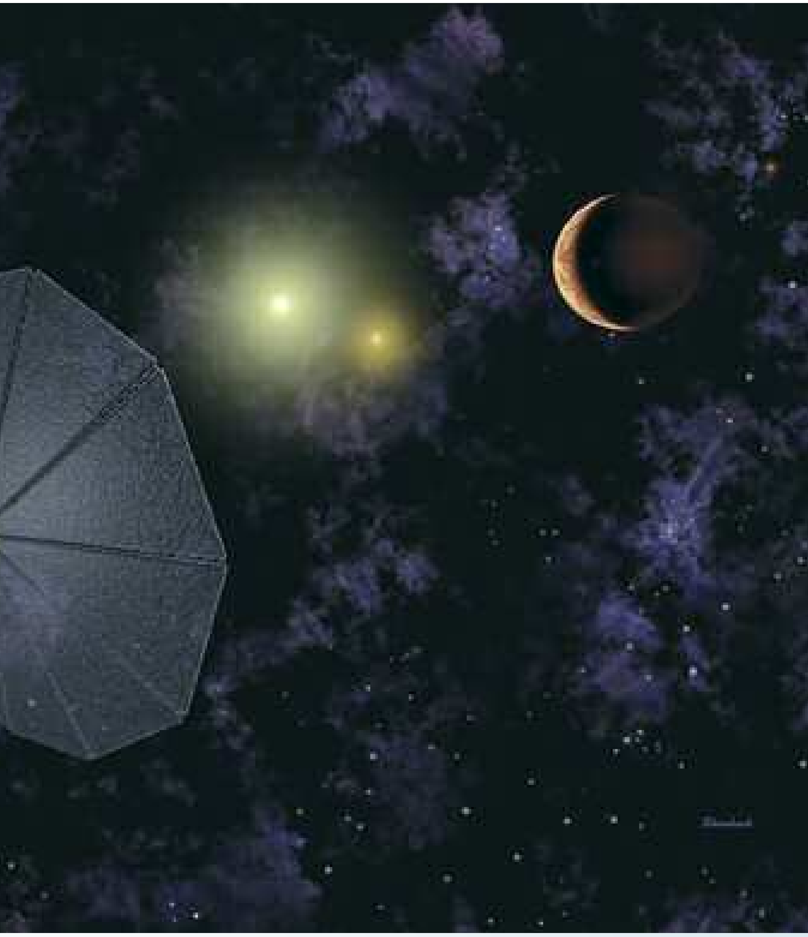
Lou: Do you mean generating a magnetic field?

Freeman: Well, interacting with interstellar plasma. But we don't really know how to do that yet.

It's not energy you need then, but mass. Something to drag you to a halt. If you want to decelerate, you don't need energy, you've got more energy than you want. You've got to have some way of dissipating the energy—something massive to absorb your momentum. So, if you could couple yourself into the interstellar plasma, which has lots of mass, you could use that to brake.

The question is, can you couple yourself magnetically to the plasma in such a way that you use it as a cushion to bring yourself to a halt? In principle, it looks as if it would work, but whether it really does, we don't know yet.

Lou: Two things have happened since the interstellar flight conference more than 20 years ago: the advancement of information processing and the microminiaturization of spacecraft. With that in mind, Freeman, would you describe



When we imagine interstellar travel, the distances involved can be difficult to comprehend. Alpha Centauri, the star system closest to Earth, is about 41 trillion kilometers (25 trillion miles) away. That's 10,000 times the distance between our planet and Pluto. It may take 500 years, but scientists and engineers are discussing ways to make this scene, a space sail approaching Alpha Centauri, a reality.

Illustration: Rick Sternbach

yourself as more optimistic or about the same in terms of robotic interstellar flight in this century?

Freeman: Well, I would say about the same. Judging from what we know now, I would say we're not going to make it this century, but that could easily be wrong.

Bruce: I have a question for Freeman that I want to be sure to get in. Carl Sagan wrote about wormholes or worm tubes as a way to travel the solar system and beyond. The physics seems to be relatively stable. What do you think?

Freeman: That certainly could change things totally. But, in fact, I don't think our understanding of wormholes has improved at all in the last 30 years. As far as we know, there's absolutely no way they could actually function. All the models with imaginary wormholes don't allow you to travel through them. There are all sorts of impossibilities you have to deal with in order to get from one end to another.

I would say that one of the best features of the universe, as far as I'm concerned, is the speed limit. It's a guarantee of privacy—you just get far enough away and you're out of sight. I find that very consoling.

Lou: But it's philosophically not very acceptable. It's a limit.

Freeman: I find it very acceptable.

Bruce: Let me ask you another off-the-wall question. By your reasoning, it will take our civilization maybe 250 years from now to send a payload, and another 250 years to send a human, to another star. If that's the case, there are presumably other planets out there with civilizations. They must have had the same opportunity. Where is everyone?

Freeman: It is a paradox. I tend to believe that life is much more difficult to get started than people seem to imagine. Of course, we know nothing about the origin of life, it is still a total mystery.

The simple explanation is that life is very rare, and that to me would be quite plausible as this planet does seem to be very suited to life or life is very suited to this planet.

It's not a big surprise that we don't see anybody out there. To me, it makes absolutely no sense to calculate probabilities. The exciting thing is to look—whether or not we find anything.

Our solar system is so big and there's so much variety out there, I think we'll be less excited about interstellar travel because there will be exciting things we'll discover along the way. It won't be such a big jump once we're traveling farther and farther from Earth and finding unexpected surprises. There may be many things going on out there of which we have no conception at the moment.

Bruce: I think that is very true, and this kind of exploration will happen because it's doable, and the technology, both the miniaturization and the computing electronics, is making it easier and easier to do.

Freeman: And I would say that biology is going to be even more important. We'll find ways of growing crops on Mars and growing potatoes on Europa and so on. As soon as we have a little better control of biology, most of these worlds will be habitable but in very different ways. We'll have totally different ecologies in each place.

Lou: We'll learn a lot about the search for life and the habitability on other planets from our experience here in the solar system—especially on Mars and Europa—and we'll make some conclusions about the rest of the universe based on that.

Freeman: The fact that we're getting stuff from Beta Pictoris also changes one's view of panspermia—the idea of life moving from place to place in space. If there are creatures living around Beta Pictoris, then they're probably already here. If an organism is already adapted to living in a vacuum, interstellar travel is not all that big a problem.

Lou: I'm glad to hear you say that, Freeman. You're well-known for being provocative and creative, with a lot of ideas that are intellectually stimulating, and yet in most of this conversation, you've been the conservative, pessimistic one.

Freeman: I only think you're asking the wrong questions. My point is that sending humans on an interstellar trip is not really the interesting thing. There are so many more interesting things you can do in the time you have available.

Bruce: Like getting material from Beta Pictoris in the lab, where we could really look at it carefully—that's exciting.

Lou: So, what is your appraisal of the *Cosmos 1* solar sail mission?

Freeman: I think it's great that somebody finally started on this technology. The main thing is not to raise expectations too high. It's important to get your feet wet and find out what the problems are. You're certainly doing that.

Lou: The vision of *Cosmos 1* has been the fact that the technology, as we've been discussing, allows us to think about traveling to the stars, but it's also technology that allows us think about traveling back and forth through the solar system.

Freeman: Oh, very much so. In fact, that, to me, is the most interesting part of solar sailing. It could become very cheap if the sails were produced in large quantity, and then solar sailing would be essentially open to everybody.

Bruce: We could park the sails in high Earth orbit, for example.

Freeman: Then you'd have your own little sailboat and go wherever you wanted.

Lou: What's your biggest technological uncertainty about sailing?

Freeman: I would say it's all a matter of operations. The physics is easy—the problem is, how do you operate the system, where do you want to go, and what do you do when you get there?

Bruce: Freeman, in your book *Disturbing the Universe*, you had a section on solar sailing. Looking back at that, what would you say differently about solar sailing or space travel or whatever?

Freeman: I don't remember what I said, but clearly progress has gone much slower than I expected. Yours is really the first serious effort, and that's a pity. NASA has been systematically opposed to any advanced technology right from the start. That more or less remains true today.

Bruce: Are you optimistic that America's, and therefore NASA's, interest will be renewed in moving beyond Earth orbit?

Freeman: Maybe you have to get NASA out of the way first.

Bruce: That's our strategy. If we can demonstrate a solar sail, even a primitive one, especially on a Russian nuclear submarine launch, NASA will be shamed into it. Also, the Europeans are beginning to look very seriously at the technology. That's The Planetary Society's job: to induce change, just as with the Mars rovers, when we got NASA seriously interested by demonstrating what you could do with them.

Freeman: Well, I would say that the initiative has to come from outside NASA. Certainly it'll happen one day, although it's taken much longer than I expected.

Lou: I guess that brings us back to the somewhat discouraging view about the possibility of interstellar flight being hundreds of years in the future. So much will happen between then and now. What will happen in genetic engineering or human evolution? What will happen in robotic technology? To me, these things are fairly unimaginable. So, trying to superimpose these unimaginable developments on the imaginable evolution of a solar sail vehicle is where I lose it. If we were looking at only a hundred years of change, I'd feel a little better about grabbing on to it.

Bruce: I have one last point. We've been thinking about humans migrating, and adapting in some form, to other worlds in this solar system at least. There's an alternative possibility: to stay here and send only sensors and surrogates elsewhere. I'm wondering, in the 30 to 40 years since you first began fantasizing about some of these things, how do you feel about this alternative vision?

Freeman: Well, I detest it. It's quite possible that if we decide to go that way, I will become a rebel and go off in my little spaceship and leave everybody else behind. So, I hope we'll all be rebels when the time comes.

Lou: So, you won't be satisfied sitting in some room with a hologram of data pouring in?

Freeman: No. I will have lost any freedom that I may have had. It's a matter of taste, of course, but I hope there will always be people who rebel against that kind of thing.

Bruce: But it's so much easier to live here than elsewhere.

Lou: None of us, to quote John F. Kennedy, is "doing this because it's easy, but because it's difficult." ☒

World Watch

by Louis D. Friedman

Washington DC—NASA has selected four Scout missions from more than 25 proposals for further study. One mission will be chosen for a scheduled 2007 launch.

Conceived by a lead scientist, or principal investigator (PI), rather than by NASA itself, Scouts are similar to the Discovery missions initiated about eight years ago. The PI handpicks the implementation team, including the company to build and operate the spacecraft and the organizations that will produce the relevant instruments.

The four selected missions involve a Mars airplane, a lander, an orbiter, and an atmospheric sample return. The mission concepts and the PIs are as follows:

- ARES (Aerial Regional-scale Environmental Survey), led by Joel Levine of NASA Langley Research Center. From a rocket-powered airplane, ARES would obtain the first in situ measurements of the near-surface atmospheric chemistry within the Mars planetary boundary layer—providing critical clues to the chemical evolution of the planet, as well as climate history and potential biological activity.
- SCIM (Sample Collection for Investigation of Mars), led by Laurie Leshin of Arizona State University, Tempe. This mission would fly through the thin atmosphere of Mars sampling atmospheric dust and gas and then return the samples to Earth. These samples could provide breakthrough understanding of Mars' chemistry, surface, atmosphere, interior evolution, and potential biological activity.
- MARVEL (Mars Volcanic Emission and Life Scout), led by Mark Allen of NASA's Jet Propulsion Laboratory. This mission proposes to conduct a global survey of the Martian atmosphere's photochemistry to search for emissions that could be related to active volcanism or microbial activity, as well as to track the behavior of water in the atmosphere across a full annual cycle.
- Phoenix, led by Peter Smith of the University of Arizona, Tucson. This mission proposes to conduct a stationary, in situ investigation of volatiles (especially water), organic molecules, and modern climate. It aims to "follow the water" in search of evidence for past life on Mars. It will land at high latitudes where *Mars Odyssey* has discovered evidence of large concentrations of ice in the Martian soil.

The Planetary Society was part of the Education and Public Outreach of two of the mission concepts and intends to work with all four teams to develop innovative opportunities for public participation.

Moscow—Since the economic and political revolution in their country, the Russians have seen their space science program stall. Nevertheless, Russia continues to be a major spacefaring nation as a key partner in International Space Station construction. They also continue to launch satellites for military and commercial customers.

But space science relies on government funding, and very little of that has gone to planetary study. Thus, in August 2002, eyebrows were raised when Russian newspapers reported that a Phobos sample return mission is being developed for a possible 2007 launch. For many years, the Russian space science community has maintained a strong interest in the Martian moon Phobos. They tried to send a mission there in 1988, and although it failed before the final rendezvous, it did yield valuable science data before the spacecraft was lost.

At a recent meeting of the International Mars Exploration Working Group, the Russians suggested that excess payload capacity on the Proton-launched mission be used to carry a small lander, similar to a Scout, to the Martian surface. Without the participation of the West, the Phobos mission is unlikely to happen, but even a low level of financial involvement might make it possible, providing a valuable addition to the national programs in the US and in Europe.

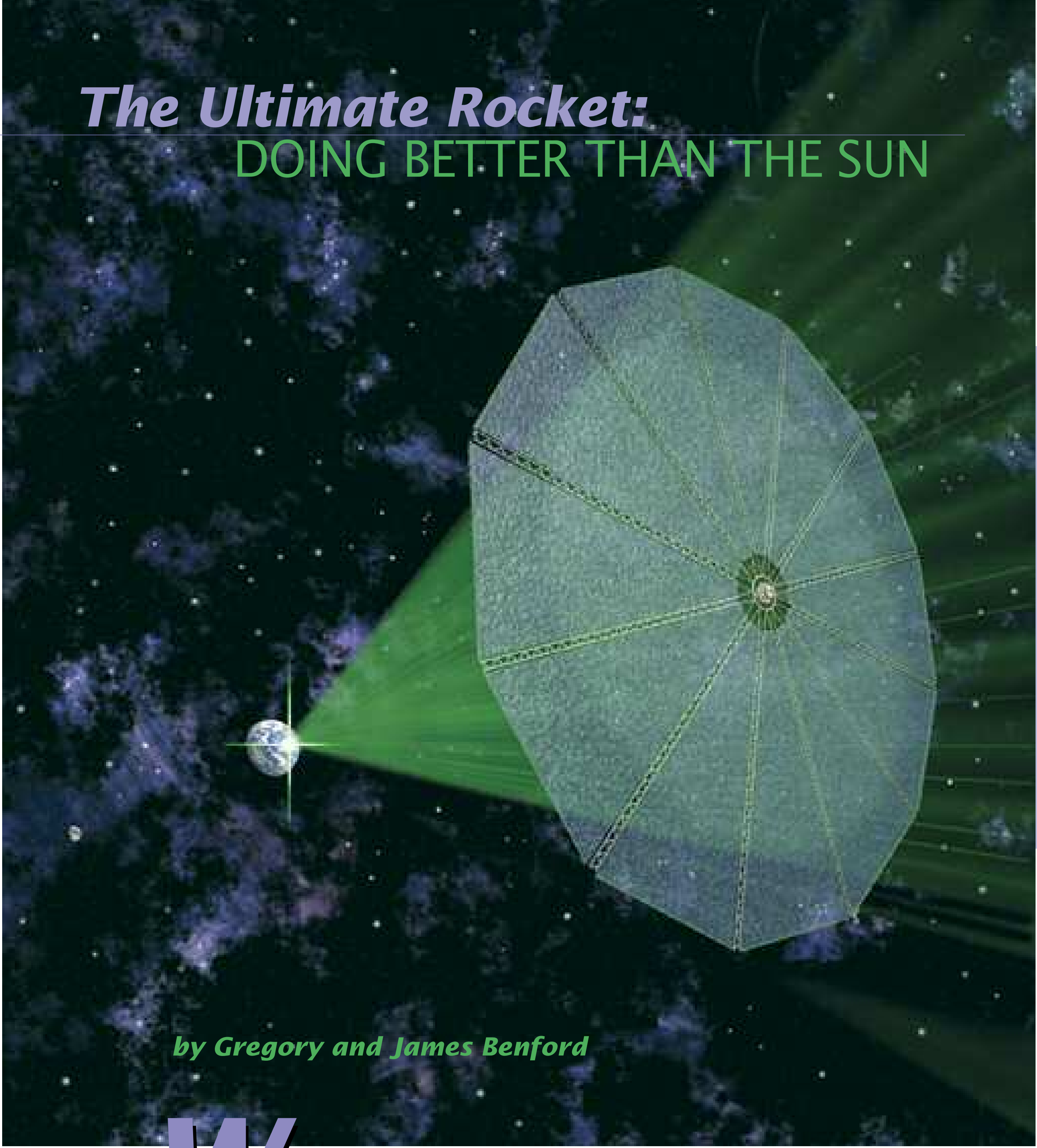
Paris—After initially eliminating the project from its planning, The European Space Agency (ESA) has decided to include *Venus Express* in its burgeoning planetary program. The welcome news came when the ESA Science Programme Committee gave its final approval at a meeting on November 5, 2002.

The mission, planned for launch in November 2005, will be the first to Venus from any nation since the launch of *Magellan* in 1989. The spacecraft, to be built by the Astrium Corporation, compares to that for *Mars Express* slated for launch in early summer 2003.

Venus Express, an orbiter, will be equipped with a magnetometer, spectrometers, and a multispectral camera. Venus' atmosphere is of major interest to planetary scientists because of its huge differences from Earth's. Study of these differences can contribute to understanding the causes and effects of global climate change, including greenhouse warming, ozone depletion, sulfuric acid rain, increases of carbon dioxide, and the effect of aerosols.

Louis D. Friedman is executive director of The Planetary Society.

The Ultimate Rocket:
DOING BETTER THAN THE SUN



A microwave beam sent from Earth gives this sail an extra push into space. Such beams, transmitted from power stations on Earth or in orbit, could supplement the Sun's accelerating power for these diaphanous spacecraft.

Painting: Rick Sternbach

by Gregory and James Benford

When The Planetary Society launches its *Cosmos 1* solar sail later this year, the event will be a first in more ways than one. Once deployed from the Russian launch vehicle, the sail will open at about 800 kilometers (500 miles) altitude, then begin to change its orbit under the subtle pressure of sunlight. But later in the mission, the Sun will get some help.

A microwave beam will strike the sail, delivering more electromagnetic pressure. This will come from the Goldstone 70-meter antenna, the biggest in the Deep Space Network (DSN) of communication antennae. The steerable dish can emit up to half a million watts of power. The result will be the first known attempt to exert forces on a spacecraft from the ground using purely electromagnetic beams.

The idea is a natural outgrowth of the basic solar sailing concept. To assist the Sun, the microwave beam will reflect from the sail's aluminized Mylar-like skin. Only about 1,700 watts will strike the sail. The beam spreads wider as it propagates, just as a flashlight beam does, so it will be much broader than the 30-meter sail diameter. Onboard accelerometers will measure the tiny increase in the sail's velocity as the beam's pressure pushes it. The craft will then relay the data to The Planetary Society's downlink center.

The effect is very small, perhaps only one 10-millionth of our gravitational acceleration. Sunlight will cause much larger accelerations, since about 1,370 watts fall on each square meter oriented perpendicular to the Sun's rays, versus 2.4 watts from Goldstone. This in-principle demonstration aims to illustrate future possibilities rather than usefully move the sail.

The basic idea of beamed sailing (creating a beam of energy to propel a sail) dates from 1966, when G. Marx proposed using lasers to push sailcraft from Earth. Indeed, when illuminating the *Cosmos 1* sail first occurred to us, we considered employing a large US Air Force laser for this experiment. But the laser costs a million dollars a minute to fire, whereas microwave beams cost only a few hundred dollars and can be created by NASA's Deep Space Network antennae.

The push given a sail depends on the power hitting the sail, not on the frequency of the beam. An advantage of microwave transmitters is that they've been under development much longer than lasers and are more efficient and cheaper to build. Also, microwaves do not damage sail materials as lasers can and do not refract while passing through our atmosphere. A disadvantage is that they must have much larger antennae than lasers for the same focusing ability. Laser light does not spread as much.

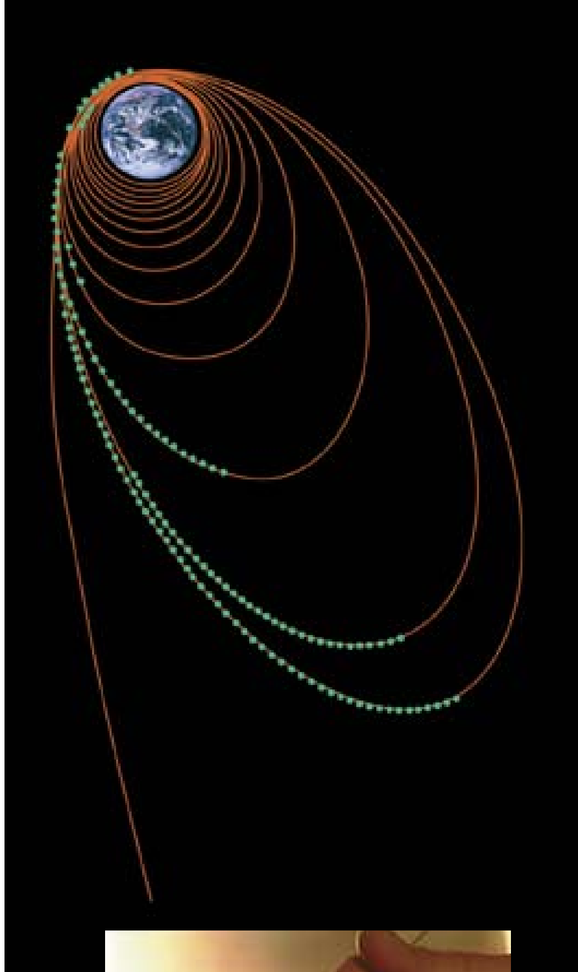
Whatever the source of the beam (power supply plus antenna, the "beamer"), the ability to move energy and force through space weightlessly is key to a genuinely 21st-century type of spacecraft. The expensive part of this utility is the beamer, which can project energy anywhere within its range and also drive one sail after another.

Like the 19th-century railroads, once the track is laid, the train itself is a small added expense. Compared with rockets, sails are very cheap once the beamer is built. Just as railroads opened up the American West, a beamer on Earth—or, at shorter range, in orbit—could send entirely new kinds of missions throughout and even beyond the solar system. Beamed sails (light or microwave) offer the promise of interstellar flight.

High-Velocity Micro-Spacecraft

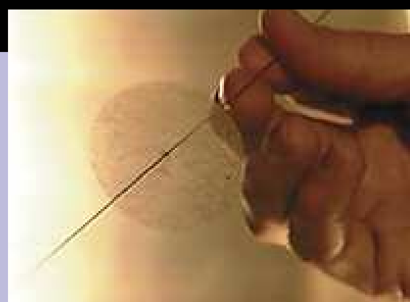
Earth-based or orbiting microwave transmitters can impart high velocities to low-mass sailing spacecraft.

Spacecraft launched from Earth must fight their way out of the planet's gravitational "well," but there is a benefit to this: sailcraft that have not escaped Earth's clasp are obliged to return on an elliptical orbit. A beamer that is itself in orbit will then be revisited repeatedly by the sail, which will climb to higher altitudes as the beamer's impulses incrementally boost the sail's velocity. After repeated "orbit boosting," the sail will depart into interplanetary space, where sunlight can push it farther. This would be ideal for quick missions to Mars, for example, in which a manned expedition may require a speedy shipment of replacement parts or medical supplies. A sail's low mass might enable deceleration by the Martian atmosphere, then a parachute descent.



A beam-driven sail would need to orbit Earth several times before escaping our planet's gravitational influence. With each elliptical orbit, the microwave beams (represented here by dots) push the sail farther away from Earth.

Diagram: G. David Nordley; redrawn by Barbara S. Smith



Optical wavelengths pass right through the carbon sail's ultralight material, but microwaves bounce off, imparting force.

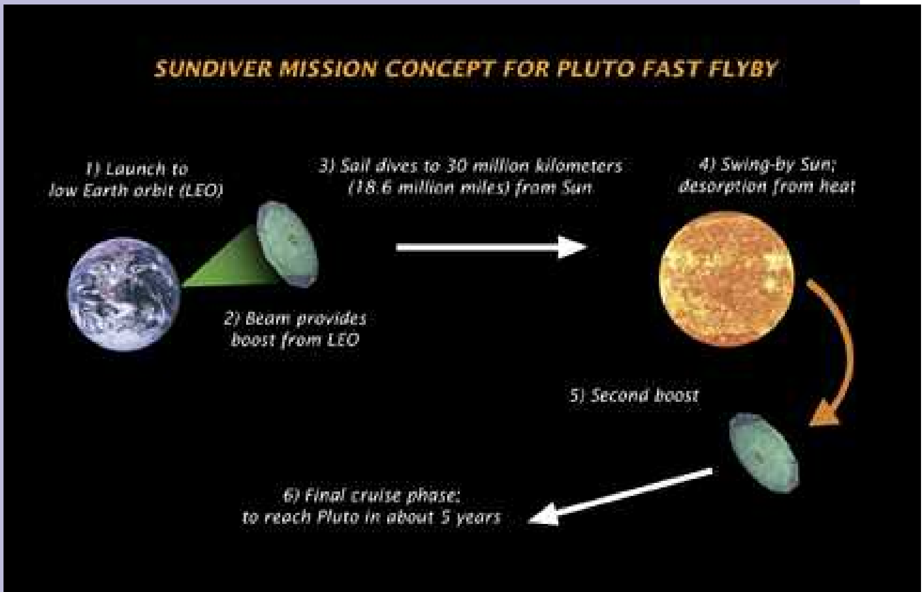
Image: Courtesy of Henry Harris

Flight in the Lab

To study such possibilities, we have, with collaborators, "flown" sails at the Jet Propulsion Laboratory and at the University of California, Irvine (UCI). Sails need not be aluminum. We performed experiments with small sails a few inches across made of pure carbon fibers, a much lighter material.

The fibers are 10 times thinner than a human hair, yet microfiber mats can tolerate very high temperatures. They weigh in the range of 10 grams (0.35 ounce) per square meter—lighter than tissue paper and competitive with the very lightest aluminized Mylar sails. Additionally, they are intrinsically stiff and can recall their shape after being rolled or folded, as deployment tests have demonstrated. Carbon sails could dive to very near the Sun and withstand heating far beyond the ability of current spacecraft.

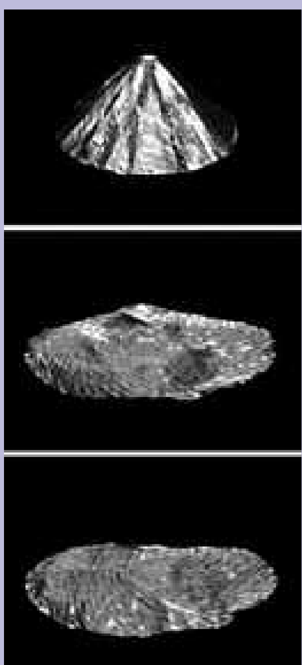
The image on page 16 shows lifting and upward flight of an ultralight sail. The carbon-carbon microtruss material easily survived several *g*'s acceleration. To propel the material, we sent a 10-kilowatt, 7-gigahertz microwave



These six steps show how a Sun Diver desorption-assisted mission could be used to send a spacecraft past Pluto in about five years. *Illustration: Courtesy of Greg Benford*

These four video frames capture the vacuum chamber flight test of the carbon sail at the Jet Propulsion Laboratory. The disk of sail material in the top frame is blasted with a 10-kilowatt, 7-gigahertz microwave beam (two middle frames). Not only did the beam launch the sail out of the picture (bottom frame), but the sail's lighter-than-tissue-paper carbon fibers survived the intense heat without melting or changing shape.

Images: Courtesy of James Benford



This computer model depicts a spinning deployment of the sail. Spinning allows the sail's delicate material to unfold gradually.

Simulation: Courtesy of Weidlinger Associates

beam into a vacuum chamber. At microwave power densities of approximately 1 kilowatt per square centimeter, the sails reached greater than 2,000 kelvins from microwave absorption without melting, a requirement for high-acceleration missions that most materials can't meet.

But in tests, a mystery arose. Data analysis and comparison with candidate acceleration mechanisms showed that the beam's purely photonic pressure accounted for 3 to 30 percent of the observed acceleration, so another cause must be present. Delving into this mystery led to still another new idea.

Propulsion by Desorption

By analyzing the gases blown off the sails with the beam on, we found that the main thrust came from ejection of molecules embedded in the carbon fibers during manufacture. This is called *sublimation* or, alternatively, *desorption*, and the higher the temperature, the more thrust results. We believe that the main lift in our experiments came from carbon monoxide being liberated from the carbon fibers at temperatures above 2,300 kelvins.

The thought immediately struck us: this might be a useful propulsion mechanism—a wedding of the solar sail idea with classic rocket engineering. But sails make poor rockets because there is no nozzle. On the other hand, they carry no engine.

How effective is desorption relative to the photon reflection for which sails are designed? The ratio of desorption acceleration to the acceleration from beam pressure is greater than 10, and can be as high as 10,000 at high temperatures. For example, for molecular hydrogen, the ratio is 10,000 for 1,000 kelvins sail temperature. This means that a beam source can drive a sail at an average acceleration exceeding the solar acceleration if it illuminates the sail for only a fraction of the sail's orbit time around the Earth. Such a large multiplier adds greatly to the appeal of the beam-driven method.

Our calculations show that this rocket-like effect could shorten the escape time from Earth's gravity well to weeks, compared with years for solar sails. As in the image on page 17, the sail returns to near the beam source on each loop of a steepening ellipse—a unique advantage to beam-driven sails, enabling repeated high accelerations and course corrections. Plausible scenarios using about 100-megawatt microwave beams allow fast beam-plus-solar-sail missions to the outer solar system. This in turn introduces a new kind of mission idea.

Sun Divers

A voyage beyond Pluto could begin with a carbon sail's deployment in low Earth orbit by conventional rocket. A nearby orbiting beamer or an Earth-based beamer would then propel the sail with a microwave beam. Once free of Earth, the spacecraft could employ sunlight to navigate inward to near the Sun—approaching edge-on in order to prevent the increasing flux of sunlight from pushing against its fall. At closest approach, the craft would turn to absorb the full glare of the intense Sun and heat up, increasing velocity as it accelerated markedly, under desorption plus solar propulsion. Exhausting the store of molecules lodged in its fibers, it would lose mass while gaining velocity. It would then sail away as a conventional, reflecting solar sail. Its final speed could be high enough to take it beyond Pluto within five years. There, it could engage in high-velocity mapping of the outer solar system, the heliopause, and beyond, to the interstellar medium—the precursor to true interstellar exploration.

Such maneuvers demand a lot of sail acrobatics. The biggest problem, as we discovered in experiments, is illustrated by a classic stunt: Chinese performers can balance plates on the end of sticks by spinning them; without spin, the plates fall. A sail riding a beam is in the same fix. Spinning helps a lot. But how to spin the sail and keep adjusting spin for the entire ride? Could we use the beam to accomplish this?

A Spinning Sail

We used circularly polarized beams in the lab to make carbon sails spin when they absorb the beam. The sail simply absorbs the electromagnetic angular momentum in the beam. But even good electrical conductors like aluminum can be spun if they are not cylindrically symmetric. This is a geometric effect, from interference of the waves in the beam when they reflect from the sail. Classic circular disk sails won't spin, but introducing cuts or struts or making them otherwise asymmetric lets them spin readily. Sometimes, this geometric approach proves more effective than does material absorption, as with carbon. As a mechanism to unfurl sails in space, circularly polarized beams allow the beamer to both push and spin with the same beam. Here, too, lasers fail. Since the spinning effect depends on the wavelength of the electromagnetic beam, the much shorter wavelengths of lasers cannot spin sails.

With spin, stability and control during beam riding become easier. Even if the beam is steady, a sail can wander off the beam if its shape becomes deformed or if a perturbation tumbles it.

Generally, sails without structural elements cannot be flown if they are convex toward the beam, as the beam pressure would make them collapse. On the other hand, the beam pressure keeps concave shapes in tension, so concave shapes arise naturally while beam riding. Such shapes will resist sideways motions if the beam moves off center, since a responding net sideways force restores the sail to position.

Therefore, we concentrated on a conical shape for the sail and studied its dynamics in numerical simulations. Experiments at UCI followed, and data showed that the beam-riding effect does in fact occur. With microwave powers of a few hundred watts, we could hold an otherwise unstable sail steady if the beam power falls off fairly quickly with angle from the central axis. We are now studying how active feedback can stabilize such sails.

Conical sails are a natural for microwave beam-riding as they keep their shape and are easy to reposition if the beam moves off center. This model of the cone sail is about 7 centimeters (about 3 inches) wide in size.

Image: Courtesy of Henry Harris

These beam ideas interconnect with another, older idea: transmitting solar energy collected by platforms in orbit down to Earth-bound consumers. Receivers on the ground could collect the microwave beams and turn them into electrical power. The concept of Space Solar Power (SSP) intersects these beam-driven sail ideas well. The beamer would serve as the SSP array, used for only minutes at a time to push a sail as it came around again in its lengthening, elliptical orbit. Domestic energy technology would thus unite with deep space exploration, answering the critics who say NASA's explorations yield little practical benefit.

The Future

More exotic approaches beckon in the future. Advanced "smart sails" could disperse electronic circuits in the sail area. Rather than wires, the circuit elements would be the carbon fibers themselves. Carbon carries electrical current and, with future developments, could perform onboard computing. Uniting such functions means that the same mass in carbon absorbs both momentum and electrical energy (charging its batteries) and even broadcasts back to Earth on command, using the type of phased array circuitry that the Deep Space Network employs every day. The sail thus becomes its own antenna.

All these possibilities are rising on the horizon. The power source for an orbiting beamer could be the SSP platforms long envisioned for collecting sunlight in orbit, which could then beam microwaves to electrical power grids on Earth. Launching sails would become a sidelight of a commercial, environmentally benign technology.

To make the solar system ours, we must envision propulsion methods that do not merely echo the chemical rockets developed more than half a century ago. The railroad gave way to the auto and the airplane. Each demanded fresh thinking and boldness. The time for beam-driven sails has come.

Gregory Benford is a professor of physics and astronomy at the University of California, Irvine, and a well-known novelist. James Benford is president of Microwave Sciences. Both received their doctorates from the University of California, San Diego. They are identical twins.

Questions and Answers

When hydrogen is detected in the upper meter of Mars' surface, how is water-ice distinguished from chemically combined water in clay and other minerals?
—John Mills,
Nashville, Indiana

Mars Odyssey's Gamma-Ray Spectrometer (GRS) can detect only hydrogen, not the complete water molecule (H_20). The detection of large amounts of hydrogen buried just beneath the surface is a firm and solid conclusion. But associating this hydrogen with water-ice takes some inference beyond just a physical interpretation of the data.

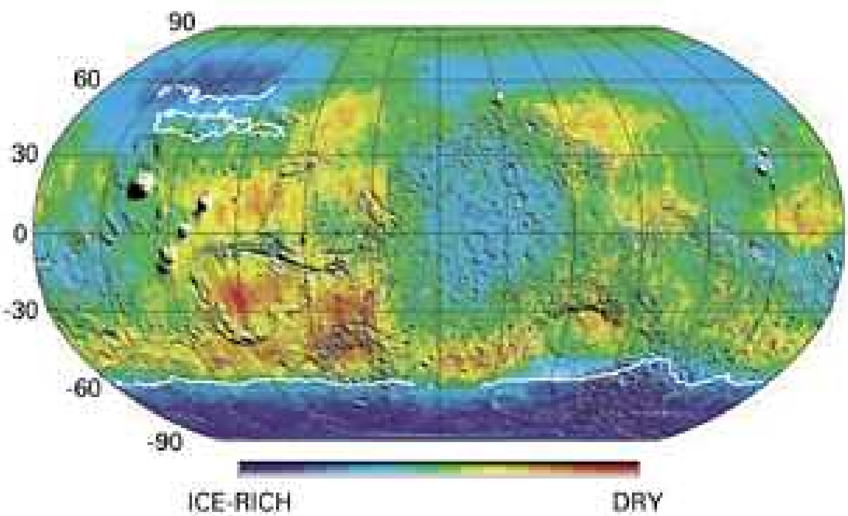
There are three arguments for why the hydrogen is in the form of ice. First, there is too much hydrogen—the equivalent of 35 percent water by weight—to be explained as water chemically combined with common minerals. Second, the hydrogen-rich material is buried beneath a hydrogen-poor layer, which has only a 1 to 2 percent water equivalent. If hydrogen were in the form of chemically bound water, we would have no reason to expect it to be so strongly segregated by depth, since meteorite impacts over long periods should have mixed the soils. Finally, the strongest argument is that we find the high hydrogen content only in the regions of Mars that are cold enough for ice to be stable against evaporation.

We all know that water evaporates if the air above it has less than 100 percent humidity, but not everyone realizes that ice will also evaporate, though more slowly, if the air above it is dry. (If you want to test this, put an ice cube on a small dish in your freezer and look at it over the following month—it will slowly disappear.) The same thing happens on Mars, but if the temperatures there get very cold, it is possible for ice to become stable and avoid evaporation.

Since the mid-1960s, several groups of scientists have calculated which regions on Mars would have ice that is stable. In most places, it cannot be stable near the surface because summertime temperatures there are too warm. However, within about 45 degrees of the poles, we calculate ice to be stable at depths comparable to those where the hydrogen-rich layer is found. The figure below shows how well the observations of the hydrogen-rich regions correlate to predictions of ice stability.

It is because the hydrogen-rich soils are present only beneath the surface, and only where Mars is cold enough for ice to be stable, that we feel the hydrogen exists mostly in the form of ice, not chemically combined water in minerals.

If the *Mars Polar Lander* had not crashed, it would have landed in this region with an instrument that could have analyzed the soil to determine how much ice is actually there. We may have to wait for another lander in the polar regions before we will get the ground truth to determine for sure if there really is as much ice as we think.
—WILLIAM BOYNTON,
Lunar and Planetary Laboratory



This map, compiled from data returned by* Mars Odyssey's *Gamma-Ray Spectrometer, shows the concentrations of hydrogen on Mars and the region where water-ice is predicted to be stable (below the white line).

Map: Courtesy of William Boynton

Your special* Voyager *edition of* The Planetary Report *(September/October 2002) brings to mind a question about Neptune's incomplete ring arcs. Since the rings of Saturn, Jupiter, and Uranus are all somewhat evenly distributed around their respective planets, does this mean that Neptune's ring material is somehow captured into arcs or clumps? Or will this material eventually disperse evenly around the planet?
—Russell E. Kempa,
Colorado Springs, Colorado

A similar question came up when ground-based observations in 1984 showed evidence for an "incomplete" ring around Neptune in 1984. *Voyager* observations later revealed that this incomplete ring is made up of five small arcs.

In principle, there are two effects that should cause the arcs to spread out. First, not all arc particles follow the same exact orbit. Those on different orbits travel around Neptune at different rotation rates. As a result, an arc should spread along its orbit to form a full ring. Second, collisions among the particles cause them to lose energy, which should lead to an even faster spreading, both lengthwise along their orbits and in breadth. Because of these two effects, it would actually take only a few months for the arcs to spread out.

However, Neptune's arcs survive because they resonate with the planet's small satellite, Galatea. The orbital distances between the arcs, Galatea, and Neptune are such that 43 orbits of the arcs correspond exactly to 42 orbits of Galatea. This resonance allows Galatea to exert a constructive gravitational pull on the particles at each encounter, which cancels out the spreading effects that would occur in an isolated arc.

The peculiar orbital configuration of Galatea and the arcs seems to exist only around Neptune. Its neighbors in the outer solar system, Saturn and Uranus, are also circled by narrow rings orbiting near small satellites. For example, Saturn's F-ring is confined in a set of narrow strands by the satellites Prometheus and Pandora, and Uranus' epsilon ring is confined in breadth by the satellites Cordelia and Ophelia. Only if the parameters of the ring material and satellites are just right, such as their masses and their relative distance, can an arc structure form.

The survival of Neptune's ring arcs is a good illustration of the endless physical possibilities that spring from Newton's law of gravity.

—FATHI NAMOUNI,
Southwest Research Institute

Factinos

Last December, *Galileo* sent home some surprising news about Jupiter's little inner moon, Amalthea. "The density is unexpectedly low," said John D. Anderson of the Jet Propulsion Laboratory. "Amalthea is apparently a loosely packed pile of rubble," he added.

The gaps between solid chunks probably comprise more of the moon's total volume than the solid pieces, and even the chunks are probably material that is not dense enough to fit some theories about the origin of Jupiter's moons. "Amalthea now seems more likely to be mostly rock with maybe a little ice, rather than a denser mix of rock and iron," said JPL's Torrence Johnson, project scientist for *Galileo*.

Amalthea's overall density is close to the density of water-ice, Anderson reported at the fall meeting of the American Geophysical Union in San Francisco. However, the moon is almost certainly not a solid hunk of ice. "Nothing in the Jupiter system would suggest a composition that's mainly ice," Anderson said.

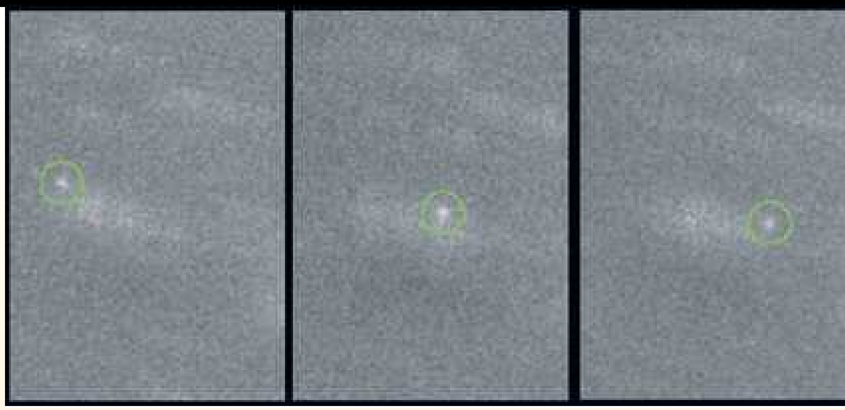
—from the Jet Propulsion Laboratory

Astronomers at Johns Hopkins University (JHU), the Observatoire de Paris, and other institutions have solved a nearly 30-year-old mystery surrounding Jupiter's moon Io, showing that volcanoes there appear to be shooting gaseous salt into the moon's thin atmosphere.

Further analysis of the results, including modeling of how the salt is broken down into sodium and chlorine atoms, could help planetary scientists move closer to determining the kinds of meteoritic materials that originally came together to form Io, according to JHU's Darrell Strobel. Astronomers winnowed the list of theoretical suspects for the source of sodium for years before determining that the most likely suspect was common salt, or sodium chloride. This conclusion was reached after the detection two years ago of chlorine in a doughnut-shaped, electrically charged cloud of gas around Io known as the plasma torus.

"The bottom line is that there seems to be enough salt in Io's volcanic atmosphere to supply both the amount of sodium that one sees in the neutral clouds and the chlorine in the plasma torus," said Strobel.

—from Johns Hopkins University



One of Neptune's recently discovered moons is circled in these images from Chile's Cerro Tololo Inter-American Observatory's 4-meter telescope. Until the International Astronomical Union designates a permanent name, the little satellite will be known as S/2002 N1. Images: Matt Holman, Harvard-Smithsonian Center for Astrophysics

Three more moons around Neptune have been discovered by a team of scientists led by Matthew Holman of the Harvard-Smithsonian Center for Astrophysics and J. J. Kavelaars of Canada's National Research Council (see image above). This elevates the number of known satellites for the blue gas giant to 11. These moons are the first to be discovered around Neptune since *Voyager 2* flew by in 1989, and they are the first to be observed from a ground-based telescope since 1949.

It now appears that the irregular satellite population of each giant planet may be the product of an ancient collision between a former moon and a passing comet or asteroid. "These collisional encounters result in the ejection of parts of the original parent moon and the production of families of satellites. Those families are exactly what we're finding," said Kavelaars.

—from the Harvard-Smithsonian Center for Astrophysics

Society News

Expedition to Argentina

We are still planning an expedition to Argentina to study some interesting outcrops in Patagonia. We are expecting to depart early in 2004. If you're interested in the expedition—even if you're just curious and want to know more—please call Lu Coffing at (626) 793-5100, extension 234, or e-mail her at *lu.coffing@planetary.org*.
—Lu Coffing, Financial Manager

The Planetary Society Scholarship Program

The Planetary Society is offering university scholarships for space-related studies at either the undergraduate or the graduate level. Full-time college students and high school seniors are eligible to apply.

Each year for the next four years, we will award two $1,000 scholarships. Members or persons nominated by members (one nomination per member) must submit their applications to The Planetary Society by April 30, 2003 for next year's awards.

For an application, call Linda Wong at (626) 793-5100, e-mail her at *tps@planetary.org*, or write to: Planetary Society Scholarships, The Planetary Society, 65 North Catalina Avenue, Pasadena, CA, 91106 USA.
—Linda Wong, Program Development Administrative Assistant

Annual Audit Completed

The firm of Hensiek & Caron has completed its yearly audit of The Planetary Society. The firm determined that the Society's 2002 financial statement conforms with generally accepted principles. Copies of the financial statement are available upon request.
—LC

Members-Only Discounts at Planetariums

The Planetary Society has been working with planetariums around the world to establish discounts ranging from 15 to 100 percent off admission prices for our members. For a complete list and more specific information, visit *http://planetary.org/html/member/planetariums.html*, or call Linda Wong at (626) 793-5100, extension 236.

If a planetarium near you is not on our list, please let us know at *tps@planetary.org*.
—Linda Kelly, Program Development Manager

Bequests Help Us "Make It Happen"

With the help of three bequests we received in 2002, The Planetary Society was able to subsidize an existing program, give an extra near-earth object (NEO) grant, and plunge into an exciting new project.

The John Getzman bequest allowed us to fully fund SETI@home for 2002. With the proceeds from the sale of a car left to us by Michael Sosnowski, we were able to award an extra NEO grant to Maximiliano Rocca. A bequest from Donald Bonk supplied the cushion for us to commit to a recent space shuttle experiment—a project not in the budget for 2003.

Over the years, bequests have allowed The Planetary Society to fund special projects and to pay for much-needed equipment. We sincerely appreciate the thoughtfulness and generosity of members who remember us in their wills and insurance policies. If you would like information about making a bequest to the Society, call Andrea Carroll at (626) 793-5100, extension 214, or e-mail her at *andrea.carroll@planetary.org*.
—LC

Visit Us at *planetary.org*
Stay up-to-date with Planetary Society projects, contests, and activities—even listen to our weekly radio show, Planetary Radio.

Surprise Year-End Grant

We are pleased to report that the Society received a year-end grant from the Richard & Rhoda Goldman Grandchildren's Fund. Mr. Goldman encourages his grandchildren to choose the charities to receive funds. We're grateful they chose us. *—LC*

Special Thanks

The following companies have promised matching funds when employees donate to The Planetary Society: Adobe Systems Inc., AES Duck Creek, Allegro, American Express Foundation, Avon Products Foundation, Ball Aerospace & Technologies, Benjamin Moore & Co., BP Amoco Foundation, Chubb, Cisco Foundation, Compaq Matching Gifts, Computer Associates, CSG Systems, Deutsche Bank Americas Foundation, Eiser Enterprises, Enron Matching Gifts Program, Equistar, Exxon Mobil, FM Global Foundation, Honeywell, Investors Bank & Trust, Ivy, John Hancock, Levi Strauss Foundation, Microsoft Matching Gifts, Monsanto Fund, Norton Company Foundation, Pfizer Foundation, Qualcomm, Safeco, Saint Gobain Corporation, Sun Microsystems, Tenet Healthcare Foundation, The Bank of America Foundation, The JP Morgan Chase Foundation, The Newhall Land & Farming Co., The Prudential Foundation, The Saint Paul Companies Inc. Foundation, The Williams Companies Inc., Tyco Simplex, Verizon, Williams, World Reach Inc., and Xcel Energy.

If you are employed by one of these companies, please inquire about their matching grant programs and double your support for The Planetary Society.
—LC

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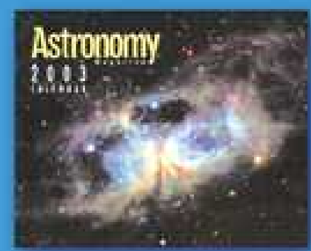

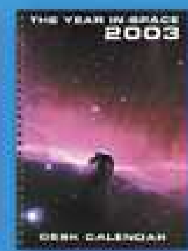

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In the distant future, when people have figured out how to traverse the immense distances to even the closest stars, this scene may become commonplace. Here, in *Landing Party*, a team of astronauts hikes over the rocky terrain of a world in a star system far, far away.

Chris Butler is an artist who specializes in science and nature illustration. His work has appeared in such publications as *The Times of London*, *National Geographic World*, and *Asimov's Science Fiction*.

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