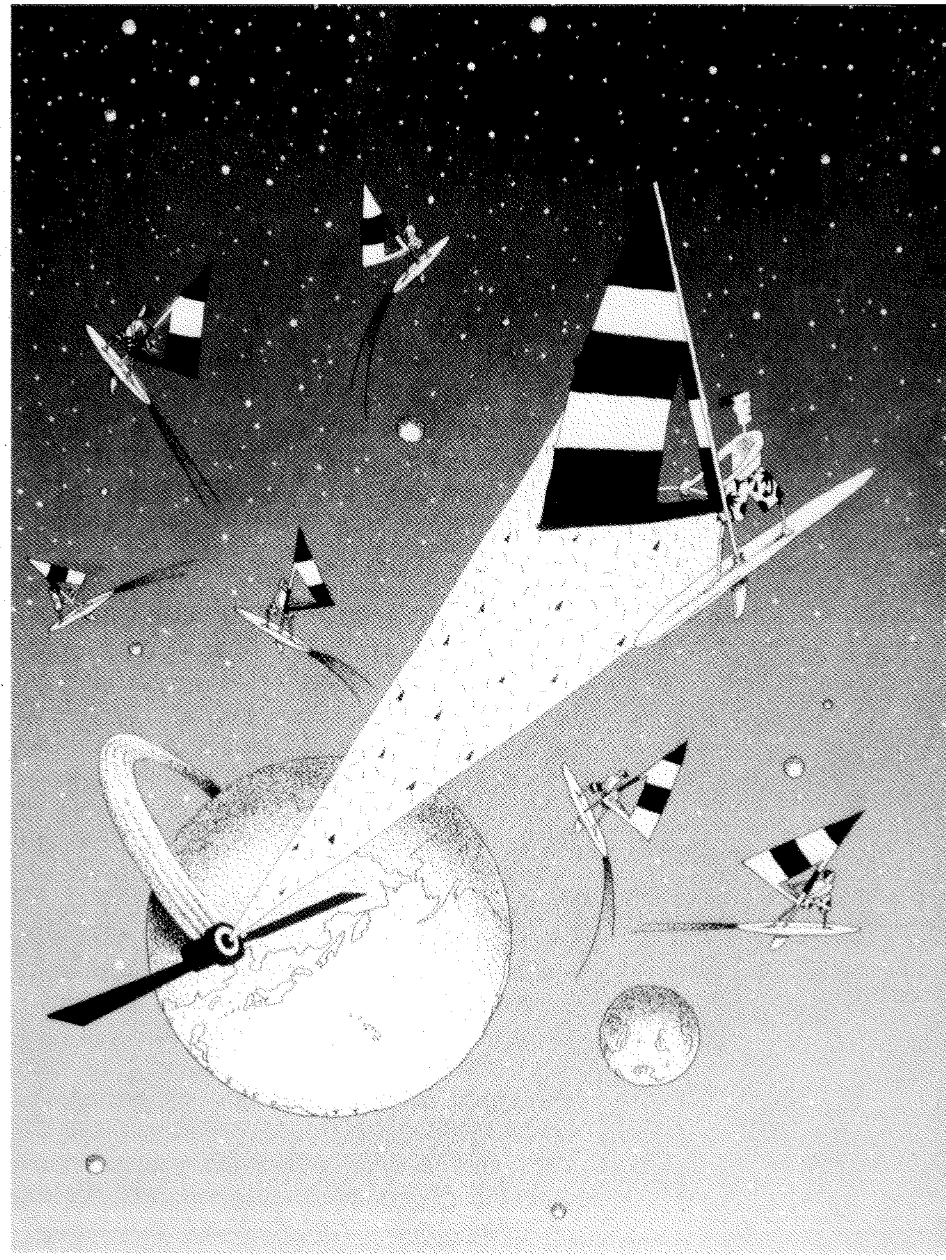

Illustration by Julie Scott

Interstellar SURFing

We may soon be traveling to the stars, at least by proxy, thanks to a group of seven Caltech undergraduates. Participants in the Summer Undergraduate Research Fellowship (SURF) program, the students investigated the possibility of sending an unmanned probe to a nearby solar system. They considered methods of propulsion, the types of instruments the probe should carry, and the best means of communicating the probe's data back to Earth. They wanted to design a spacecraft that could feasibly be launched in 50 years or so, one that would reach the nearest stars in a reasonable amount of time. This requires a final velocity of at least one-tenth the speed of light for a 50-year mission.

The design work on the probe is far from complete — there remain fundamental disagreements within the group on which propulsion system is best, for example — but a look at how these students spent their summer vacation affords an interesting glimpse at the earliest stages of one of humankind's greatest adventures. The sponsors for the project are Joel G. Smith, JPL's manager of telecommunications and data acquisition technology development, and Edward C. Posner, a member of the JPL staff and visiting professor of electrical engineering. There was also a JPL advisory board consisting of specialists in propulsion and engineering. The SURFers themselves are Allen Gee, Ara Kassabian, Charles Neugebauer, Stephan Pietrusiak, Dana Pillsbury, Gino Thomas, and Stephen Winters.

Of the three main aspects of the problem — propulsion, payload, and data communications — the first is certainly the most critical. The choice of propulsion system determines whether the probe will reach its destination in 10 years or 200 years and whether the probe will be able to carry 1 kilogram or 10,000 kg worth of scientific instruments.

An antimatter annihilation drive presents by far the most attractive possibility, at least on paper. In such a system, fully 61 percent of the fuel mass is converted directly to energy. (This compares with 0.4 percent for fusion and 0.07 percent for fission.) Ara Kassabian evaluated both electron-positron and proton-antiproton propulsion systems and discovered that, while both work in theory, electron-positron propulsion is probably unworkable in practice. The problem is that the products of electron-positron annihilation are two gamma rays. The only way of expelling these uncharged particles out the back of the spacecraft to produce propulsion would be to use some sort of mirror. But the gamma rays would be certain to burn up any physical mirror. Says Kassabian, "You'd have to have a really fancy kind of electron cloud mirror. There are a few that have been proposed, but they don't seem to work that well."

Proton-antiproton annihilation, on the other hand, produces pions and kaons. Two-thirds of these particles carry a charge, and can therefore be reflected with magnetic fields. Just 331 kg of antiprotons could accelerate a 10,000 kg spacecraft to a tenth of the speed of light (0.1c). And the quantity of antiprotons could be reduced significantly if the annihilation energy were used to heat a propellant, which in turn would be expelled out the back of the spacecraft. In such a scheme, the same 10,000 kg ship would require only 39.75 kg of antiprotons to reach 0.1c, but it would have to carry about 40,000 kg of propellant.

Unfortunately, 39.75 kg of antiprotons is a bit hard to come by, for antimatter is one of the most costly commodities in the world and one of the rarest in the universe. Present-day antimatter production is extremely inefficient and highly energy intensive. Even if present efficiencies were to be upgraded by three orders of magnitude, as is expected in the not-too-distant future, antiprotons would still cost about a million dollars a milligram. The spacecraft's fuel alone would thus cost an astronomical $40 trillion. This cost would have to come down by at least a factor of a thousand to make antimatter propulsion even remotely conceivable.

One of the great attractions of an antimatter-propelled ship is its extremely low mass ratio — the ratio of the mass of the fully fueled ship to the mass of the ship after its fuel has all been expended. The lower the mass ratio, the less energy is wasted in accelerating the fuel itself. Several propulsion systems that make use of nuclear fission or fusion also have acceptably low mass ratios, but they have their own problems.

Fusion engines, for example, could produce a large amount of energy from a small amount of fuel, but fusion is still in an early stage of technical development. And it requires drastic conditions to get a fusion reaction going: a small bit of deuterium has to be either compressed by a huge magnetic field or subjected to inertial confinement and bombarded on all sides with extremely powerful laser beams produced by extremely bulky lasers. So even though a fusion-powered vehicle would use a relatively small amount of fuel, the engine would be so large that much of its energy would be wasted in accelerating its own enormous mass.

Several schemes employing nuclear fission seem to hold more promise. One idea, worked out by Kassabian, is based on the Orion Project developed by Freeman Dyson and Theodore Brewster Taylor. The Orion Project involves an immense manned interstellar spacecraft, propelled by atomic bombs that explode, one after the other, at the ship's back end. (Gino Thomas appreciates the economy of such a scheme. "You kill two birds with one stone. You go to the stars, and you also get rid of a lot of nuclear bombs.") Dyson and Taylor designed a scaled-down prototype of Orion, designated "Putt-Putt," and Kassabian's idea for an unmanned ship is scaled down further from this; he calls it the Tuff-Tuff engine.

The Tuff-Tuff engine uses fission microexplosions to propel the vehicle. The fission fragments from these explosions compress a magnetic field produced by a superconducting coil, and the compressed magnetic field pushes the vehicle forward. The microexplosions would be produced in small pellets of uranium 235, each with a mass of only 0.02 grams. Since the critical mass of ^{235}U is 20 to 40 kg, the pellets need an external source of neutrons to get the chain reaction going. This would be provided by a jacket of californium 252, which in turn would be surrounded by beryllium 9, a neutron reflector. The californium is one of the weak links in this scheme. It costs $100 million per gram.

But the most serious problem with the Tuff-Tuff engine is that when the microexplosion starts, the pellet will rapidly expand, the neutron density will rapidly decrease, and the fission reaction will quit after only a small fraction of the uranium is consumed. Even present-day atomic bombs have an efficiency of only about 0.8 percent, and the efficiency of the micropellets is likely to be worse, although Kassabian has found this difficult to determine since much of the relevant data is classified.

Another scheme, called the Vulpetti engine, could overcome the low efficiency problem. In this design, jets of ^{235}U are exposed to a neutron source. The reaction fragments are redirected by a magnetic field, and the unburned uranium is recycled. The problem with the Vulpetti engine is that it's extremely complex, even in theoretical form. Says Kassabian, "When you draw up plans for a rocket it may look simple on paper, but when you give it to the engineers, they give you a blueprint that's miles long. So if the plans are complicated to start with, it's probably going to be unworkable."

Some of the students considered the possibilities of nuclear electric propulsion (NEP), a type of ion drive. In an NEP thruster the fuel — mercury is one possibility — is first ionized and then accelerated through grid electrodes and out the back of the ship. The fuel itself contributes no energy. The energy is supplied by a fission or fusion power plant aboard the ship whose function is to hold the grid electrodes at a very high electrical potential. In order for this design to be workable, however, present-day ion thrusters would have to have their power supply mass ratios improved more than three orders of magnitude: from 0.05 to 100 kilowatts per kilogram. And even then, the spacecraft would take 225 years to reach Proxima Centauri, the nearest star.

Several of the SURFers favor spacecraft powered by external laser or particle beams. The main advantage of such schemes is that the spacecraft would carry no fuel whatever. The beam would use between 10^{11} and 10^{15} watts of power for several minutes to several months — total world power output is currently about 10^{12} watts — and would be placed in Earth or moon orbit. Although laser or particle beams of this strength do not yet exist, the Strategic Defense Initiative (also called Star Wars) may soon make them available. The spacecraft itself would have a sail-like structure against which the photons or charged particles would push, accelerating it to high speeds. Since most of the expense in a beam-rider spacecraft would be in the power source, it's possible that many such spacecraft could be sent out sequentially, all in different directions.

If a laser were chosen as the power source, it would have to be focused onto the spacecraft's light sail by an immense lens system 100 kilometers in diameter. The sail would be about 40 meters in diameter and the photons would accelerate the 100 kg ship at 80*g* for two months. The ship would reach Proxima Centauri (4.2 light years away) in just 17.5 years. The laser beam's high temperature presents some problems, though. It could melt its own optical system, and even if a way were found around this, the beam would heat the spacecraft itself, possibly causing damage to delicate components.

Heating would not be a problem with particle beam acceleration, since the particles never make physical contact with the sail, which in this case would be a charged plate of some sort. But particle beams have their own problems. If a beam of positively charged protons were sent out, for example, electrical repulsion would quickly cause the beam to spread out, dissipating its energy. To get around this, Allen Gee conceived a scheme in which electrons could be added to the protons, so the beam would essentially be sending out a stream of hydrogen atoms. The spacecraft would then have to strip the electrons, and the remaining protons would push against a positively charged plate. But even then such a beam would diverge quickly due to random collisions, unless its temperature were kept very low — on the order of 10^{-5} K. To avoid the problems of beam divergence, the ship would have to be accelerated very rapidly. In one scheme a 10^{15}-watt beam would accelerate a 100 kg ship at 10^4g for just five minutes to reach a speed of 0.1c. Of course, all the spacecraft's components would have to be built to withstand such high accelerations.

Although getting the spacecraft to another solar system is the biggest problem, the SURFers also investigated what it would do once it got there. Virtually none of the scenarios assume a rendezvous mission (the NEP drive scenario is an exception) so the spacecraft will zip through the other solar system in at most a few weeks. And the instruments will have to be very compact and lightweight; in many of the scenarios the spacecraft will only be able to carry 10 kg worth of instruments. This may not be a problem, according to Dr. Posner. "Ten kilograms these days is a lot. At less than half a kilogram, for example, you can get a portable cellular telephone with a battery, an antenna, a 99-digit memory for telephone numbers, the entire FM transmitter and receiver, and an error correcting code, and it all fits in a space smaller than two cigarette packs. And

that's today, not 50 years from now. It isn't clear that the spacecraft is going to have to be much more complicated."

Since the spacecraft's main objective will be to characterize the star and any orbiting planets, it will have to carry an imager of some sort. Using the Sun-Jupiter system as a model, Gino Thomas tried to determine the best way to pick out a planet like Jupiter at a reasonable distance. The Sun, of course, is much brighter than Jupiter at all wavelengths of light, but Jupiter shines brightest relative to the Sun at a wavelength of 21 micrometers in the infrared. At this wavelength the Sun is only 1,000 times as bright as Jupiter. Given this wavelength, and data on the mean separation between the Sun and Jupiter, Thomas calculated that the spacecraft would have to carry a 1.3 meter telescope with a rather large aperture. But a better plan, according to Thomas, would be to use a one-meter interferometer with somewhat smaller apertures. Such an instrument would be able to resolve a Jupiter-like planet at a distance of two light years, far enough away to make the minor course changes that would allow the spacecraft to come close to the planet.

The interferometer would not be trained only on its destination. In combination with Earth-based telescopes, it would also make parallax measurements of other stars. Such long-baseline parallax measurements would lead to a considerable refinement of our distance scale of the universe. On its way out, the spacecraft would also be in an ideal position to make measurements of the interstellar medium. For this it would probably carry a fly-paper-type contraption: sticky strips of metal that would capture and analyze interstellar dust.

Communicating the data back to Earth does present some problems. At a distance of four or five light years, both radio frequency beams (30 cm wavelengths and longer) and microwave beams (1 to 30 cm) would diverge too much. Stephan Pietrusiak investigated this problem and determined that wavelengths of light on the order of one micrometer, just beyond the visible region, would be best. This light would be produced by a relatively modest 1,000-watt laser carried on board the spacecraft. In this scheme precise pointing would not be necessary, since at the receiving end the beam would still be larger than the orbit of the Earth. A spaceborne photon bucket could capture the signal and relay it to ground stations no matter where the Earth was in its orbit.

The communications system will be able to transmit an amazing 10 bits of data per photon. This seemingly paradoxical result would be achieved with a JPL system called Pulse-Position Modulation (PPM). In this PPM system there would be 1,024 (2^{10}) possible time slots in which a signal could arrive, so the actual time of arrival would stand for 10 bits of information. A PPM system that communicates 2.5 bits per photon has already been demonstrated, and a 10-bit-per-photon system could be developed. Such a system would only be able to communicate between 10 and 100 bits per second, so the large amount of data the ship collects during its breakneck race through the other solar system may have to be parceled out and sent to Earth slowly, over a period of months to years.

The SURFers considered propulsion, payload, and communications, but there remain several important aspects of the mission that they were unable to study this summer. The spacecraft, for example, will need to be largely autonomous, since closed-loop control is not possible at a distance of several light years. And all the spacecraft's components will have to be extremely long-lived; however, given the excellent record of Voyagers I and II as well as other spacecraft, this is not expected to present much of a problem. Many of these design considerations may be worked out soon, since a number of JPL scientists are interested in launching a precursor mission, called TAU, that will travel a Thousand Astronomical Units from the Sun. (An astronomical unit is the distance from the Earth to the Sun. Pluto orbits the Sun at 39.5 a.u.)

Once a commitment is made to embark on an interstellar mission, the launch date would be at least 50 years away. Travel time will take another 20 to 200 years, and the data won't all be returned for another decade beyond that. This may seem a long time to wait but, as Dr. Posner says, "The mission does not require science-fiction type breakthroughs or unknown physical laws or unknown economic will on the part of the Earth. It may require vision to have a hundred-year mission. I personally believe that humans are capable of that. After all, some of the cathedrals of Europe took over a hundred years to build, and it may take longer than that to get the Long Beach Freeway through South Pasadena." □ — *RF*