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Introduction to Starflight

> There can be no thought of finishing, for "aiming at the stars," both literally and figuratively, is a problem to occupy generations, so that no matter how much progress one makes, there is always the thrill of just beginning . . .
>
> Robert H. Goddard, 1932, in a letter to H. G. Wells

> The finer part of mankind will, in all likelihood, never perish—they will migrate from sun to sun as they go out. And so there is no end to life, to intellect and the perfection of humanity. Its progress is everlasting.
>
> Konstantin E. Tsiolkovskii, 1857–1935

Whys and Wherefores

Interstellar travel is real, despite what the doubters say. We'll begin by differing politely but emphatically with that distinguished radio astronomy pioneer from Harvard University, Edward Purcell, who at the dawn of the space age made many classic pessimistic assumptions about how starflight might be accomplished. Then, in 1960, he penned the boldest denial of interstellar flight on record, a distinction of dubious honor:

> All this stuff about traveling around the universe in space suits—except for *local* exploration which I have not discussed—belongs back where it came from, on the cereal box.

It was not the first time that an otherwise perceptive scientist had displayed a peculiar failure of imagination about space travel. Witness the remarkable pronouncement by a British scientist in the 1920s about a venture requiring much less expansive thinking:

> This foolish idea of shooting at the moon is an example of the absurd length to which vicious specialization will carry scientists. To escape the Earth's gravita-

tion a projectile needs a velocity of 7 miles per second. The thermal energy at this speed is 15,180 calories [per gram]. Hence the proposition appears to be basically impossible.

A.W. Bickerton, 1926

Not only are the first emissaries to the stars already under way (Pioneers 10 and 11 and Voyagers 1 and 2, therefore starflight of an extremely primitive kind is being done right now), but also many thinkers have devoted considerable attention to finding ingenious ways to make trips to the stars by craft much fleeter than these early "slow boats." The plans these visionaries have developed in the past three decades are impressive.

Some plans are extraordinarily far-reaching like the British Interplanetary Society's Daedalus study that envisioned an admittedly "proof-of-concept" thermonuclear pulse rocket that could reach nearby Barnard's star with scientific instruments in about half a century (2). Others, such as the Jet Propulsion Laboratory's study of an interstellar precursor mission, have much more limited objectives: exploring the interstellar medium to a range less than 1% of the distance to the nearest star (3). Yet such a mission could be mounted within 20 years assuming only conservative extensions of technology.

But to be frank: Interstellar travel is not easy. It cannot be accomplished simply by wishing for a convenient wormhole in space-time to drop through to the other side of the universe or for a short hop to a nearby sun. Interstellar travel, "starflight" for short, may never be done by Earthlings in the ways outlined here, although we believe that some or all of these methods will eventually be used. But the inexorable and difficult buildup of technology and science on the platforms of past labors insures a significant place for starflight in humankind's future. Some or all of the propulsion systems described in this book will play a role in taking at first machines (robotic probes), and then people, to the stars.

The big problem with starflight is, of course, distance, and that is why the bulk of this handbook is devoted to methods of interstellar propulsion. The ancillary problems of guidance and navigation, payload content, reliability, and so on, though difficult, are relatively minor issues compared with the primary hurdle of attaining speed sufficient to reduce to tolerable lengths transit times to the stars.

Why would we want to go to the stars in the first place? Is it not enough to be near the one—the nearest star—that lights up our days? Surely, we can study the Sun, study the Solar System's planets, moons, asteroids, and comets. We have already made dramatic progress through millennia of astronomical observations, and much more recently, interplanetary spaceflight. But soon in cosmic history we will have examined the tiny piece of galactic real estate that is the Solar System and it will be time to move on. We will probably want to begin starflight in earnest even before the Solar System has been completely explored—*just because the stars are there* and since by nature we are driven to be explorers. Or, if you prefer Alfred North Whitehead's dictum, because, "without adventure civilization is in full decay."

What draws us to the stars are not those fusion fires themselves but the planets that attend many if not most suns—at least 50% by some recent informed estimates. As children of a blue-green oasis planet in a wheeling system of at least nine major worlds and a multitude of moons, we yearn to explore those imagined realms so far, far away. Solar System-based instruments are gradually revealing more and more about the probability of the existence of planets surrounding the nearer stars, and it will not be long before we have definite proof of their presence. There is the possibility that we may eventually be able to form crude images from afar of even small Earth-size planets within other solar systems, using highly specialized and very expensive optical techniques (see Chapter 16).

But to sift the sands of these truly remote worlds, to explore those planets and moons for the first glimmerings of life or the remains of extinct life, to sense the beauty of their environments through the dispatch of robot instruments, or from the reports returned by human crews—these are our dreams and the legitimate goals of interstellar travel.

First we must confront a controversy—a genuine and unfortunate though understandable split in the ranks of science. There are many, among them Edward Purcell, who suggest that exploration or colonization by humans of extrasolar planets—or even probing by remote instruments—will never be done because there is a way to accomplish this for "free," albeit vicariously. We can simply cock our radio telescope ears to the heavens, search patiently for signals from other civilizations, and tune into a galactic network of interstellar information. The sensible and noble idea of "conventional" SETI—the search for extraterrestrial intelligence—has great promise and deserves fervent support.

But it is by no means certain that such interstellar signaling will be a prevailing mode of galactic discourse, even though we would like to believe that it is. One can imagine, for example, a civilization of dolphinlike ocean creatures among whom are philosophers, mathematicians, poets, and musicians, but who have not had the means or interest to develop technology. Arthur C. Clarke's words about starflight in *The*

Promise of Space (1967) ring true, "This proxy [robot probe] exploration of the universe is certainly one way in which it would be possible to gain knowledge of star systems which lacked garrulous, radio-equipped inhabitants; it might be the only way."

On the other hand, compelling scientific reasons may arise within the next fifty years to encourage serious thought at least about robotic probes to nearby solar systems. Advanced techniques in optical astronomy (see Chapter 16) may make possible not only the detection of Earth-size planets orbiting nearby stars but also the determination by spectroscopy of the hallmarks of living extrasolar worlds: chemical constituents in planetary atmospheres such as oxygen coexisting with methane. The scientific interest in such worlds would be enormous and would warrant intense scrutiny by SETI researchers. If the examination of the radio spectrum of these nearby "Earthlike worlds" (ELWs) revealed no evidence of technological civilizations, starflight would be the only way to investigate them in detail.

But starflight is much more than a hedge against failure of the many active SETI efforts now ongoing and soon to be inaugurated around the world. Starflight is indeed the ultimate means by which terrestrial life and human culture—of the enlightened sort, it is hoped—can stabilize itself against local astrophysical or even provincial biological catastrophes. By providently spreading terrestrial seeds far beyond this Solar System, we will be insuring the longevity of what has begun on this tiny world.

The interstellar imperative—the "bottom line" of starflight—is that ours should become a civilization that can outlive its star. The life-giving Sun will not always remain benign. About five billion years from now, its core of hydrogen fusion fuel nearly spent, the Sun will expand in an angry "red giant" phase, incinerating all the creations of humanity that might still exist in the inner Solar System. There are other possible astrophysical events that could doom civilization: a nearby supernova explosion producing radiation that would scour the Solar System of life; the Sun's entry into a region of dense interstellar material; or the bombardment of the inner Solar System by millions of rogue comets from the Oort Cloud—the consequence of the close passage of another star.

Some people say, "Not to worry. Millions or billions of years is a very long time and we need not concern ourselves about the distant future." We say *stardust* to that, though we were really thinking of a stronger term! It is *never* too soon to start thinking about interstellar expansion for the long-term preservation of terrestrial life. The time is now!

After a Long Distance, Another Long Distance

Starflight is not just very hard, it is very, very, very hard! It is essential to really *feel* the fundamental cosmic distance scale we are up against. Say the Sun, about 1.4 million kilometers in diameter, is reduced to the size of a small marble with a diameter of 1 centimeter. On this scale, Earth is a barely visible dot about 0.1 millimeters in diameter, approximately one meter away from the marble Sun. The outer bounds of the Solar System—the orbit of Pluto—hover slightly beyond 42 meters on this scale. Another way of looking at it: the marble Sun could sit in the middle of a football field and the orbit of Pluto would then fit snugly between the two opposite goal posts!

Where on this scale is Proxima Centauri, which is the nearest known star beyond the Sun and is an actual distance of 4.3 light years away? On this scale, Proxima is about 292 kilometers removed, more than 80% of the distance from New York to Boston or from Washington to New York. Our present interstellar vehicles are literally much slower on this scale than crippled ants traveling between those cities. The ***astronomical unit***, or AU, the average distance between Sun and Earth, is the relevant dimension to compare the realms of interplanetary and interstellar flight ($1\ \text{AU} \approx 149 \times 10^6$ kilometers). Proxima is 273,000 AU from the Sun. The piddling regime of interplanetary flight out to 40 AU is nearly 7,000 times less than this typical interstellar distance.

By the way, the small red dwarf, Proxima, is the third component of the triple star system, Alpha Centauri. The system's Sunlike "A" and "B" components revolve about a common center with a period of 80 years, separated by only 20 times the Earth–Sun distance. Proxima revolves around this pair far away with a period of millions of years.

Interplanetary flight, the kind of space travel we have done up until now, is thus about four powers of ten (four orders of magnitude or 10,000 times) less demanding in duration at any achievable cruise speed. Pioneers 10 and 11 leave the confines of the Solar System with an escape speed of about 2.5 AU/year, and Voyager 1 has already achieved and Voyager 2 will achieve (in August 1989 after encountering Neptune) a Solar System departure velocity of about 3.5 AU/year—that is, tens of thousands of years to over a hundred thousand years travel time if these spacecraft were on a direct trajectory to Proxima, which of course they are not (see Technical Note 1–1).

Because the velocity of a starship so dominates discussions of interstellar flight, it is important to consider units useful for measuring it. In the current era of chemically propelled rockets, units of kilometers per

Technical Note 1-1

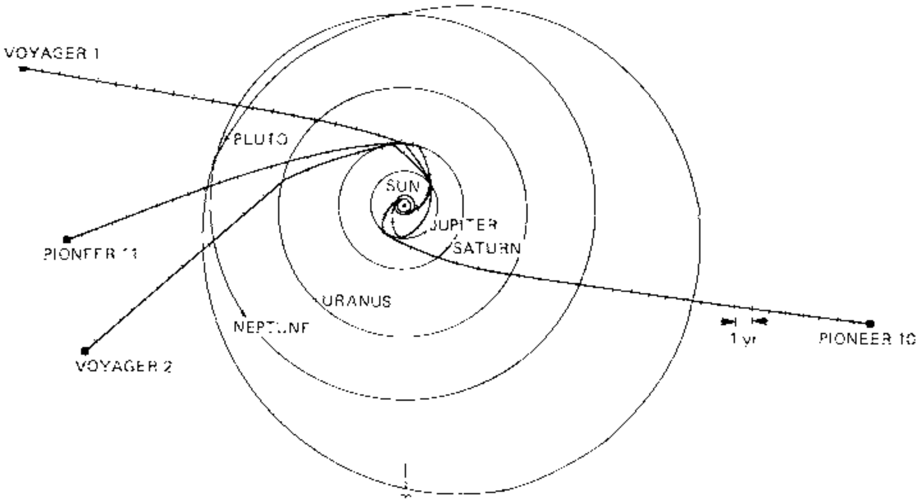
The First Starships

The trajectories and fate of the first interstellar vehicles have been beautifully explored by Cesarone, Sergeyevsky, and Kerridge of the Jet Propulsion Laboratory, in a technical article that should be read to appreciate the reality of starflight *in the 20th century* (9). A summary of the authors' key projections:

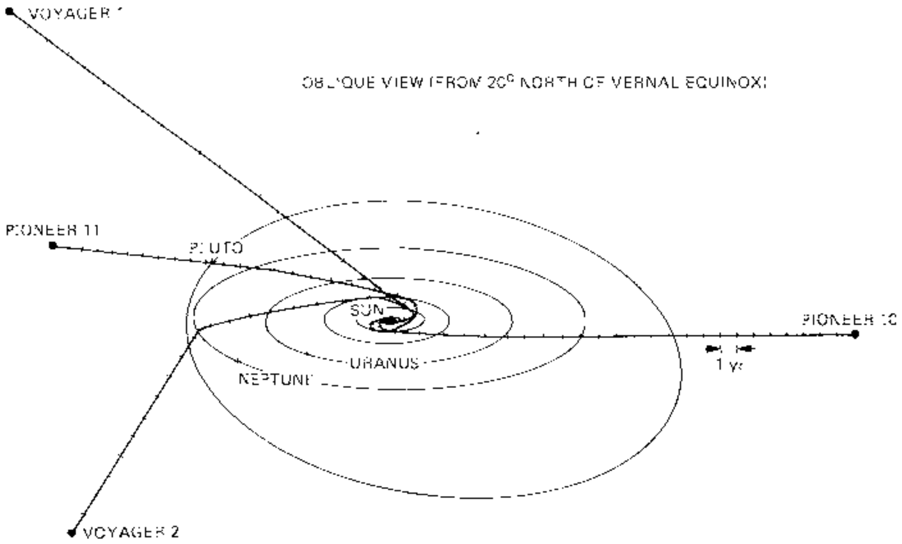
	Pioneer 10	Pioneer 11	Voyager 1	Voyager 2
Launch Date	Mar. 3, 1972	Apr. 5, 1973	Aug. 20, 1977	Sept. 5, 1977
Loss of Signal	1994 (at 59 AU)	1996 (at 45 AU)	2012 (at 121 AU)	2013 (at 106 AU)
Departure Velocity Asymptotic (AU/yr)	2.4	2.2	3.5	3.4
Trajectory Angle to Earth Orbit Plane (degrees)	2.9	12.6	35.5	− 47.5
Closest Stellar Approach:				
Distance (ly)	3.27	1.65	1.64	0.80
Star	Ross 248	AC + 79 3888	AC + 79 3888	Sirius
Years to reach	32,600	42,400	40,300	497,000

Voyager 1 exceeded Pioneer 10's distance from the Sun in mid-1988 at 43 AU and subsequently will remain the most distant from the Sun of the four craft.

Voyager 2 exceeded Pioneer 11's separation from the Sun in early 1988 at 25 AU.



ECLIPTIC PLANE PROJECTION. PLANETS AND SPACECRAFT POSITIONS SHOWN IN 2000 A.D.



Pioneer and Voyager trajectories. (Courtesy Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, and JBIS)

second (km/sec) are quite suitable for describing spacecraft velocity. Moreover, km/sec is an appropriate unit for typical orbital speeds within the Solar System and even the velocity required to escape it. The speed of a spacecraft in a low Earth orbit is about 7.9 km/sec; the minimum velocity required to escape completely from Earth is 11.2 km/sec; Earth's orbital velocity about the Sun is 30 km/sec; and the minimum velocity required to escape the Solar System altogether starting 1 AU from the Sun is 42 km/sec (Technical Note 1–2).

Tens of kilometers per second are still insignificant compared to light speed, c, which is approximately 300,000 km/sec in free space. (The speed of light in vacuum is 299,792.458 km/sec.) Thirty km/sec, these days a luxurious pace, is only the fraction 10^{-4} c or 0.01% of light speed. Remember these often repeated facts: light sprints to the Moon from Earth in about 1.3 seconds and, if held to a circular path, light would in one second wrap 7.5 times around Earth's equator. The forementioned unit of AU/year might be useful in gauging the progress of some early precursor interstellar missions, but it is incompatible with decent starship velocities, considering that light speed is 63,500 AU/year.

By far the best measure of starship speed turns out to be simply the *fraction of light speed*, f_c, at which a spacecraft is traveling. What more

Technical
Note
1–2

Escape from the Sun

One convenient simplification in analyzing interstellar flight is the lack of significant gravitational perturbation by nearby stars of a starship's velocity when the ship is reasonably distant from the departure or destination solar system, that is, for much more than 99% of interstellar transit. But a starship does have to leave and then enter a solar system. Achieving enough velocity to permanently escape a star requires, from elementary mechanics, achieving $\sqrt{2}$ or 1.414 . . . times the speed in circular orbit around a star at the departure point, a distance R_0 from the center of a single star:

$$V_c = \sqrt{\frac{GM_*}{R_0}}$$

Circular orbital velocity
Where G = universal gravitational constant
M_* = mass of the star

$$V_e = \sqrt{2}\, V_c$$

Stellar escape velocity

These orbital and escape velocities, we have said, are generally *minute* compared with starflight cruise speeds necessary for reasonable transit times. Exceptions would be departure from circular orbit about a dense white dwarf star, or even more so, a neutron star. Any additional velocity beyond V_e that a starship achieves is referred to as its *hyperbolic excess velocity*, and is designated V_∞, read "V-infinity." For example, the hyperbolic excess velocities of the Pioneers and Voyagers are, respectively, 2.5 and 3.5 AU/yr. Once safely beyond the Solar System, they will cruise indefinitely at these speeds on trajectories that closely approximate straight lines.

appropriate standard to choose than the speed of the "craft" that do the fastest interstellar travel all the time—photons of light. It is much more convenient to speak of "0.1 c" than 30,000 km/sec or 635 AU/year. Moreover, f_c is easily converted to absolute terms by simply multiplying by about 300,000 to get speed in km/sec and by 63,500 for AU/year. But the really marvelous thing about the fraction of light speed unit is its relation to interstellar distances that are indelibly impressed on our psyches as light years. Despite the great utility to astronomers of the *parsec* ("parallax second," the distance from which 1.0 AU appears to subtend one arc second of angle [1 degree = 3600 arc sec.], the equivalent of 3.26 light years), the light year will forever be the unit of choice of the human starfarer, who reckons the cycles of life in years.

Light speed can be represented as 1.0 light year/year (ly/y), so whatever interstellar distance in light years is the objective, simply divide the light speed fraction, f_c , into it and get the time of the journey (at least as seen by home-based observers, i.e. neglecting relativistic time dilation for the star travelers). If a star is 15 ly removed and your speed is 0.1c, then it will require (15 ly)/(0.10 ly/y) or 150 years in transit (ignoring time to accelerate and decelerate in the case of a complete mission).

Scales of Distance

The boundaries of the Solar System's known planets fit within a sphere 50 AU in radius. What comes after that? First there is a vast belt, called the Oort Cloud, containing what are believed to be trillions of primordial icy comet nuclei, so sparsely spread through space that a starship departing the Solar System is unlikely to collide with a single one. This beehive of comets probably extends with decreasing density to a distance of 100,000 AU.

The nearest waypoint beyond the comet belt is the triple star system Alpha Centauri, at 4.3 ly, one of whose orbiting members, Proxima, happens to be the closest known star beyond the Solar System. Within a sphere of radius 21 ly, there are 75 known star systems (including the Sun) which contain 105 known stars, many of these being gravitationally linked double stars, with a few triples, quadruples, and even one quintuple system (see tables in Appendix 3 and illustrations in Chapter 2). Traveling beyond 21 light years, the number of stars in the expanding sphere of exploration increases approximately eight-fold with each subsequent doubling of the distance from the Sun. So within 40 ly there may be nearly 1000 stars, within 80 ly nearly 10,000 stars, and so forth. The formula can be extended only so far, however, because of the Sun's location out on an arm of a pancake-shaped spiral galaxy, the Milky Way, a whirl of stars that may contain between 400 billion and a trillion members. The Milky Way is approximately 70,000 ly in diameter, but is only a few thousand light years thick at the position of the Sun.

The spiral galaxy Andromeda is the major neighboring galaxy—at a distance of two million light years. Both Andromeda and the Milky Way, in turn, are members of a gathering of 20 galaxies called the Local Group, which stretch over millions of light years. Two minor galaxies, the Magellanic clouds—irregular aggregations of billions of stars—are closer to us than Andromeda. In fact, the spectacular supernova 1987 A exploded in one of these 160,000 years ago, and light from it has just arrived at the Sun.

The Local Group is gravitationally wedded to the Virgo supercluster, itself consisting of thousands of galaxies. Superclusters and even larger organizations of galaxies in the cosmos extend to the horizon of present visibility in the expanding universe—15 to 20 billion light years. The *visible* universe is defined by the age of the cosmos, an estimated 15 to 20 billion years. As the universe ages, this horizon grows farther away. Radiation from more distant parts of what may well be a virtually infinite cosmos (according to the new inflationary theory of cosmology) simply has not had time to get to us since the beginning of everything in the Big Bang "explosion." Hundreds of billions of galaxies populate the visible universe, but according to theory now seriously considered, even this visible universe may be a mere "atom" compared to the larger manifold of the inflationary cosmos. (See "The Self-Reproducing Universe," Eugene F. Mallove, *Sky & Telescope*, vol. 76, no. 3, September 1988, pp. 253–256.)

Of what significance to starflight is the architecture of this astonishing hierarchy? Its overwhelming size suggests, at least in the beginning, that we should be content to consider starflight out to a very limited range, perhaps to several tens or at most to one-hundred light years. There is ample interesting territory to explore within that realm. For neophytes, there is not much point in aiming at the stars beyond this zone before testing coastal waters. But someday. . . .

The Not-So-Fixed Stars

Though over the course of a human lifetime and even during long historical periods the stars may seem "fixed" on the celestial sphere, they are indeed moving with respect to one another. Referenced to the Sun, they have radial velocities toward or away from us that can be measured by the *Doppler* shifts of emission and absorption lines in their light spectra. They also have apparent *proper motion* across the sky, that is, movement tangential to the line of sight. So the stars are moving in three dimensions, and unless extremely fast starships are employed, it will be necessary to substantially "lead" a target star in order to rendezvous with it.

This is a consideration that will be taken up in greater detail in Chapter 12, but for now it suffices to note that typical stellar motions in the Sun's neighborhood are on the order of tens of kilometers per second. In other words, if starship velocities are of this same order (tens of km/sec, as they are now), the trajectory to a star from the Sun will be one side of a not very thin triangle (see Figure 1.1). The triangle would be

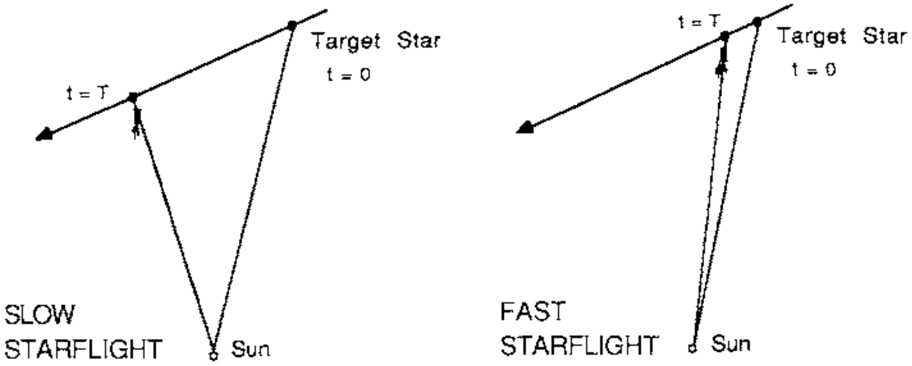


Figure 1.1 Aiming at a star.

very acute for extremely fast starflight. The other two sides of the big triangle are the initial Sun-target line and the star's approximately straight path through space to the rendezvous point.

Regimes of Starflight

Generating taxonomies of starflight will not get us one step closer to the stars, but it will help to put subsequent discussions in perspective. Above all, starflight has to do with patience—human patience, and human lifetimes. Without requisite patience and commitment, no one, no nation, and no world is going to try to cross the interstellar ocean. Therefore, the regimes of starflight are best characterized not by distances and velocities, but by transit times *as observed from the departure point*. At high velocity, the relativistic effect of time dilation makes shipboard time run slower, as the reader will no doubt have heard. (See Appendix 5.)

Our suggested categories of starflight are outlined in Table 1–1.

A few decades ago humanity was incapable of even Type-4 starflight. Now with the Pioneers and Voyagers we have embarked on a proof-of-principle version of Type-4. The once interplanetary craft will reach stellar distances by virtue of gravity whip momentum transfer in swings past the outer planets. But they will return no information other than the self-congratulatory "we did it"—if anyone on Earth is still around to check the calendar. Except for the possible dispatch of large human exploration colonies to the stars, *world ships*, humanity will probably leapfrog Type-4 starflight and before long embark on Type-3, with instrumented probes and perhaps even inhabited vessels.

Table 1–1 Categories of Starflight

Starflight Class	Transit Time	Rationale
Type 1:	10 to 100 years	Current human lifespan and planning horizon.
Type 2:	100 to 500 years	Enlightened extension of human planning horizon.
Type 3:	500 to 2,000 years	Major epochs in human history.
Type 4:	2,000 to 100,000 years and beyond	Beyond history, perhaps beyond the feasible global "attention span."

As we shall see, when and how Type-2 and Type-1 starflight will be accomplished gets considerably more speculative. The rationale for this schema is largely dependent on the average human *lifetime* and *lifespan* (the maximum age ever recorded at death) remaining what it is presently. However, even though contemporary lifespan is not far over 100 years, the explosive development of biomedical research holds great promise for major life extension, if we should choose to achieve it. The social consequences of a large increase in lifespan would of course be dramatic, pervasive, and possibly profoundly troubling. Perhaps one of the most predictable consequences, however, would be the more ready acceptance of extremely long-duration starflight. Thus, the problem of starflight is not only deeply entwined in human cultural perceptions, it is also inextricably tied to fundamental biology (see Chapter 14).

"Catch Me If You Can"

The potential long durations of early interstellar voyages create a glaring problem that has no parallel in human experience: A relatively slow vehicle dispatched too soon may be passed, long before it reaches its destination, by a more advanced technology, higher speed craft sent out much later. Would-be explorers of the New World may have been deterred by fears of sea monsters and falling off the edge of a flat Earth, but they did not hold back while anticipating a more efficient ride on the Queen Mary or hopping across the drink on the supersonic Concorde! Yet this is precisely the dilemma that may face initial voyages to the stars by people, and to a lesser degree by instrumented probes. The problem is one of setting out too soon: the "catch up" quandary.

In a way this is a very sticky subjective problem because it entails estimating technological and economic progress far into the future, a skill for which no good track record exists. However, Brice N. Cassenti considered a particular extrapolation of propulsion technology and concluded, "Missions on the order of 10 ly should be possible 200 years from now (4).Therefore, at this time, it appears that only propulsion systems capable of traversing distances at speeds that are a considerable fraction of the speed of light should be pursued, and only when these are shown to be infeasible should the Space Ark be considered." Curiously, physicist Freeman Dyson has arrived at the same time frame, albeit for different reasons. Dyson believes that we will launch large interstellar vehicles when annual GNP (gross national product)—or gross world product—grows to something like 1000 times its present level.

The "Space Ark" to which Cassenti refers is a self-contained world ship whose initial inhabitants would have long since died when their descendants reached the destination star system. The concept is venerable in the lore of starflight and science fiction, though as far as we are aware its earliest suggestion was published in 1929 by British crystallographer, J. Desmond Bernal (5). Since then, the idea has been elaborated in much greater detail by many other people, particularly in conjunction with efforts to establish orbiting space colonies within the Solar System (6,7). Generation ships, space arks, or world ships, have considerable merit for missions of interstellar colonization, and they will appear regularly in subsequent discussions.

Cassenti's and Dyson's conclusion seems to us reasonably secure, though we remain optimistic that unforeseen developments in propulsion technology will make feasible human missions to the stars beginning in the next two centuries. (In honor of the "catch me if you can" fable, perhaps we should name the first human interstellar mission Gingerbread Man–1.)

Starflight Propulsion

"Propulsion, propulsion, propulsion," might well be the interstellar explorer's equivalent of the real estate agent's exhortation of "location, location, location." Propulsion is the heart of interstellar transport, so before launching our tour through the "nuts and bolts" of starflight, behold the imposing array of candidate propulsion methods for attaining the stars:

- First, the classical generic self-contained rocket that gets both its energy and expellent mass completely from on-board reserves. Chemical rockets are all abysmally ineffective for starflight. Then there are the self-contained rocket's modern variants: the ion rocket (electric propulsion), which expels charged atoms (ions) at high velocity and perhaps uses a nuclear reactor to generate the requisite electric power; and the fission nuclear rocket: a nuclear reactor as power source to energize thermally accelerated hydrogen atoms (the reactor may be either a solid or liquid structure, or even gasified for maximum performance). Just over the horizon of technological feasibility is the fusion rocket, harnessing the energy of thermonuclear reactions to a high-speed particle exhaust. More far reaching still in their ultimate performance are varieties of anti-matter rockets, employing anti-matter/matter annihilation reactions as an energy source to accelerate and expel different kinds of particles and/or photons.

- Nuclear pulse propulsion resembles classical rocketry, as its energy supply and "propellant" are in the form of on-board micropellets of fusion fuel or rearward ejected bombs, which when detonated thrust the vehicle forward.
- Beamed power propulsion decouples the internal energy source of the classical rocket and puts it in either a laser, microwave, X-ray, or other kind of energy beam stationed within the Solar System. The beamed power can either energize propellant obtained from the interstellar medium or carried in the vehicle, to be expelled as in a rocket, or the beam can push the craft ahead by direct momentum transfer, thus eliminating the need for propellant.
- The interstellar ramjet is the analog of the terrestrial atmospheric ramjet. Interstellar space is a remarkably good vacuum, but using what little ambient matter exists in these barren reaches may make various types of interstellar ramjet feasible. A huge frontal area would be required to collect material in a large zone forward of the accelerating craft. Fusion reactions in the ingested material could create a high velocity exhaust jet.
- Interstellar solar sails. A close, high velocity pass near the Sun with a craft that unfurls a reflective sail could eject a payload from the Solar System at high velocity, using only the pressure of sunlight.
- Classical rockets, nuclear pulse, beamed power, interstellar ramjets, and advanced solar sails, though of primary interest, by no means exhaust the known possibilities of starflight propulsion (not to mention the ones yet to be conceived). An interstellar vehicle could accelerate by impulses received from impinging pellet streams beamed from the Solar System; it could increase velocity by traveling down a long linear electromagnetic launcher; or it could be propelled from a rotary momentum storage and transfer device.
- Speculative space propulsion. The sky is not the limit, if we can

find ways to make use of undiscovered "loopholes" in physical law that may allow extremely fast transit between widely separated points in space-time.

- Combinations of many of the above. Often a symbiosis of systems has more interesting properties than any one by itself: for example, boosting an interstellar ramjet to high initial velocity using some form of classical rocket propulsion.

Ad Astra!

Completing this brief introduction to starflight, we remind skeptics that interstellar travel may, indeed, be virtually impossible, *if* their self-defeating assumptions are put in the way. Robert L. Forward, a pioneer inventor in the field of interstellar propulsion, has neatly outlined the artificial roadblocks typically set up by the nay sayers (8):

Stumbling Block 1. A starship must accelerate continuously at one earth gravity. Within a year, such a craft would reach about 0.77 c. (See the relativistic rocket equations in Technical Note 3–3, page 54.) But to continue accelerating at 1.0 gravity dictates greater and greater energy consumption—wasteful by orders of magnitude as the ship gets closer and closer to the speed of light, because the vehicle's mass increases from an effect mandated by relativity.

Stumbling Block 2. Interstellar travel must be performed with round trip times of only a few decades. First, a round trip is not the only kind of useful and interesting interstellar mission. But even if the vehicle must return, performing such a trip to one of the nearer stars over a minimum of *many* decades dramatically cuts the speed and energy requirement.

Stumbling Block 3. An interstellar vehicle must contain its entire reaction mass and energy supply on board. Nonsense! Make use of the abundant reserves of energy and matter in space. Think of beamed power and beamed mass. Consider sunlight and solar sails, and don't forget the interstellar ramjet.

If we at once admit the foolishness of these perennially suggested "impediments" to starflight, we will be well on our way to understanding that interstellar space does not need a bridge too far. Interstellar travel may still be in its infancy, but adulthood is fast approaching, and our descendants will someday see childhood's end.