fraction of a percent of its lifetime, ▽ an unlikely, but not impossible coincidence. △

When, in the comparatively near future, unmanned and then manned expeditions are landed on Mars, the fascinating problem of the nature of its moons will be solved. ▽ If, some hundreds of millions of years ago, a Martian civilization was advanced enough to launch 10-million-ton satellites, then their works on the planet must have been mighty indeed. Are the sands of Mars today drifting over the edifices and monuments of an ancient civilization? If that society were still extant, it seems likely that we should have some sign of it; and if it is now extinct, evidence of its past existence, character, and achievements can likely be garnered by the first Martian exploration teams. △

A partial test of my hypothesis can be made earlier, from the surface of the Earth. Precision photoelectric photometry of Phobos and Deimos obtained over a long period of time can lead to a determination of the shape of the satellites and a characterization of their axial rotation. If it transpires that the satellites have some particular and special shape, this could conceivably provide a serious argument for artificial origin. Neither the observations nor their interpretations are very easy to perform.

Photographs of Phobos and Deimos can be obtained at close range by Mars flyby vehicles, and the data telemetered back to Earth. This is, however, a delicate operation, requiring precise guidance and faultless operation of the automatically-controlled photographic equipment. In particular, the camera would have to be aimed precisely at Phobos and Deimos. However, such technical problems will likely be solved during the next decade.

As soon as it was published, in the form of a newspaper interview, the hypothesis of the artificial origin of the moons of Mars became the subject of wide discussion. The majority of scientists were skeptical, a reaction which of course is completely understandable. However, not one scientific argument was advanced against the hypothesis. An article in the American press by the American astronomer G. M. Clemence, of the U.S. Naval Observatory, stated that the British astronomer G. A. Wilkins, who worked for some time at the Naval Observatory, had obtained results indicating that Sharpless' data were in error. In response to my inquiry, Wilkins indicated that no new results had been obtained concerning the motion of the moons of Mars. Thus, the assertion in the American press was repudiated by Wilkins himself.

▽ Subsequent to the publication of the Russian edition of this book, Dr. Wilkins kindly supplied the following information for this edition:

"So far I have re-reduced practically all of the observations of the satellites of Mars that were made from their discovery up to 1941—i.e., for the period covered by Sharpless' note. . . . The values found for the secular variations of the mean motions were insignificant, but I have not yet fully confirmed this result nor taken into account even those later observations that have been made available to me.

"There is no doubt that visual observations of the positions of these satellites with respect to the centre of the disk of the planet are difficult to make, but I do not have sufficient evidence to be able to state that Sharpless' determination was based on inadequate observations or that the method of treatment was not suitable. I consider that the question of existence of the secular accelerations should be regarded as an open one until a new and more complete analysis of the observations is made; I do not consider that the evidence is sufficiently strong to justify any attempt to look for artificial causes." △

It is possible that Sharpless' results are incorrect. In this case, the hypothesis that Phobos and Deimos have an artificial origin would lose its scientific support. Only when new and very precise observations are carried out will we be able either to disprove or verify Sharpless' results. ▽ A reanalysis of the previous observations, in particular those from 1941 to the present time, could also shed some light on this tantalizing subject. △

Even if future observations indicate that the reported secular acceleration of Phobos is spurious, the hypothesis that the moons of Mars are of artificial origin has nevertheless been provocative, and thereby has served a useful purpose. It reminds us that the activity of a highly developed society of intelligent beings could have cosmic significance and could produce artifacts which would outlive the civilizations that constructed them. This conclusion, as we shall see in the following chapters, has significant implications for the problem of intelligent life in the universe.

27

Radio contact among galactic civilizations

I know perfectly well that at this moment the whole universe is listening to us—and that every word we say echoes to the remotest star.

Jean Giraudoux, *The Madwoman of Chaillot*

In previous chapters, we have presented arguments to support our contention that there are several billion planetary systems in our Galaxy, and that of them about a billion worlds are populated with their own varieties of living organisms. On some of these planets, life may have existed for such a long period of time that there may have evolved intelligent forms which, in turn, may have produced technologically advanced civilizations. The assumption that technical civilizations must *necessarily* make an appearance, even after many billions of years of biological evolution, implies that the ultimate purpose, or goal, in the formation of stars and planets is the production of intelligent beings and technical civilizations, an idealistic and teleological view. We must not forget that the Earth existed for billions of years before highly intelligent life forms and technical civilizations arose.

On the other hand, as we discussed in Chapter 25, the rise of intelligent life in a universe filled with planetary systems seems to be a likely phenomenon. At the present time, since we do not adequately understand the factors leading to the evolution of intelligence and technical civilizations, we cannot reliably estimate the probability that intelligence and technical civilizations will emerge. At one extreme, this probability may be close to one; at the other extreme, the Earth may be the only cradle of intelligence in the Galaxy. We believe—but this is a belief, not a demonstrated fact—that there are a certain number, perhaps even a large number, of planets in the Galaxy which have highly developed technical societies.

▽ We cannot guess what the character of such advanced extraterrestrial civilizations would be. But the laws of physics are universal in character, and the same discoveries that have been made on Earth will be made on planets of other stars, although perhaps not in the same sequence. The ability to generate and receive radio waves has developed on our planet in tandem with the development of electromagnetic theory, in the last quarter of the nineteenth century. An important verification of the electromagnetic theory of the British physicist James Clerk Maxwell was provided by the German physicist Heinrich Hertz, who showed that an oscillating dipole, which is oppositely charged at its two ends, generates electromagnetic waves, including radio waves. Similar discoveries have probably been made countless times on other worlds, during the lifetime of our Galaxy. Advanced technical civilizations have likely developed radio transmission and reception for long-distance communication, as we have.

▽ If familiarity with electromagnetic theory and radio waves is a common patrimony of all technological civilizations in the Galaxy, is it possible to establish radio contact among Galactic civilizations? △ We need not question the great importance of such communication. If we were to succeed in establishing contact with an extraterrestrial civilization, especially one possessing a high degree of scientific development, the impact on our lives, our society, and our philosophical outlook would be incalculable.

▽ The possibility of radio contact with intelligent beings on other planets was clearly held by such pioneers in the development of radio transmission as Marconi and Tesla, each of whom, incidentally, believed they had detected intelligent signals of extraterrestrial origin. Their preliminary reports resulted in a deluge of popular interest and scientific skepticism. This double-pronged attack reduced Tesla and Marconi to silence, and the accounts available today of the signals which these radio pioneers claimed to have detected are fragmentary at best. In 1959, the prospect of interstellar radio contact was revived by the Italian-American physicist Giuseppe Cocconi and the American physicist Philip Morrison, then both at Cornell University. △ They concluded that electromagnetic radiation is the most natural and feasible interstellar communication medium. There are two obvious advantages: the signal is propagated at the highest possible velocity—the velocity of light; and the energy can be concentrated within relatively small areas in the sky without significant scattering into other directions.

Because of absorption and scattering by the interstellar medium and by the atmospheres of the planets involved, the range of potentially useful wavelengths for interstellar communication is restricted. Cocconi and Morrison pointed out that if wavelengths longer than 300 meters (corresponding to a frequency of one megacycle per second = 10^6 cps) were used, the radiation would be absorbed by the interstellar medium. (▽ A frequency of one megacycle per second—1000 kilocycles per second—is the frequency in the middle of the ordinary AM broadcast band. △) Radiation near a frequency of one megacycle per second tends to be absorbed by the charged particles in planetary ionospheres. There is reason to believe that all planets have ionospheres of varying extents, and only radiation of wavelength less than about 10 or 15 meters can pass through such ionospheres and reach the surfaces of the planets. Planetary atmospheres also limit radio propagation at short wavelengths. For example, a planetary atmosphere of the terrestrial type absorbs radiation at wavelengths of about 1 cm or less, because of the presence of water vapor molecules. Thus, allowing for absorption by the interstellar medium and by familiar planetary ionospheres and atmospheres, interstellar radio communication should be restricted to the wavelengths between 3 cm and about 10 or 15 meters. ▽ Ordinary radar operates at wavelengths of 3 cm and longer. △ Of course, if the receiver and transmitter were located above the planetary atmosphere and ionosphere—for example, in an artificial satellite—then the upper limit to the wavelength interval useful for interstellar communication could be as large as several kilometers, and the lower limit could be as small as desired.

The interstellar medium and the planetary atmosphere and ionosphere are not, however, the only factors which limit the range of wavelengths useful for interstellar communication. Of equal importance is the natural "noise level" of the universe.

▽ All the matter in the universe radiates at all wavelengths, including radio wavelengths. Much of the interstellar material is very cold (see Chapter 5), so the intensity which it radiates at radio wavelengths is low. △ But because of the vast distances which must separate planetary civilizations, the power of the received signals will also be extremely weak. The radio radiation from the Galaxy and the metagalaxy will seriously interfere with the detection of weak signals of artificial origin. Cosmic radio radiation has a continuous spectrum, and its intensity (per unit frequency interval) increases towards longer wavelengths. The thermal radio radiation emitted by the molecules in planetary atmospheres would also interfere with interstellar radio contact. Here, the intensity decreases as the wavelength increases. In Figure 27–1, we see how these two types of interference are related

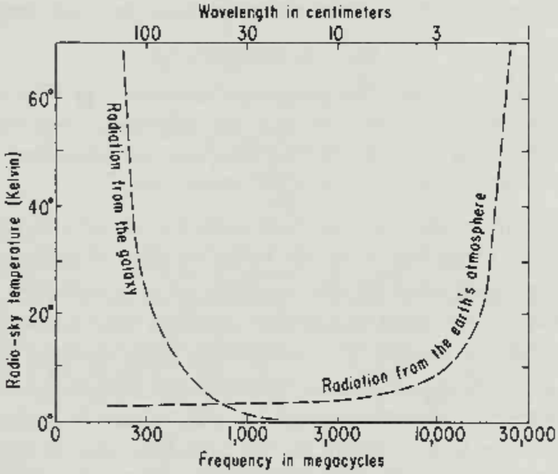

FIGURE 27–1. *Estimated noise levels in the radio frequency spectrum. Shown are two principal sources of background noise; the radio noise of galactic origin which dominates at low frequencies and the radio noise which arises in the Earth's atmosphere, which dominates at high frequencies. The sum of these two curves has a minimum near 2000 megacycles, which corresponds to a wavelength of about 15 cm. (Courtesy of Dr. Frank Drake and* Sky and Telescope.)

to frequency. It is apparent that the lowest level of potential interference occurs in the frequency interval between 10^3 and 10^4 megacycles per second, corresponding to the wavelength interval between 3 cm and 30 cm.

Now let us assume that a given planet somewhere in the Galaxy holds a highly developed technical civilization which wishes to make its presence known. The inhabitants of this planet, which we shall call planet A, decide to send a radio signal in the direction of a suspected planet B, which orbits a distant star and which is suspected to contain a technical civilization. However an immediate difficulty is encountered. The star which planet A orbits is a powerful source of continuous radio emission. ▽ The radio receivers on planet B will be unable to distinguish a signal radiated by planet A from a similar signal radiated from the star about which planet A orbits. △ Thus it appears on first examination that to transmit an artificial radio signal we must have radio transmitters which are at least as powerful as the radio emission of our sun at the same wavelengths if the signal is to be detected by a distant civilization. Actually, the required conditions on the transmitter power are not quite this stringent, as we shall see.

▽ In order to estimate how powerful the planetary emission must be, so it can be detected above the local stellar interference, △ let us assume that the sun of the transmitting civilization radiates at radio frequencies in the same way as does our Sun during a period of low sunspot activity, when it is relatively "quiet." So that we can calculate specific numbers, we will consider a wavelength of 10 cm. At this wavelength, the quiet Sun radiates as if it were a blackbody with a surface temperature of approximately 50,000°K. Using the Rayleigh-Jeans approximation to the blackbody intensity distribution, we can write the intensity of solar radio emission per unit frequency interval as

$$W_{\odot} = 4\pi R_{\odot}^2 (2\pi k T_B / \lambda^2),$$

where the wavelength $\lambda = 10$ cm, the Boltzmann constant $k = 1.38 \times 10^{-16}$ erg$(K°)^{-1}$, the radius of the Sun $R_{\odot} = 7 \times 10^{10}$ cm, and the brightness temperature of the quiet Sun at 10 cm wavelength is $T_B = 50{,}000$°K. Inserting the numerical values, we obtain $W_{\odot} = 2.6 \times 10^{10}$ erg sec^{-1} (cps)$^{-1}$ $= 2.6 \times 10^3$ watts (cps)$^{-1}$.

We must bear in mind that the Sun radiates at all frequencies. The total power emitted by the quiet Sun is of the order of tens of billions of kilowatts. In addition, the Sun radiates isotropically—equally in all directions. By contrast, the artificial signal has a very narrow bandwidth, perhaps only a few thousand, or even a few hundred, cycles per second. If a sufficiently large antenna is used, almost all the power of the artificial signal can be concentrated within the limits of a narrow cone, of angular size approximately equal to λ/D, where D is the diameter of the antenna dish. This cone is determined by the principal lobe of the antenna, shown in Figure 27–2, ▽ a typical diagram of the directivity of a radiotelescope. The figure shows the power output in various directions. Since the straight line is perpendicular to the antenna dish, we see that the bulk of the power emitted or received by a radio antenna—it may do either—is in the direction to which the telescope is pointing.

▽ The gain of a radio antenna, a measure of the directivity, is the ratio of the power transmitted or received in the direction the dish is pointing to the smaller amounts of power received from other directions in the side lobes. △

The antenna gain is given by $G = 4\pi A/\lambda^2$, where A is the effective area of the antenna, a quantity close to its geometric area. If we use an antenna with a diameter of 100 meters (well within the limits of contemporary radio technology), then at 10 cm wavelength, the antenna gain $G \simeq 10^7$. ▽ With the 1000-foot semi-steerable radiotelescope of Cornell University, in Arecibo, Puerto Rico, even larger gains are possible. △

If the total power radiated by the antenna at 10 cm wavelength were equal to that of the Sun, the antenna would radiate ten million times more power in the direction to which the dish is pointed than will the Sun. The power of the transmitter need only be 10^{-4} watts $(\text{cps})^{-1}$ for the signal in the principal lobe to be approximately the same as that of the Sun. Such a highly directional, narrow-band, artificial radio signal would permit us to obtain information from a space vehicle even when it is headed towards the Sun ▽ and must contend with the noise of the solar radio emission. The direct investigation of at least the outer reaches of the solar atmosphere is one objective of space exploration in the next decade. △

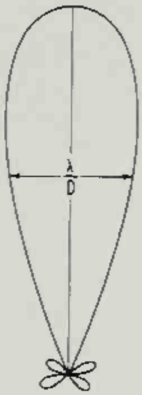

FIGURE 27–2. *A typical diagram of the directivity of a radio antenna, imagined to be at the apex of the rosette. The large lobe is oriented perpendicular to the antenna and indicates that by far the greatest reception of the antenna is in the approximate direction to which it is pointing. The four smaller lobes indicate that some weak reception will be made of signals incident from the sides of the radio telescope. In the principle lobe the radio telescope is capable of an angular resolution of λ/D where λ is the wavelength of the radio frequency observed and D is the aperture of the antenna. Were this same antenna being used for radar transmission rather than passive reception the same directivity diagram would apply.*

Thus, the natural radio emission of the local sun will not necessarily interfere with interstellar communication undertaken by an advanced technical civilization. A far more important source of interfering noise is the background cosmic radio radiation, from which the artificial signal must be discriminated by the receiving civilization.

In radio astronomy, the ability to so discriminate is determined by the so-called antenna temperature, T_A, which is defined as

$$T_A = \left(\frac{\pi^2}{16k}\right) \left(\frac{W}{r^2}\right) \left(\frac{D_1^2 D_2^2}{\lambda^2}\right),$$

where D_1 is the diameter of the receiving antenna, D_2 is the diameter of the transmitting antenna, r is the distance between civilizations, and W is the power per unit bandwidth of the transmitter. Thus, to discriminate the artificial signal from the background, the antenna temperature due to the artificial radio emission must not be less than T_B—here, the brightness temperature of the sky at the same frequency. ▽ From Figure 27–1 we see that the brightness temperature of the sky at 10 cm is about 10°K. △ Thus, the condition for detection of signals is

$$T_A \geq T_B.$$

We should note, however, that in a number of cases the signal can be extracted from the noise even when T_A is less than T_B—for example, when $T_A = 0.1\ T_B$. But for the present we consider only the case that $T_A \geqq T_B$.

Assuming $D_1 = D_2 = 100$ meters, $W = 100$ watts $(\mathrm{cps})^{-1}$, $\lambda = 10$ cm, and $T_A = T_B = 10°\mathrm{K}$, we find that $r \simeq 10^{19}$ cm, or about 10 light years, corresponding to the distance to the nearer stars.

Thus, transmitting and receiving civilizations at the present terrestrial level of technology are capable of radio communication over interstellar distances. This remarkable fact is often very hard for the layman to comprehend. Older generations can remember when transatlantic radio contact was first established. In 1945, a radar signal was bounced off the Moon for the first time. Fourteen years later, in 1959, Venus was located by radar. Radar contact with Venus is a much more difficult problem than radar reflection from the Moon, because the power required for a radar transmitter to make contact with a target must be proportional to the fourth power of the distance to the target. In 1961, a Soviet cosmic rocket was launched in the direction of Venus, and radio contact was maintained up to a certain point in its trajectory.

▽ The United States spacecraft Mariner II sent meaningful signals over 86 million km of interplanetary space on January 3, 1963, with a transmitter operating on three watts of power. Three watts is barely enough to light an electric bulb to incandescence! How can it possibly be adequate for communication over interplanetary distances? The answer is that the transmitted beam is directed and monochromatic. Instead of radiating in all directions, as an electric light bulb does, the antenna of a spacecraft is beamed directly towards the Earth. Instead of radiating over the entire electromagnetic spectrum, as an electric light bulb does, the spacecraft antenna radiates in a narrow frequency range, or bandwidth. In addition, substantial advances in receiver sensitivity have been made in recent years. By pouring all the transmitter power into a very small bandwidth and a very tight beam, and by improving receiver sensitivity, communications over immense distances may be achieved with small power. Spacecraft communications over a distance of several billions of kilometers are now feasible. △

But the radio transmitters of interplanetary space vehicles are necessarily of low weight and therefore of low power. For radio contact over interstellar distances, very large, stationary, groundbased antennas are available. ▽ Figures 27–3, 27–4 and 27–5 show photographs of three of the largest radiotelescopes now in operation. In Figure 27–3, we see the world's largest radio dish, the Arecibo radiotelescope of Cornell University, in Puerto Rico. The diameter of the Arecibo dish is 300 meters. If we were to repeat the calculations we just performed but assume that both transmitting and receiving civilizations were able to use equivalents of the Arecibo dish, interstellar radio communication over a distance of 100 light years would be possible. △

In addition to the increase in the dimensions of radio dishes, there have been

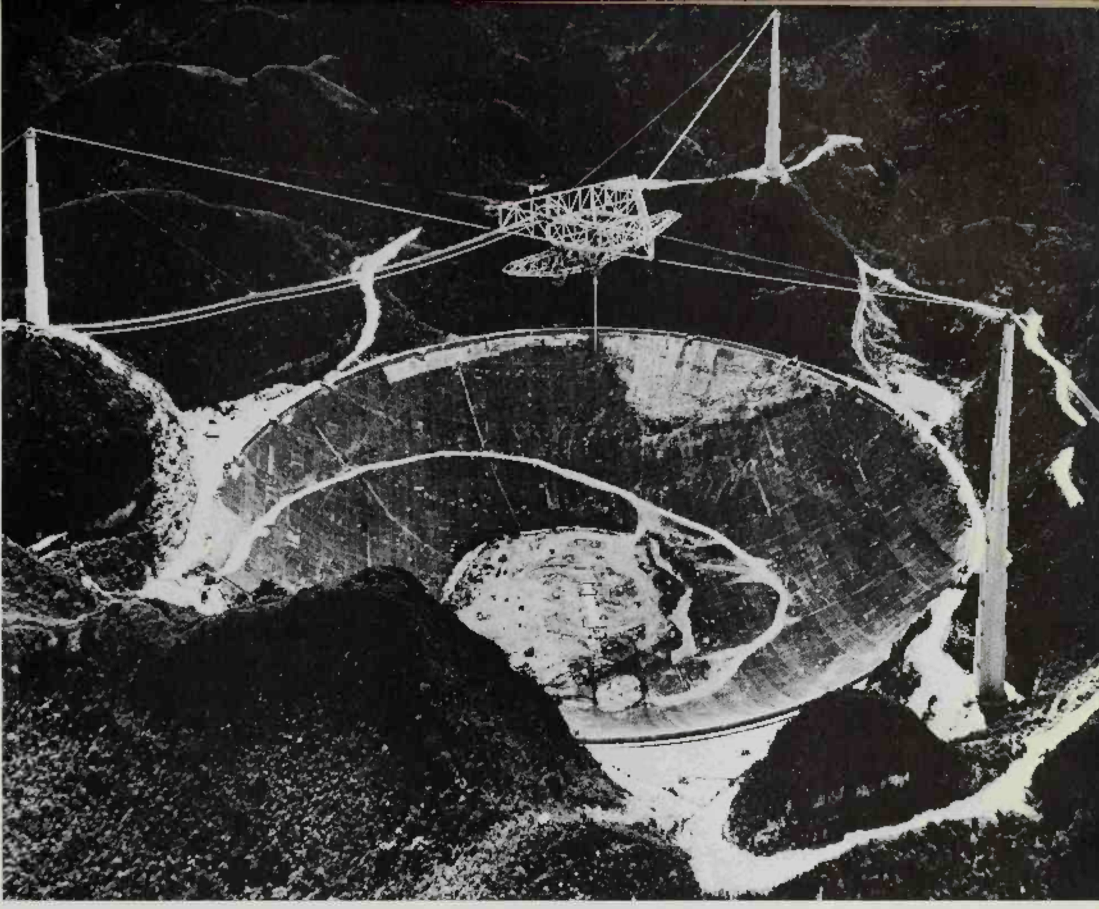

FIGURE 27–3. *The Arecibo Ionospheric Observatory, the world's largest radio telescope now in operation. It has an aperture of 300 meters and is semi-steerable. The cables comprising the antenna itself are layered down into a deep depression smoothed out into an already existing valley in Arecibo, Puerto Rico.*

improvements in recent years in the sensitivity of the receiving apparatus for radiation of centimeter and decimeter wavelengths—that is, between 1 and 100 cm. These refinements have been achieved through the wide application of quantum amplifiers—the so-called masers. Such devices, in conjunction with increased precision in the manufacture of radio dishes, will enable us to detect signals from a point source even when the antenna temperature is significantly less than the brightness temperature of the sky.

Let us consider this problem in more detail. Even if an antenna receives a signal of constant intensity, the output detected by the receiver will not be quite constant. One measurement will differ slightly from the next. These fluctuations can be minimized, but never completely eliminated, because they are inherent in the receiver itself. It is customary, in radio astronomy, to characterize the receiver by T_N, the noise temperature, ▽ proportional to the energy of the noise which originates within the receiver. △ An average value (actually, the root-mean-square value) can then be expressed as

$$\Delta T_N = T_N(\tau\,\Delta f)^{-\frac{1}{2}},$$

FIGURE 27–4. *The 85 foot radio telescope at the National Radio Astronomy Observatory, Greenbank, West Virginia which was used in project Ozma.*

where τ is the integration time during which the recording apparatus at the receiver output accumulates information about the incoming power, and Δf is the receiver bandwidth—that is, the range of frequencies admitted by the receiver.

To detect a weak signal, the antenna temperature, which is dependent on the signal, must not ordinarily be less than the noise fluctuation ΔT_N. Otherwise expressed, $T_A \geqq \Delta T = T(\tau \Delta f)^{-\frac{1}{2}}$. At centimeter wavelengths, the brightness temperature of the sky is approximately 10°K (cf. Figure 27–1). With masers now in use, the receiver noise temperature is 50 to 100°K. Therefore, the level about which the fluctuations occur is primarily determined by the receiver noise, and not by the cosmic background noise. These expressions can be rewritten as

$$r \leq (\pi/4)(W/kT_N)^{\frac{1}{2}}(\tau \Delta f)^{\frac{1}{4}}(D_1 D_2/\lambda),$$

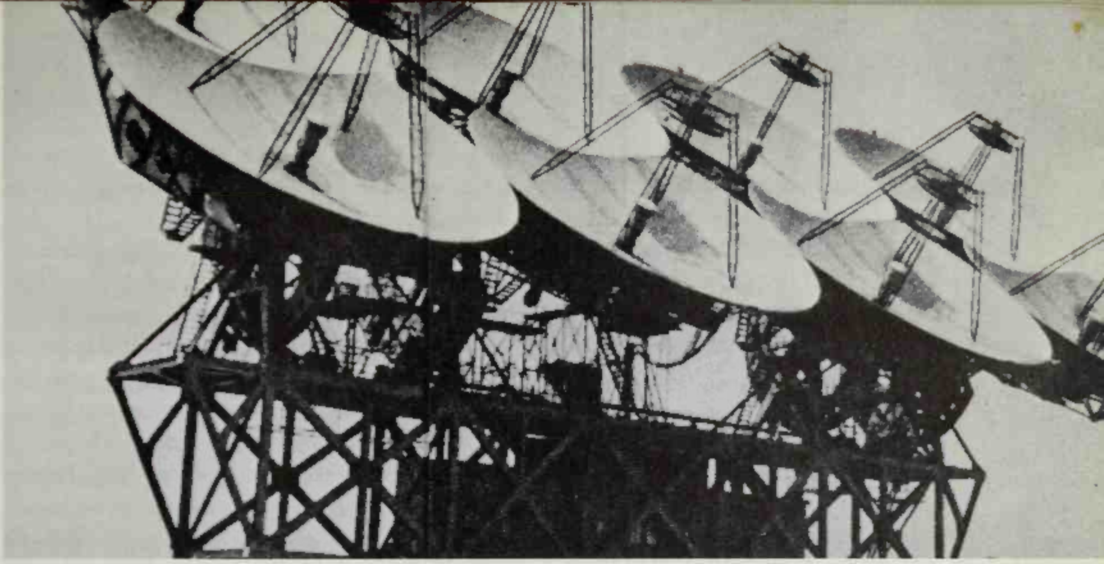

FIGURE 27–5. *An array of eight 22 meter dishes used in the Soviet Union for tracking Soviet space flights. This array is also of great utility for radio astronomy and an instrument like it may have been used in the Russian studies of the radio source CTA 102.*

an expression relating the range of interstellar radio communication to the transmitter power, the dimensions of the transmitting antennas, and the characteristics of the receiver.

▽ Note that in the algebraic expression above, the distance of interstellar communication, r, is proportional to the square root of W, where W is not the total transmitter power, but the transmitter power per unit bandpass—that is, per cycle per second. If the total transmitter power, therefore, is funnelled into a bandpass of 1 cps, interstellar radio contact can be effected over a hundred times greater distance than if the power is spread over a bandpass of 10^4 cps. But then we must pay the price of bandpass compression elsewhere—for example, in a longer integration time. △ For numerical values, let $D_1 = D_2 = 100$ meters, $\tau = 100$ seconds, and $\Delta f = 10^4$ cps.

What, then, must be the power of a transmitter, in order to establish contact over a distance of 10 parsecs, or about 30 light years? This equation indicates that the required power would be about 10 kilowatts ▽ spread over the 10,000 cycles per second, △ a very modest figure in terms of contemporary radio technology. ▽ At 10 cm wavelength, transmitters exist today which deliver 500,000 watts of power with a frequency bandpass of 1 cps. If we imagine transmitting and receiving antennas of the size of the Arecibo dish (300 meters), we find that interstellar radio communication over distances approaching 100 parsecs becomes possible at the present stage of terrestrial radio technology. How might we improve this figure even further? We may increase the power per unit frequency interval of the transmission, decrease the noise temperature of the receiver, increase the apertures of the transmitting and receiving antennas, or decrease the wavelength of the transmission. Because of the small exponent, the communication distance does not depend sensitively on the integration time of the receiver. These parameters cannot, however, be varied independently of one another. They are mutually dependent variables. It does not seem unlikely that civilizations in moderate advance of our own can, in the absence of interstellar absorption, communicate over much greater distances than 100 parsecs—perhaps even over distances comparable to the dimensions of our Galaxy. △

By astronomical standards, the power required is insignificant. For example, the power of the radio emission of the quiet Sun at wavelengths between 10 and 100 cm is approximately 10^9 kilowatts. Yet the emission of even the nearest star at these wavelengths cannot be detected, because stars radiate equally in all directions (isotropically), and over a wide range of wavelengths. On the other hand, an artificial radio signal of this power, transmitted from the nearest star, would be easily detectable, because it would be narrow-beam and monochromatic.

We indicated earlier that the most effective wavelengths for negotiating interstellar radio contact lie between 3 cm and 300 m, ▽ or, when the effects of cosmic radio noise are considered, between 3 and 30 cm. These wavelength intervals are fairly broad. △ It seems almost impossible for the target civilization to detect an interstellar signal, unless the frequency of transmission were known beforehand. ▽ 3 cm wavelength corresponds to 10^{10} cps; 30 cm wavelength corresponds to 10^9 cps. If the bandpass of the transmission is 1 cps, there are nine billion possible transmission frequencies between 3 and 30 cm. If we multiply the number of possible frequencies by the number of possible inhabited planets, we see that even in a Galaxy heavily populated with technical civilizations, the establishment of interstellar radio contact may be an intractable problem.

▽ However, if every civilization which approached the problem could arrive at an identical conclusion on the preferred transmission frequency, interstellar radio contact would be greatly simplified. △ Cocconi and Morrison arrived at the elegant idea that nature itself provides a standard calibrating frequency within this wavelength range—namely, the 21 cm (1420 megacycles per second) radio frequency line of neutral hydrogen [see Chapter 5]. Each advanced civilization must have discovered this line in the spectrum of cosmic radio radiation at an early stage of its technological development. Hydrogen is the most abundant element in the universe, and 1420 Mc sec^{-1} may be considered the fundamental frequency of nature. Radioastronomical observations at this wavelength provide a powerful tool for the investigation of the Galaxy, as we have seen [Chapter 3]. On other worlds as well there must be very sensitive apparatus tuned to this wavelength. Cocconi and Morrison concluded that there is a language of nature comprehensible to technical societies throughout the universe.

▽ No matter how obvious this choice of wavelength is to us, there still remains the question of whether Earthly clarity may be extraterrestrial nonsense. If technology has advanced at a different pace, and discoveries have been made in a different sequence on other worlds, the 21 cm wavelength may not be the preferred interstellar communications channel. Beyond this, there are other reasons to examine alternative frequencies. △ The background radiation of the sky is appreciable at 21 cm wavelength. When contact at distances beyond 3000 light years is attempted—beyond our present capabilities, but within the grasp of a more advanced civilization—the signal would be strongly absorbed by interstellar hydrogen. This would be particularly true if the signal were confined to a small angle within the plane of the Galaxy. Within the Galactic plane, the brightness temperature of the sky at 21 cm wavelength can reach 50 to 100°K. But at shorter wavelengths (see Figure 27–1), it is less than 10°K. ▽ At those shorter wavelengths, there seems to be no natural frequency such as the hydrogen line at 21 cm. △ There is always the possibility that the signal frequency may be a whole multiple of the fundamental hydrogen frequency, for example, ▽ 2840 megacycles per second (10.5 cm wavelength), or 4260 megacycles per second (7 cm wavelength).

▽ There are other possibilities as well. Recently, an interstellar radio frequency line due to the molecular fragment OH has been discovered near 18 cm wavelength. Perhaps the preferred communications channel is 18 cm, or 12 cm, or 6 cm. There must be other radio absorption lines which have not yet been discovered. Still, even if some score of such natural frequencies and their overtones exist, a search for communication at these channels is vastly simpler than the nine billion possible channels of a random search in frequency. △ We may conclude that if intelligent life is widespread in the universe, and civilizations are removed from each other by distances of tens or hundreds of light years, the most probable communication channel is 1420 megacycles per second. (▽ Note, however, that this is for local transmission only; long distance communication—for example, with the dense star clouds of the Galactic center—require other frequencies. △)

The 1420 megacycle per second channel is noisy, as we have said. How do we recognize an artificial signal? ▽ First, we might expect it to have a narrow-band character. △ Second, we would expect the power of such a signal to vary regularly with time; that is, the signal would be modulated. It could consist of a regular sequence of relatively short pulses, one sequence separated from another by distinct time intervals. The number of pulses in each sequence might represent a natural series of numbers—e.g., 1, 2, 4, 8, 16, 32, . . . , etc.—a concept probably common to all technically advanced civilizations. The length of each pulse must not be too short; otherwise, it would be impossible to obtain a long enough integration time, τ, for the reception of the signals. The necessity for a long time period per pulse increases with distances. ▽ We have seen that the communication distance goes as $\tau^{1/4}$; thus, a large increase in τ is required for even a small increase in the communication distance. In our calculation of 100 parsecs as a possible communication distance for civilizations at our state of technical advance, we assumed 100 seconds for the integration time. If we assume 3 hours per pulse instead, leaving the other quantities unchanged, the communication distance increases to about 300 parsecs. △ The length of each pulse may be more than several hours in duration. The signal could contain complex information, but initially it should be quite simple. In Chapter 30, we pursue in more detail the question of the nature of the signals.

After the signal is received, two-way interstellar radio contact could be established, followed by the exchange of information. ▽ Even an exchange of interstellar salutations would take tens or hundreds of years, depending on the separation of the communicants. △ But the immense significance of such an exchange of information would certainly compensate for the somewhat sluggish nature of the conversation.

Even if we are unsuccessful in detecting a regular variation in the power of the signals with time, the artificial character of the signals would soon be revealed by systematic observations. The radial velocity of the transmitter would vary periodically with respect to the receiver, because the transmitting planet is revolving about its star. Because of the Doppler effect, a periodic variation in the frequency of the transmitted signal must occur, ▽ unless it is purposely compensated for by the transmitting civilization. △ Since the orbital velocity of the planet must be several tens of kilometers per second, the amplitude of the periodic variations in frequency may reach hundreds of kilocycles per second, ▽ that is, values much greater than the bandwidth of the transmitted signals. △ The period of such frequency variations could range anywhere from several months to several years, depending on the period of revolution of the transmitting planet about its local sun. Thus, an analysis of an uncompensated signal would immediately yield information about the duration of the year in that distant technical civilization.

We may also expect periodic variation in the transmission frequency due to the rotation of the planet about its axis. Since this velocity is likely to be less than the orbital velocity, frequency variations of rotational origin would probably have an amplitude that is smaller but nevertheless detectable through careful observations. Thus, we could extract from the signal the length of the day on the transmitting planet.

With this information in hand, we could derive many other features of the environment of the transmitting planet. After we identified the star about which the planet is rotating, we could determine the stellar mass from its spectral type; the star would probably be a star of the main sequence [see Chapter 6]. Knowing the period of revolution of the planet, we can find, from Kepler's Third Law, the distance between the planet and the star. Knowing the luminosity of the star, we could then make a rough estimate of the average planetary surface temperature. Knowing the velocity of rotation of the planet about its axis and the length of its day, we could estimate the planetary radius. A more detailed analysis might even allow us to determine the latitude on the planet at which the transmitter is located. Thus, a wide range of interesting physical information could be obtained from systematic observations of the variations in transmission frequency ▽ of an uncompensated signal, even if it were otherwise incomprehensible.

▽ If the Doppler variation of frequency due to planetary rotation and revolution are uncompensated by the transmitting civilization, there are certain attendant difficulties in the reception of the signals. If the receiver bandpass is 1 cps, and yet the frequency variation due to planetary revolution is of the order of 10^5 cps, at any instant there is only one chance in 100,000 that the transmitted signal will be accepted by the receiver. Thus, the receiving civilization, searching the skies with radiotelescopes, may lock onto the transmitting planet, receive no signal, and move on to another star before the transmitted signal fortuitously coincides with the frequency bandpass of the receiver. There are two solutions to this difficulty: First, both transmitting and receiving civilizations may have reasoned as we just have, and utilized only broader bandpasses, comparable to or slightly less than the 100 kilocycle per second frequency broadening due to planetary revolution. Alternatively, the transmitting civilization may exactly compensate for the rotation and revolution of the transmitting planet, and the receiving civilization likewise may compensate for the motions of the receiving planet. This has the advantage that the entire power of the transmitter may be funnelled into a very small bandpass. The communications channel would then be, for example, the exact center of the hydrogen emisson line. The frequency would have to be known to ten significant figures, and even then the relative proper motions of the two stars in question would Doppler shift the frequency off the line center. It remains open to conjecture whether such relative motions could be compensated for in a universe with no absolute standard of rest.

▽ The pace of science is now swift. In earlier times, the suggestion of Cocconi and Morrison would never have been accepted for scientific publication; it would have been considered too speculative by far. Now the temper of the times is different. △ In 1960, the American radioastronomer Frank D. Drake, then at the National Radio Astronomy Observatory in Green Bank, West Virginia, developed a special receiver to detect interstellar radio signals of intelligent origin at 21 cm wavelength. ▽ This enterprise was dubbed Project Ozma, after the queen of the land of Oz, in Frank Baum's series of children's stories. △

Figure 27–6 shows a photograph of Drake's receiver. The receiver has a very stable narrow-band, superheterodyne design, since the desired signal must be narrow-band. At the focus of the 27-meter antenna [Fig. 27–4] there are two horns. Radiation from a small area near the star under investigation, where one might expect to find a transmitting planet, enters one horn. Radiation from a neighboring region of the sky enters the other. Each horn alternately feeds into the receiver, with the aid of an electronic switch. Thus, the radiotelescope alternately looks first at the star, and then at a nearby section of the sky. For this reason, the signal consists of short pulses, periodically interrupted, at a rate equal to the switching frequency between the horns. The synchronous detector at the output of the receiver isolates the variable component of the current derived from the radio signal. Similar schemes, widely used in radioastronomy, are described as modulation. They enable us to separate out the desired signal even when it is much weaker than the noise level of the apparatus. Unfortunately, an extremely weak signal cannot be detected by this method, because of the inherent fluctuations due to the recording apparatus itself. However, in a number of cases at least, the modulation scheme enables us to obtain a sensitivity close to the theoretical maximum sensitivity given by the formula we have already encountered, $\Delta T = T(\tau\,\Delta f)^{-1/2}$.

Four successive conversions of the signal frequency are made. These conversions are required because the expected signal is narrow-banded. Thus, the intermediate frequency of the receiver must be low. As is usual in superheterodyne receivers, the frequency conversion is carried out by mixer stages. The corresponding local oscillators must have very high frequency stability. The frequency must not vary by more than 1 cps in each 100 seconds of operation. Particularly high stability is required of the first local oscillator, since its frequency is very high—1390 megacycles per second.

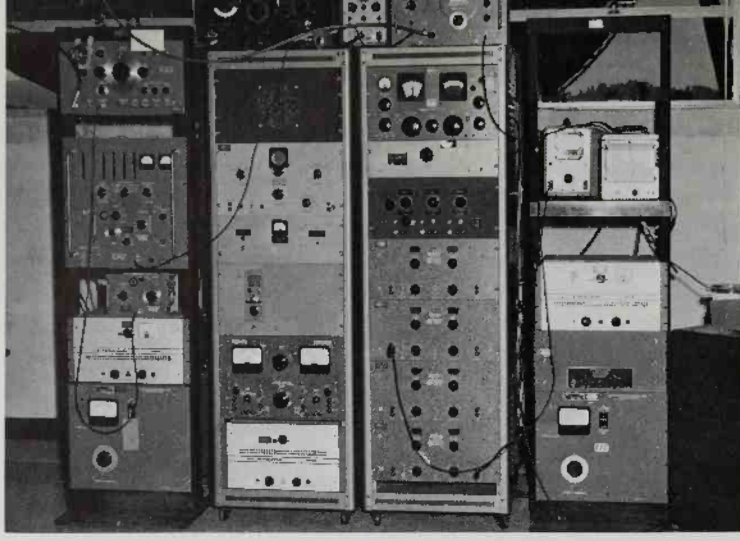

FIGURE 27–6. *The receiving equipment used by Frank Drake at the National Radio Astronomy Observatory for Project Ozma. The 85 foot radio telescope may be seen out the window. The additional equipment not on hand for ordinary radio astronomical studies which Drake required in this investigation cost a few thousand dollars.*

After these four stages of amplification, the signal is divided into two parts, and then passed through electronic filters. One filter is broad-banded; the other is narrow-banded. These filters are arranged in such a way that their output currents are identical when receiving a broad-band signal. If subsequently the two currents are electronically subtracted from each other, a zero output is obtained. However, if an incoming narrow-band signal passes through the filters, the output current of the narrow-band filter will exceed that of the broad-band filter, and the resulting current, after subtraction, will be different from zero. Thus, the receiver is sensitive only to narrow-band signals. The filters precede the synchronous detector, and pass only the switching frequency. A signal will be obtained at the output of the synchronous detector only when a narrow-band signal enters the receiver and the direction of the arriving signal corresponds to the direction of the star under investigation.

Drake chose the nearby stars Epsilon Eridani and Tau Ceti as the first objects of investigation with this receiver and the 27-meter Green Bank antenna. We have previously encountered these stars in Chapter 24, in our discussion of nearby stars likely to have habitable planets. Epsilon Eridani and Tau Ceti are approximately 11 light years distant. The observations of Project Ozma began in the autumn of 1960, and continued for several months. ▽ The results of Project Ozma were described to a meeting of the American Astronomical Society in approximately the following manner by Russian-American astronomer, the late Otto Struve, then Director of the National Radio Astronomy Observatory: "I am reminded," he said, "of a cartoon showing the return to Earth of the first astronaut to land on Mars. 'Tell us,' say the reporters, 'is there any life on Mars?' 'Well,' the astronaut replies, 'there's a little on Saturday night, but it's pretty dull the rest of the week.' "Well, ladies and gentlemen," Struve concluded, "it was pretty dull on Epsilon Eridani and Tau Ceti eleven years ago."

▽ These pioneering investigations were unsuccessful; yet the investment of ancillary equipment was only a few thousand dollars. Only two nearby stars were investigated, and the total time actually spent in observing the stars was about 200 hours. Success of this first venture would have been astounding indeed. △ It is highly probable that the nearest technical civilizations are at much greater distances than 11 light years, as we shall discuss in Chapter 29. If the nearest civilizations are 100 light years away, it would be a much more time-consuming task to determine which of the tens of thousands of stars at that distance might hold an advanced technical civilization. The separate investigation of each such star would be a humdrum and expensive task, ▽ one requiring a long-term commitment for a systematic study. But by any reckoning, the consequences of success would more than balance the pains which went before. △ Only the first tentative steps have been taken so far, on our planet, towards interstellar radio contact. Perhaps we shall soon be able to broadcast our own existence. This would not be immodest. What would happen if all Galactic civilizations worked only on receiving, and not on transmitting interstellar radio signals?

▽ Drake has suggested that it may be possible for us to "eavesdrop" on local planetary radio communications of a distant civilization. The radio signals which a civilization uses for its own purposes have a certain characteristic distribution in frequency. If we point our radiotelescope at such a civilization and scan in frequency, we record the frequencies characteristically utilized by the civilization. Perhaps none of the signals will be detectable individually. But if a second such frequency scan is performed, the two records can be checked for cross-correlation. The frequency distribution of cosmic radio noise will show no such cross-correlation; artificial transmission will. Drake estimates that such cross-correlation techniques can increase the distance over which we may detect radio transmission by a factor of ten—with present equipment, from 300 light years to 3000 light years.

▽ Conversely, our civilization may be detectable over interstellar distances, even though we make no effort to announce our presence. Large-scale radio communication on Earth has been in operation for only some 40 years. We may imagine those earliest radio transmissions—for example, a cadenza sung by Enrico Caruso—traveling forever at the speed of light across interstellar space from the position which the Earth was in some 40 years ago. By now, the signal has propagated some 40 light years into space. If there is an advanced technical civilization within 20 light years of the Sun, they may have received that signal 20 years ago, correctly interpreted it as the result of another technical civilization, and immediately beamed their response to us. We should receive that signal any day now. But if the nearest technical civilization is many hundreds of light years away, we will have to wait a little longer. A relatively nearby civilization in substantial advance of our own may be able to detect some of our domestic radio transmission. There are two general channels which are in heavy commercial use and which are transmitted by the terrestrial ionosphere. One is the entire television band; the other is the high frequency end of the AM broadcast band, between about 1000 and 1400 kilocycles per second, which is occasionally transmitted by the ionosphere. Thus the characteristic signs of life on Earth which may be detectable over interstellar distances include the baleful contents of many American television programs and the mindless outpourings of rock-and-roll stations. It is a sobering thought indeed that the Beverly Hillbillies may be our only interstellar emissaries.

▽ In our discussion up to this point, we have considered only interstellar radio contact among civilizations at or just slightly beyond our present state of technical adance. Yet the bulk of technical civilizations in the universe may be immensely more advanced than ours—perhaps even billions of years beyond. The Soviet astrophysicist N. S. Kardashev, an associate of I. S. Shklovskii at the Sternberg Astronomical Institute, has considered the possibility of the detection of signals from such greatly advanced civilizations. He classifies possible technologically advanced civilizations in three categories: (I) A level of technological advance close to that of the contemporary terrestrial civilization. The rate of energy consumption is about 4×10^{19} ergs sec^{-1}. (II) A civilization capable of utilizing and channeling the entire radiation output of its star. The energy utilization would then be comparable to the luminosity of our Sun, about 4×10^{33} ergs per second. In Chapter 34, we will consider a specific proposal for the harnessing of such power. (III) A civilization with access to the power comparable to the luminosity of an entire galaxy, some 4×10^{44} ergs per second.

▽ Kardashev then examines the possibilities in cosmic communication which attend the investment of most of the available power into communication. A Type II civilization could transmit the contents of 100,000 average-sized books across the Galaxy in a total transmitting time of 100 seconds. It would, of course, take some tens of thousands of years for the signals to make the journey. The transmission of the same information intended for a target 10 million light years distant, a typical intergalactic distance, would take a few weeks' transmission time. A Type III civilization could transmit the same information over a distance of 10 billion light years, approximately the radius of the observable universe, with a transmission time of 3 seconds. The journey would take, of course, 10 billion years. Thus, enormous, almost unbelievable quantities of information can be communicated over immense distances, if such civilizations exist. Signals from one Type II civilization among the nearby galaxies, or one Type III civilization in the observable universe—transmitting appropriately long ago in the past—would stand out as a beacon in the dark, if only we knew how to look.

▽ Kardashev has called attention to two cosmic radio sources with the California Institute of Technology designation numbers CTA 21 and CTA 102. They display small angular diameters and had not been identified with any known source of visible radiation at the time Kardashev was writing. Moreover, the peak emission of CTA 102 seems to be at approximately 30 cm; of CTA 21, at approximately 37 cm. These are not quite at the wavelengths of minimum cosmic noise, nor at what we have concluded are probably the natural communication frequencies. Furthermore, CTA 21 and CTA 102 have bandpasses some thousands of megacycles wide, an apparently extravagant inefficiency. The radio signals of a Type II or a Type III civilization should have small angular diameter, as seen from Earth, and should probably be associated with no known optical object. We expect its wavelength to be between 3 and 30 cm, and probably at some natural and universal radio frequency or an overtone thereof. The frequency considerations, however, have been derived in the interest of economy. A Type II or Type III civilization can probably afford to be extravagant. We must recall that a bandpass of 10^9 cps makes detection immensely easy. The radio emission of CTA 21 and CTA 102 might profitably be examined for possible content.

▽ Following the publication of Kardashev's paper, the Soviet radio astronomer G. B. Sholomitskii of the Sternberg Astronomical Institute undertook a study of the radio source CTA 102 with a large radiotelescope—probably the array of eight 15 meter dishes shown in Figure 27–5. Sholomitskii announced that CTA 102 was varying significantly in intensity with an apparent period of about 100 days. At the time of this announcement in early 1965, speculation on its significance was rife, especially because of the previous interest which had been expressed in this radio source. It was speculated that the oscillation might serve the purpose of a beacon, calling attention to CTA 102, and that on a much shorter time-scale than 100 days individual words of an interstellar communications channel might be deciphered. It was also suggested that the oscillations corresponding to individual words had a time scale of 100 days, implying centuries even to receive the simplest message. In the Soviet press Kardashev was quoted as concluding that CTA 102 was definitely an artificial radio source, but this news report was roundly criticized the following day by Shklovskii in a press conference. Attempts to confirm Sholomitskii's announcement have been equivocal. The Norwegian radio astronomer P. Maltby and the American radio astronomer A. T. Moffet at the Owens Valley Radio Observatory of the California Institute of Technology were unable to find in records of CTA 102 for 1961 and 1962 any sign of a systematic variation in the intensity of this source. More recently, other observers have found no variation. In Figure 27–7, Sholomitskii's observations over a period of many months are displayed.

▽ The great interest in the radio spectrum of CTA 102 has encouraged improved optical studies of this region in the sky. The astronomer J. D. Wyndham of the California Institute of Technology has obtained a photograph of a faint object which is just in the radio position of CTA 102. [Figure 27–8] From its spectrum Wyndham and Sandage have identified CTA 102 as a quasar [see Chapter 9] with a probable distance of some billions of light years from the Earth. Quasars have been known to vary in intensity at optical frequencies with periods comparable to 100 days. Sholomitskii's discovery, if confirmed, will be the first time that a quasar has been observed to oscillate at radio frequencies. The great distance which now seems likely for CTA 102 does not in itself dispose of the possibility of intelligent origin of its radio emission; we might consider it a product of a civilization of Type III. But the argument for the artificial origin of the CTA 102 radio source does seem considerably eroded by its identification as a quasar, despite the fact that we do not fully understand the origin and nature of quasars [see Chapter 9]. △

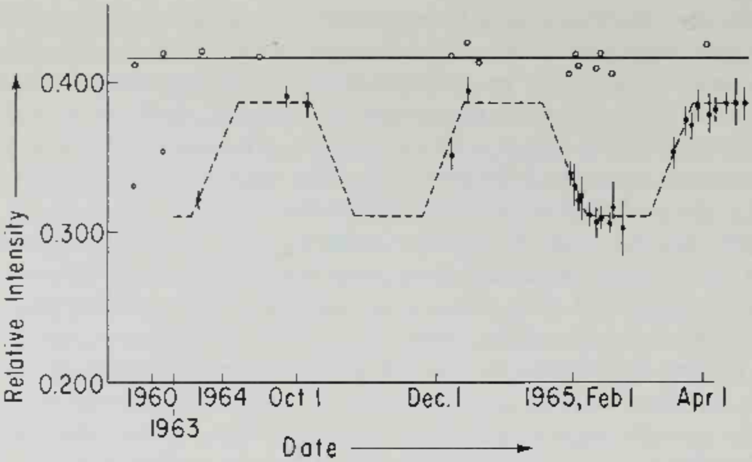

FIGURE 27–7. *A summary of observations of the radio source CTA–102 as measured by G. B. Sholomitskii. The open circles represent the intensity of the radio source CTA–21, relative to the intensity of the radio source 3C–48. The closed circles represent the intensity of CTA–102, relative to the presumably unchanging intensity of 3C–48. We see that over the five year period represented here, CTA–21 has varied its intensity a negligible amount and its emission can be represented by the solid horizontal line. CTA–102, on the other hand, has varied significantly, by far more than the probable error of a single measurement, as indicated by the short vertical slashes. The radio emission from CTA–102 can be represented approximately by the dashed line, suggesting an intensity variation with a period of about 100 days, at a wavelength near 325 cm.*

▽ The most recent observations of CTA 102 have interesting implications. Sholomitskii's observations were performed near the maximum in the emission spectrum of CTA 102; negative searches for variation have been performed in recent years at longer and at shorter wavelengths, but not near Sholomitskii's wavelength of 32.5 cm. From the optical red shift, we can show that the radio emission maximum of CTA 102 has a wavelength near 18 cm *if measured at CTA 102*. This is a wavelength previously proposed for interstellar communication, particularly over intergalactic distances, when the 21 cm line will be noisy (cf. p. 389). In general, we expect Type III civilizations to have their signals significantly shifted to longer wavelengths, because of the expansion of the universe. While it is not yet even likely, the possibility should be borne in mind that CTA 102 has a general radio spectrum designed to call attention to the wavelength of peak emission, at which information is being transmitted. It will be interesting to see, after CTA 21 is observed optically, if it is receding at an even larger velocity than CTA 102—in order to account for its longer wavelength of maximum emission; and if it is varying near 37 cm.

▽ More narrow-band searches for Type I civilizations should be encouraged. Except by the sheerest stroke of fortune, interstellar radio communication will be detected by our just-emerging technical civilization only after a commitment to a long and careful search. But imagine if one day the contents of 100,000 books of a

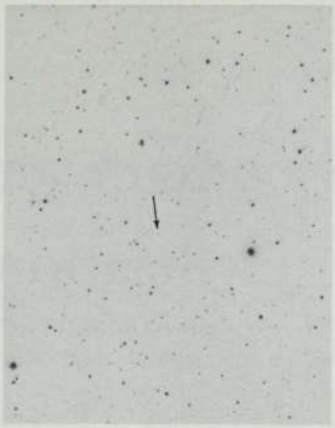

FIGURE 27–8. *A photograph of the star field around the radio source CTA 102, itself indicated by the arrow. (Courtesy of Dr. J. Wyndham, Mount Wilson and Palomar Observatories.)*

Type II civilization suddenly fluttered through the receivers of our radiotelescopes, a kind of Encyclopedia Galactica for children! The rewards of success are inestimable. △

Such pioneering investigations as those of Frank D. Drake are of the greatest potential value to our civilization. As Cocconi and Morrison have quite properly pointed out, the chances for success in such an endeavor are not great; but they are zero, if nothing is attempted.

28

Optical contact among galactic civilizations

Our eye-beams twisted, and did thread
Our eyes upon one double string;
So to intergraft our hands, as yet
Was all the means to make us one;
And pictures in our eyes to get
Was all our propagation.

John Donne, *The Ecstasy* (1633)

The possibility of radio communication among Galactic civilizations, which we discussed in the last chapter, has a number of valuable advantages. A relatively modest transmitter can send signals over distances of some tens of light years. The artificial signal can easily be separated from the thermal radio radiation of the local sun. The excellent frequency resolution of contemporary radio receivers enables us, after detailed study of a signal, to obtain significant information about distant planetary systems and the intelligent beings which may inhabit them. But is the radio band the only frequency range useful for interstellar communication? In this chapter, we discuss the possibility of using much higher frequencies, near the spectral region of visible light, to effect interstellar contacts.

At first glance, it might seem that sending a narrow beam of light from one planet to another would be a simple communications mode. But we soon encounter difficulties in trying to devise a practical light source for interstellar communication. Even the best projectors of the usual type do not send parallel beams of light. The rays are always slightly diverging, and it is impossible to produce a point source of light in focus from such a beam. Although this divergence is relatively unimportant over terrestrial distances, it poses a problem over interplanetary and interstellar distances.

As an example, suppose that the divergence in angle of a cone of radiation beamed by our light source is 30 minutes of arc, corresponding to the tightest beam which can be achieved by ordinary contemporary projectors. Such a beam, transmitted from one point on Earth to another 50 km away, will have a diameter of 450 meters when received. If the power level of the projector is 10 kilowatts, the energy flux at the distance of 50 km would be 5×10^{-6} watts cm^{-2}, a quantity some tens of thousands of times smaller than the solar flux during daytime, but nevertheless a detectable flux at nighttime.

Now imagine that such a projector is used to transmit a light beam to the nighttime hemisphere of the Moon. Since the average distance to the Moon is 380,000 km, the illuminated area on the Moon would be approximately 3,000 km across. The resulting illumination of the Moon would be extremely feeble—about 10^7 times smaller than the illumination of the nighttime hemisphere of the Moon by Earthshine, sunlight reflected from the Earth. ▽ Studies of Earthshine reflected from the dark hemisphere of the Moon have permitted scientists to estimate that on the average the Earth reflects about 40 percent of the sunlight shining on it back to space. But such measurements are extremely difficult to perform. △ Thus, the artificial beam reflected back from the Moon could obviously not be detected. However, the projector would be seen by an observer on the Moon as a star of approximately the third magnitude, even against the bright background of the

Earth, illuminated by the Sun. At a distance of 100 million km—roughly corresponding to the distance to Mars or to Venus—the light from our projector, if raised above the Earth's atmosphere, would be visible through a fairly large telescope as a weak star of the fifteenth magnitude. The beam would have approximately the same magnitude as the moons of Mars, observed from Earth. Of course, the beam would have to be directed precisely at the planets, in order to be observed from them.

Thus, optical projection techniques of the conventional sort would be useless for interstellar contact. Not only could the beam not be detected over such vast distances; in addition, the visible radiation of the Sun in the direction in which the projector is pointing would be vastly more intense than the radiation emitted by the projector itself.

Despite these difficulties, we must not discount optical devices as a possible means of future interstellar contact. Recently, intensive research has been performed on quantum generators and amplifiers of radiation. At radio frequencies, this has led to the development of receivers of ultra-high sensitivity, called *masers.* ▽ "Maser" is an acronym for "microwave amplification by stimulated emission of radiation." △ The same principles, applied to the optical and infrared frequencies, have led to the development of devices called *lasers,* ▽ a parallel acronym for "light amplification by stimulated emission of radiation." △ Of special interest to us here are the lasers, which are generators of intense, narrow beams of visible and infrared radiation.

Many contemporary lasers (as well as masers) utilize synthetic ruby crystals, although other substances have also been used. Under certain conditions, these crystals can be induced to emit relatively short pulsed beams of radiation with a power level approaching 100 kilowatts, or pulses of longer duration with power levels approaching 10 kilowatts. In addition, there are lasers which operate continuously, with appreciably less power, around 2×10^{-2} watts. In this latter case, the reflecting surface of the artificial ruby is approximately 1 cm in diameter. Undoubtedly much larger crystals will be made in the near future. The wave emitted by this laser is in phase over the entire reflecting surface. ▽ In optics, the angular resolution of a telescope of aperture D is approximately λ/D, where λ is the wavelength of the observed light, and the angular resolution is measured in units of radians (2π radians $= 360°$). If the telescope mirror were used to transmit radiation, rather than receive it, the angular size of the transmitted beam would still be about λ/D, provided that the transmitted beam is in phase. Hence, contemporary lasers with a diameter of only 1 cm, operating at a wavelength of 5000 Å $= 5 \times 10^{-5}$ cm, have a beam width of approximately 5×10^{-5} radians. But 1 radian $= 360/2\pi° \times 60$ minutes per degree $\times$ 60 seconds per minute, which is approximately 200,000 seconds. Therefore, laser beams with a beam width of 10 seconds of arc are entirely realistic. △ If such a beam were projected onto the Moon, the illuminated area of the lunar surface would be approximately 20 km across. ▽ Since the power would not be distributed over as large an area as by conventional projection systems, the laser radiation reflected from the dark hemisphere of the Moon could be detected by telescopes on the Earth. Such experiments have, in fact, been performed successfully, both in the United States and in the Soviet Union. △ The angular size of the beam could be made significantly smaller, if the laser were combined with special optical systems.

Consider a lens of high quality, with its diameter equal to its focal length. If such a lens were placed in a beam of light, then the entire image would have a diameter of λ in the focal plane. Let this image coincide with the focal plane of another ideal lens (or mirror) of significantly greater diameter, A, and let the focal length of the larger lens be $\geqq A$. In this case, the beam emerging from the larger mirror would have an angular width, limited by diffraction at its aperture, of λ/A. Although such a system has not yet been developed, it is theoretically feasible. The difficulties in its construction are great, but they are problems of technology, not of science. It would be necessary, for example, to develop a system which would automatically correct the geometry of the large mirror's surface for distortion due to the heat of the high-intensity laser beam.

Another important advantage of the lasers is the extremely pure monochromaticity of the beam. Contemporary lasers, which produce a continuous beam, have frequency bandwidths as small as 10 kilocycles sec^{-1}—more than 10^{10} times smaller than the frequency of the optical radiation. We shall see later that a high degree of monochromaticity is a very valuable property for interstellar communication.

At the present time, great efforts are being made ▽ in both the United States and the Soviet Union △ to develop more powerful lasers. In the United States, the government is spending millions of dollars each year, and more than four hundred firms are working on the problem. This interest is not accidental. Lasers of great power could provide a new type of weapon with extraordinary destructive capabilities. A laser of advanced design would not be dissimilar to the famous "heat ray" of H. G. Wells' *The War of the Worlds*. Such a laser could probably also be a very effective anti-missile weapon. ▽ Similar interests in the possible military potentialities of lasers have been manifested by the Soviet Union. △ Of course, we fervently hope that the vast potential of the laser will be employed only for peaceful purposes. This new technology can be used in a number of fields of practical interest to mankind, but most particularly in cosmic communications.

The first men seriously to consider using the laser for interstellar contact were the American physicists C. H. Townes and R. N. Schwartz of the Massachusetts Institute of Technology. ▽ Townes had previously played a very prominent role in the development of the maser. △ As their basic equipment, Townes and Schwartz suggested two laser systems, neither of which has as yet been developed, but both of which are feasible in principle:

SYSTEM A:

Power level, 10 kilowatts, continuous;

Wavelength, 5000 Å;

Bandwidth, 1 megacycle per second (or, in wavenumbers, 3×10^{-5} cm^{-1});

Diameter of light-collecting area, $D = 500$ cm (maximum size of present telescopes);

Beam width, $\lambda/D = 10^{-7}$ radians, or 2×10^{-2} seconds of arc.

SYSTEM B: A group of 25 lasers, each with the same individual characteristics as in System A, but with an effective system aperture, $A = 10$ cm, and therefore a beam width of 5×10^{-6} radians, or 1 second of arc. The entire group of 25 lasers is to be pointed in the same direction, within the accuracy of the beam width.

If System A were implemented on the surface of the Earth, the beam width, ▽ because of seeing conditions in the Earth's atmosphere, would be restricted to about one second of arc. △ The performance of the laser would be accordingly limited. Therefore, it would be expedient to place such a system in an artificial satellite beyond the atmosphere. System B, however, could work from the surface of the Earth, within the seeing limitations.

Townes and Schwartz formulated two fundamental conditions for detecting extraterrestrial laser signals: (1) the beam must be sufficiently intense to be detected with a practical telescope and in a reasonable time; and (2) the signal must be distinguishable from the background radiation of the local star of the transmitting civilization. At radio frequencies, this second condition is satisfied almost automatically; but in the optical frequency range the separation of an artificial signal from the background radiation of a star constitutes a very difficult problem.

Let us assume that a signal is sent by means of System A, operating from just outside the Earth's atmosphere. Let the distance, r, from the receiving planet to the Earth be 10 light years, or 10^{19} cm. Then the flux of radiation being beamed from the vicinity of the Earth will be $F = W/r^2\ \Omega$ watts cm^{-2}, where W is the transmitter power, and Ω is the solid angle of the beam. Substituting $W = 10$ kW and $\Omega = 10^{-14}$ radians^2, we find $F = 10^{-20}$ watts cm^{-2}. We may compare this figure with the flux due to the sun at a distance of 10 light years. ▽ The luminosity of the sun is 4×10^{33} ergs/sec or 4×10^{26} watts. The sun does not radiate in a tight beam as does the laser, but radiates into a solid angle Ω of 4π radians^2. Using the same equation for the flux that we just used in the laser application we find that the solar flux at a distance of ten light years is 3×10^{-13} watts cm^{-2}. △ Knowing the ratio of the flux from the laser to the flux from the Sun, it is easy to calculate the apparent stellar magnitude of the laser as seen from any distance. △ Corresponding to any flux, F, there is an apparent stellar magnitude, m; the relation between them has been touched upon in Chapter 3. △ The well-known astronomical equation which relates them is

$$m_1 - m_2 = 2.5 \log (F_2/F_1)$$

▽ The difference in apparent magnitude between the Sun and the laser beam as seen from a distance of 10 light years is therefore $2.5 \log (3 \times 10^{-13}/10^{-20}) = 18.7$ magnitudes. At a distance of 10 light years the sun has an apparent magnitude of about 2.2 magnitudes. △ Therefore the apparent magnitude of the laser at the same distance is about $m_1 = 21$. ▽ This is the approximate apparent magnitude of the faintest visible stars observable with the 200-inch telescope at Mt. Palomar Observatory, in California.

△ Thus, if a large telescope were used at a distance of 10 light years, such a laser beam could be detected. However, in order to insure detection, it would be advisable that the power of the transmitter be increased several tens of times above the power level proposed by Townes and Schwartz.

The radiation flux from System B would be 100 times less than from System A, ▽ corresponding to an apparent magnitude of about 26 at a distance of 10 light years. △ Therefore, System B does not seem suitable for interstellar communications ▽ among civilizations at the level of technological advance assumed in this discussion. △

How would it be possible to separate the signal of the laser (with flux $\sim 10^{-20}$ watts cm^{-2}) from the signal of the Sun (flux $\sim 3 \times 10^{-13}$ watts cm^{-2})? Such discrimination can be achieved only by exploiting the high degree of monochromaticity of the laser radiation. Let us consider a star which has a maximum radiation output near 5000 Å—such as our Sun. Then the radiation intensity per unit frequency interval and per unit solid angle will be 4×10^{10} watts $(c.p.s.)^{-1}$ sterradians.$^{-1}$ ▽ (A steradian can be considered a square radian.) △ The radiation from the laser will exhibit an intensity which is equal to the radiation flux divided by the solid angle of the beam and by the laser bandwidth. **Thus:**

$$\frac{10^4 \text{ watts}}{10^{-14} \text{ ster} \times 10^6 \text{ c.p.s.}} = 10^{12} \text{ watts (c.p.s.)}^{-1} \text{ ster}^{-1}.$$

Because the laser has all its radiation concentrated in a very narrow frequency band one megacycle wide, its spectral intensity is 25 times that of the Sun, ▽ despite the vastly greater flux from the Sun over all visible wavelengths. △ If the laser operated at ultraviolet or infrared frequencies, its spectral intensity would exceed that of the Sun, since the spectral intensity of the Sun will be less there than near 5000 Å. The spectral intensity of the Sun at wavelengths greater than 15,000 Å or less than 2500 Å is more than 10 times less than at 5000 Å; at wavelengths greater than 40,000 Å or less than 2000 Å, it is hundreds of times less than at 5000 Å.

In addition, we may recall that there are many Fraunhofer absorption lines in the solar spectrum. These lines have frequency bandwidths significantly greater than the bandwidth of the laser. At the frequencies of these lines, the spectral intensity of the Sun is decreased by several orders of magnitude, ▽ and, as Townes and Schwartz have emphasized, the detectability of the laser signal will be even further enhanced. △

The Earth's atmosphere completely absorbs ultraviolet radiation of wavelength less than 2900 Å, and a significant fraction of the infrared radiation. If a laser operating near 1500 Å could be sent aloft in a satellite above the atmosphere of the Earth, it could attain a spectral intensity some tens of thousands of times greater than that of the Sun. However, we must bear in mind the great technical difficulties which must be overcome, to produce an operational system at these wavelengths. Not only would such a laser be very difficult to construct; but also the reflectivity of the mirrors—the system needs mirrors—abruptly declines towards ultraviolet wavelengths. If we used a laser operating in the infrared part of the spectrum, we would also run into difficulties, but of a different nature: the beam produced by the laser has an angular width of λ/D. Thus, at longer wavelengths, the divergence of the beam would increase. With these limitations in mind, it appears that the most suitable laser for interstellar communications ▽ (at least for the near future for terrestrial technology) △ would operate at visible frequencies in the middle of a strong absorption line in the solar spectrum—for example, at the well-known H and K lines due to ionized calcium. The spectral intensity of the laser we have described, with a frequency bandwidth of one megacycle sec^{-1}, would then be some 300 times greater than that of the Sun.

If such a laser were directed towards the Earth from a distance of 10 light years, and the beam were observed through a very narrow band filter, the radiation emitted by the laser could be discerned from the background radiation of the star. In other words, if a good spectrum of the star could be obtained, then the very narrow lines due to the laser could also be detected. However, it is technically difficult to construct good narrow band filters. Moreover, the resolving power of the spectrograph is a limiting factor.

What resolving power must a spectrograph have, in order to discriminate a line of artificial radiation from the background radiation of the star? Ideally, to be detected, the intensity of the line would have to be only 10 percent greater than the continuous spectrum. Unfortunately, even an intrinsically very narrow spectral line seems to be spread over neighboring frequencies by the limited resolving power of the spectrograph. The intensity of the line, per unit frequency interval, is thereby reduced. If, for example, the resolving power of the spectrograph were 1 Å (in frequency units, about 10^{11} c.p.s.) then the intensity of a very narrow laser line spread over this frequency interval would be 300 times less than the intensities at neighboring frequencies of the stellar spectrum. Thus, to obtain a 10 percent contrast of the laser line over the stellar background with the laser systems we have been discussing, the resolving power of the spectrograph must be 0.03 Å. This resolving power is extremely high but can be obtained by using high precision spectrographs and interferometric techniques. Thus, for the systems we have been describing, it would be possible to detect a weak spectral line of artificial origin in the spectra of the nearest stars, by using the largest existing telescopes. If, however, the power of the transmitter were increased by a multiple of 10, the detection of such a line would not be extremely difficult, even for telescopes of moderate dimensions, provided good spectrographs were used.

There is yet another obstacle to overcome in making such observations: due, for example, to the rotation of the transmitting planet, or the revolution of a transmitting satellite about its planet, there will be continuous changes in the velocity of the artificial radiation source, a velocity change which, through the Doppler effect, will induce a frequency variation in the signal. In order to detect the laser beam, its frequency must not vary during the time when the spectrum of the star is photographed—say, about an hour—beyond the frequency limits defined by the resolving power of the spectrograph. ▽ But as in the case of radio frequency communication over interstellar distances, the transmitting civilization may be able to compensate for the motion of the source. △

To summarize, in order for an artificial laser signal to be distinguishable from the natural radiation background, the following characteristics are necessary: First, the emitted intensity must be confined to an exceedingly narrow frequency bandpass. Second, it must in some respect be distinct from any known ▽ stellar emission △ lines. Finally, if it is to be used for the transmission of information, as a kind of light telegraph, the intensity in the spectral line must vary with time.

As soon as the presence of an artificial line is detected in the spectrum of a star, it can be recorded in detail through the use of photoelectric techniques which permit us to increase the integration time of a signal (analogous to a time exposure in photographic observations) up to several minutes. This is desirable for deciphering a ▽ slowly △ modulated light signal. All of our discussion on the detection of optical signals of artificial extraterrestrial origin has assumed that the very narrow cones, or beams, of light are aimed precisely at the Earth. Since the assumed beam width of the laser—10^{-7} radians, or 0.02 seconds of arc—is very small, the pointing accuracy of the signal must be maintained to within 10^{-7} radians. This degree of accuracy is barely within the limits of contemporary terrestrial astronomical technology.

If our solar system is viewed from a hypothetical planet surrounding one of the nearest stars, the angular diameter of the Earth's orbit is approximately one second of arc. For the laser systems we have discussed, the width of the beam transmitted by the extraterrestrial civilization will be about 10 million km across by the time it reaches the solar system. This is one-fifteenth of the distance between the Earth and the Sun. Since the extraterrestrial civilization will presumably not know beforehand where our planet is located, the laser beam will have to be moved about within the speculated limits of our solar system, in order to find the Earth. For this reason, the Earth will be exposed to the laser beam only occasionally, and the possibility of detection of this beam will be accordingly decreased. I believe that this is a very important consideration which Townes and Schwartz failed to take into account. It might decrease significantly the value of lasers for interstellar communication. ▽ However, Professor Townes has since suggested that the beaming civilization might be able to determine the position of habitable planets in the target solar system. △

The difficulty can also be circumvented by assuming that the width of the beam is several times greater than the distance between the Earth and the Sun. For the laser system we have previously discussed, and for stars tens of light years distant, the power of the laser beam would have to be increased by several thousand times. This increased power requirement does not, however, constitute a decisive argument against the possible use of lasers for interstellar communications. In fact, we are convinced that lasers, after optimal improvement, will be entirely suitable for interstellar contact, ▽ at least over the distances discussed to this point. △ As we mentioned previously, there is good reason to believe that laser power levels will be greatly increased within the next few decades, because for lasers to be of substantial military significance their power levels must be increased to millions of kilowatts.

▽ With a power level of millions of kilowatts, a laser beam which fills the entire inner solar system of the target star would be useful for interstellar contact over hundreds of light years. If the light-gathering devices of the receiving civilization involve collecting areas more than 200 inches (500 cm) in diameter, communications over much greater distances are possible. Note that the collecting area need not have the fine optical properties of the mirrors of reflecting telescopes. We are interested not in forming a point image of the transmitting star —only in obtaining a high-resolution spectrum of the transmitting laser beam. For this purpose, we could use a large, perhaps faceted, "light bucket," composed not necessarily of glass, but rather of metals or plastic materials, and much more easily constructed than a conventional reflecting telescope of comparable dimensions. When such substantial improvements become possible, it may be that the limiting factor in the range of interstellar communication at optical frequencies will be absorption by the interstellar medium, a limitation particularly relevant for any attempt to communicate with civilizations in the direction of the Galactic center. △

At the present stage of terrestrial technology, radio wavelengths—for example, near 21 cm—are more economical means of interstellar communication than optical wavelengths. However, our criteria of economy may not be the same as those of other planetary civilizations. ▽ Townes and Schwartz point out that in the evolution of terrestrial technology, the development of the laser might well have antedated the development of radiotelescopes. △ We are basing the technical and economic possibilities of interstellar communication on contemporary conditions, but these conditions may change.

▽ While discussing optical frequency interstellar contact, we should mention independent suggestions by Drake and Shklovskii that, if not the communication of large amounts of information, at least the communication of the presence of a technical civilization, can be effected through the use of *markers*. Drake and Shklovskii envision the dumping of a short-lived isotope—one which would not be ordinarily expected in the local stellar spectrum—into the atmosphere of the star. In any case, the material of the marker should be of a type that is difficult to explain, except as a result of intelligent activity. Drake considers an atom with a strong, resonant absorption line, which may scatter about 10^8 photons sec^{-1} in the stellar radiation field. A photon at optical frequencies has an energy of about 10^{-12} ergs, so each atom will scatter about 10^{-4} erg sec^{-1} in the resonance line. A typical line width might be about 1 Å, and we assume that a 10 percent absorption will be detectable. We must then scatter about

$$\frac{1\ \text{Å}}{5000\ \text{Å}} \times 10^{-1} = 2 \times 10^{-5}$$

of the total solar flux. The solar flux is 4×10^{33} erg sec^{-1}, so for the line to be detected, it must scatter about 8×10^{28} erg sec^{-1}. Thus, we need $(8 \times 10^{28})/10^{-4} = 8 \times 10^{32}$ atoms. The weight of a hydrogen atom is 1.66×10^{-24}

gm; the weight of an atom of atomic weight μ is $1.66 \times 10^{-24} \times \mu$ grams. Thus, if the atom has an atomic weight of 10, we must distribute some 10^{10} grams, or 10^4 tons of it into the stellar spectrum. If the atom has an atomic weight of 100, we must inject 100,000 tons. If a one percent absorption were detectable, 1,000 tons would be adequate for an atom of atomic weight 10. The injection of 1,000 tons of material into the Sun does not seem vastly beyond contemporary rocket technology.

▽ Remarkably enough, the spectral lines of one short-lived isotope, technetium, have in fact been found in stellar spectra. Its half-life is around 2×10^5 years. However, technetium lines have not been found in stars of solar spectral type, but rather only in peculiar stars known as *S* stars. In fact, as we saw in Chapter 8, the discovery of technetium in the *S* stars has been used as an argument for contemporary stellar nucleosynthesis. This example illustrates one of the difficulties with such a marker announcement of the presence of a technical civilization. We must know a great deal more than we do about both normal and peculiar stellar spectra before we can reasonably conclude that the presence of an unusual atom in a stellar spectrum is a sign of extraterrestrial intelligence. △

To conclude this chapter, let us consider the possibility of optical contact between planets within our own solar system. If the laser system we have described in this chapter as System A were directed at Mars during its closest approach to the Earth, when it is some 50 million km distant, the diameter of the laser beam on the Martian surface would be between 5 and 7 km. To the Martian observer, the laser flash would appear as a bright star of magnitude -7, that is, approximately 10 times brighter than Venus appears in the sky of the Earth. Such a bright light source could be modulated to transmit any type of information to a small region of Mars. Such a beam, directed at the unilluminated hemisphere of the Moon, would produce a spot with a diameter of only 40 meters, and the illumination would be only 100 times less than that of direct solar radiation. Thus, we see that the prospects for laser communication within the confines of the solar system are very favorable.

29

Distribution of technical civilizations in the galaxy

Far and few, far and few,
    Are the lands where the Jumblies live:
Their heads are green, and their hands are blue;
    And they went to sea in a sieve.

    Edward Lear, *The Jumblies*

▽ In the last two chapters, we have seen that the prospects for interstellar communication over distances of some tens of light years seem reasonable; over hundreds of light years, more difficult; and over thousands of light years, only possibly by civilizations in substantial advance of our own. If it seemed likely that technical civilizations existed on planets only 10 or 20 light years away, or civilizations greatly in advance of our own, at larger distances, a serious effort to establish contact might be justified. On the other hand, if we can only reasonably expect civilizations at about our level of technical advance thousands of light years away, attempts at communication would not seem profitable, at least at the present time. In the present chapter, we shall make some effort to compute the number of extant technical civilizations in the Galaxy, which will permit us to estimate the average distances between civilizations. To perform such estimates, we must select numerical values for quantities which are extremely poorly known, such as the average lifetime of a technical civilization. The reliability of our answers will reflect this uncertainty. △ The analysis will have an exclusively probabilistic character, ▽ and the reader is invited to make his own estimate of the numerical values involved, and to draw his own conclusions on the numbers of advanced technical civilizations in the Galaxy. △ However, these analyses are of undoubted methodological interest and illustrate very well the potentialities and limitations of this type of investigation.

▽ We shall be concerned with two general approaches: first, a simple discussion due essentially to Frank Drake, and then a more elaborate treatment due to the German astronomer Sebastian von Hoerner, when he was working at the National Radio Astronomy Observatory, Green Bank, West Virginia.

▽ We desire to compute the number of extant Galactic communities which have attained a technical capability substantially in advance of our own. At the present rate of technological progress, we might picture this capability as several hundred years or more beyond our own stage of development. A simple method of computing this number, N, was discussed extensively at a conference on intelligent extraterrestrial life, held at the National Radio Astronomy Observatory in November, 1961, and sponsored by the Space Science Board of the National Academy of Sciences. Attending this meeting were D. W. Atchley, Melvin Calvin, Giuseppe Cocconi, Frank Drake, Su-Shu Huang, John C. Lilley, Philip M. Morrison, Bernard M. Oliver, J. P. T. Pearman, Carl Sagan, and Otto Struve. While the details differ in several respects, the following discussion is in substantial agreement with the conclusions of the conference.

▽ The number of extant advanced technical civilizations possessing both the interest and the capability for interstellar communication can be expressed as

$$N = R_* f_p n_e f_l f_i f_c L$$

R_* is the mean rate of star formation, averaged over the lifetime of the Galaxy; f_p is the fraction of stars with planetary systems; n_e is the mean number of planets in each planetary system with environments favorable for the origin of life; f_l is the fraction of such favorable planets on which life does develop; f_i is the fraction of such inhabited planets on which intelligent life with manipulative abilities arises during the lifetime of the local sun; f_c is the fraction of planets populated by intelligent beings on which an advanced technical civilization in the sense previously defined arises, during the lifetime of the local sun; and L is the lifetime of the technical civilization. We now proceed to discuss each parameter in turn.

▽ Since stars of solar mass or less have lifetimes on the main sequence comparable to the age of the Galaxy, it is not the present rate of star formation, but the mean rate of star formation during the age of the Galaxy which concerns us here. The number of known stars in the Galaxy is $\sim 10^{11}$, most of which have masses equal to or less than that of the Sun. The age of the Galaxy is $\sim 10^{10}$ years. Consequently, a first estimate for the mean rate of star formation would be ~ 10 stars yr^{-1}. The present rate of star formation is at least an order of magnitude less than this figure, and according to the Dutch-American astronomer Maarten Schmidt, of Mt. Wilson and Palomar Observatories, the rate of star formation in early Galactic history is possibly several orders of magnitude greater. According to present views of element synthesis in stars, discussed in Chapter 8, those stars and planets formed in the early history of the Galaxy must have been extremely poor in heavy elements. Technical civilizations developed on such ancient planets would of necessity be extremely different from our own. But in the flurry of early star formation, when the Galaxy was young, heavy elements must have been generated rapidly, and later generations of stars and planets would have had adequate endowments of the heavy elements. These very early systems should be subtracted, from our estimate of R_*. On the other hand, there are probably vast numbers of undetected low-mass stars whose inclusion will tend to increase our estimate of R_*. For present purposes, we adopt $R_* \sim 10$ stars yr^{-1}.

▽ From the frequencies of dark companions of nearby stars, from the argument on stellar rotation, and from contemporary theories of the origin of the solar system [see Chapters 11–13], we have seen that planets seem to be a very common, if not invariable, accompaniment to main sequence stars. We therefore adopt $f_p \sim 1$.

▽ In Chapter 11, we saw that even many multiple star systems may have planets in sufficiently stable orbits for the origin and development of life. In our own solar system, the number of planets which are favorably situated for the origin of life at some time or another is at least one, probably two, and possibly three or more [see Chapters 16, 19, 20, and 23]. We expect main sequence stars of approximately solar spectral type—say, between F2 and K5—to have a similar distribution of planets, and for such stars, we adopt $n_e \sim 1$. However, the bulk of the main sequence stars—well over 60 percent—are M stars; as we mentioned in

Chapter 24, if the planets of these suns are distributed with just the same spacings as the planets of our Sun, even the innermost will be too far from its local sun to be heated directly to temperatures which we would consider clement for the origin and evolution of life. However, it is entirely possible that such lower-luminosity stars were less able to clear their inner solar systems of nebular material from which the planets were formed early in their history. Further, the greenhouse effect in Jovian-type planets of M stars should produce quite reasonable temperatures. We therefore tentatively adopt for main sequence stars in general $n_e \sim 1$.

▽ In Chapters 14–17, we discussed the most recent work on the origin of life on Earth, which suggests that life arose very rapidly during the early history of the Earth. We discussed the hypothesis that the production of self-replicating molecular systems is a forced process which is bound to occur because of the physics and chemistry of primitive planetary environments. Such self-replicating systems, with some minimal control of their environments and situated in a medium filled with replication precursors, satisfy all the requirements for natural selection and biological evolution. Given sufficient time and an environment which is not entirely static, the evolution of complex organisms is, in this view, inevitable. The finding of even relatively simple life forms on Mars or other planets within our solar system would tend to confirm this hypothesis. In our own solar system, the origin of life has occurred at least once, and possibly two or more times. We adopt $f_l \sim 1$.

▽ The question of the evolution of intelligence is a difficult one. This is not a field which lends itself to laboratory experimentation, and the number of intelligent species available for study on Earth is limited. In Chapter 25, we alluded to some of the difficulties of this problem. Our technical civilization has been present for only a few billionths of geological time; yet it has arrived about midway in the lifetime of our Sun on the main sequence. The evolution of intelligence and manipulative abilities has resulted from the product of a large number of individually unlikely events. On the other hand, the adaptive value of intelligence and of manipulative ability is so great—at least until technical civilizations are developed—that if it is genetically feasible, natural selection seems likely to bring it forth.

▽ The American physiologist John C. Lilley, of the Communication Research Institute, Coral Gables, Florida, has argued that the dolphins and other cetacea have surprisingly high levels of intelligence. Their brains are almost as large as those of human beings. These brains are as convoluted as our brains, and their neural anatomy is remarkably similar to that of the primates, although the most recent common ancestor of the two groups lived more than 100 million years ago. Dolphins are capable of making a large number of sounds of great complexity, which are almost certainly used for communication with other dolphins. The most recent evidence suggests that they are capable of counting, and can mimic human speech. Large numbers of anecdotes supposedly illustrating great intelligence in the dolphins have been recorded, from the time of Pliny to the present. The detailed study of dolphin behavior and serious attempts to communicate with them are just beginning and hold out the possibility that some day we will be able to communicate, at least at a low level, with another intelligent species on our planet. Dolphins have very limited manipulative abilities, and despite their apparent level of intelligence, could not have developed a technical civilization. But their intelligence and communicativeness strongly suggest that these traits are not limited to the human species. With the expectation that the Earth is not unique as the abode of creatures with intelligence and manipulative abilities, but also allowing for the fact that apparently only one such species has developed so far in its history, and this only recently, we adopt $f_i \sim 10^{-1}$.

▽ The present technical civilization of the planet Earth can be traced from Mesopotamia to Southeastern Europe, to Western and Central Europe, and then to Eastern Europe and North America. Suppose that somewhere along the tortuous path of cultural history, an event had differed. Suppose Charles Martel had not stopped the Moors at Tours in 732 A.D. Suppose Ogdai had not died at Karakorum at the moment that Subutai's Mongol armies were entering Hungary and Austria, and that the Mongol invasion had swept through the non-forested regions of western Europe. Suppose the classical writings of Greek and Roman antiquity had not been preserved through the Middle Ages in African mosques and Irish monasteries. There are a thousand "supposes." Would Chinese civilization have developed a technical civilization if entirely insulated from the West? Would Aztec civilization have developed a technical phase had there been no *conquistadores?* Recorded history, even in mythological guise, covers less than 10^{-2} of the period in which the Earth has been inhabited by hominids, and less than about 10^{-5} of geological time. The same considerations are involved here as in the determination of f_i. The development of a technical civilization has high survival value at least up to a point; but in any given case, it depends on the concatenation of many improbable events, and it has occurred only recently in terrestrial history. It is unlikely that the Earth is very extraordinary in possessing a technical civilization, among planets already inhabited by intelligent beings. As before, over stellar evolutionary timescales, we adopt $f_c \sim 10^{-1}$.

▽ The multiplication of the preceding factors gives $N = 10 \times 1 \times 1 \times 1 \times 10^{-1} \times 10^{-1} \times L = 10^{-1} \times L$. L is the mean lifetime in years of a technical civilization possessing both the interest and the capability for interstellar communication. For the evaluation of L there is—fortunately for us, but unfortunately for the discussion—not even one known terrestrial example. The present technical civilization on Earth has reached the communicative phase (in the sense of high-gain directional antennas for the reception of extraterrestrial radio signals) only within the last few years. There is a sober possibility that L for Earth will be measured in decades. On the other hand, it is possible that international political differences will be permanently settled, and that L may be measured in geological time. It is conceivable that on other worlds, the resolution of national conflicts and the establishment of planetary governments are accomplished before weapons of mass destruction become available. We can imagine two extreme alternatives for the evaluation of L: (a) a technical civilization destroys itself soon after reaching the communicative phase (L less than 10^2 years); or (b) a technical civilization learns to live with itself soon after reaching the communicative phase. If it survives more than 10^2 years, it will be unlikely to destroy itself afterwards. In the latter case, its lifetime may be measured on a stellar evolutionary timescale (L much greater than 10^8 years). Such a society will exercise self-selection on its members. The slow, otherwise inexorable genetic changes which might in one of many ways make the individuals unsuited for a technical civilization could be controlled. The technology of such a society will certainly be adequate to cope with geological changes, although its origin is sensitively dependent on geology. Even the evolution of the local sun through the red giant and white dwarf evolutionary stages may not pose insuperable problems for the survival of an extremely advanced community.

▽ It seems improbable that surrounded by large numbers of flourishing and diverse galactic communities, a given advanced planetary civilization will retreat from the communicative phase. This is one reason that L itself depends on N. Von Hoerner has suggested another reason: He feels that the means of avoiding self-destruction will be among the primary contents of initial interstellar communications. If N is large, the values of f_l, f_i, and f_c may also be larger as a result. In Chapter 15, we mentioned the possibility of the conscious introduction of life into an otherwise sterile planet by interstellar space travelers. In Chapter 33, below, we shall discuss the possibility that such interstellar space travelers might also affect the value of f_c.

▽ Our two choices for L—$< 10^2$ years, and $>> 10^8$ years—lead to two values for N: less than ten communicative civilizations in the Galaxy; or many more than 10^7. In the former case, we might be the only extant civilization; in the latter case, the Galaxy is filled with them. The value of N depends very critically on our expectation for the lifetime of an average advanced community. It seems reasonable to me that at least a few percent of the advanced technical civilizations in the Galaxy do not destroy themselves, nor lose interest in interstellar communication, nor suffer insuperable biological or geological catastrophes, and that their lifetimes, therefore, are measured on stellar evolutionary timescales. As an average for all technical civilizations, both short-lived and long-lived, I adopt $L \sim 10^7$ years. This then yields as the average number of extant advanced technical civilizations in the Galaxy

$$N \sim 10^6.$$

Thus, approximately 0.001 percent of the stars in the sky will have a planet upon which an advanced civilization resides. The most probable distance to the nearest such community is then several hundred light years. (In the Space Science Board Conference on Intelligent Extraterrestrial Life, previously mentioned, the individual values of N selected lay between 10^4 and 10^9 civilizations. The corresponding range of distances to the nearest advanced community is then between ten and several thousands of light years.) △

We now take up von Hoerner's alternative discussion of the probable distance between Galactic civilizations. He defines ν_0 as the number of stars about which habitable planets could exist; T_0 as the time that elapses between the formation of a given planetary system and the appearance of a technically advanced society; and L as the lifetime of a technically advanced society. Further, let T be the age of the oldest stars, and let ν be the number of stars around which technically advanced civilizations in fact currently exist.

Von Hoerner then assumes that the rate of star formation remained constant over the period T, ▽ an assumption which, as we have seen, is probably not quite valid. △ It then follows that

$$\nu = \nu_0(T - T_0)/T$$

if $L \geqq T - T_0$, and

$$\nu = \nu_0 L/T$$

if $L \leqq T - T_0$. Let d_0 be the average distance between neighboring stars. Then the average distance between neighboring technical civilizations will be

$$d = d_0\nu^{-\frac{1}{3}}.$$

Von Hoerner considers the following five possibilities on the limitation of the lifetime of a technical civilization: (1) the total obliteration of all life on the planet; (2) destruction of only the higher forms of life; (3) physical or intellectual degeneration and decay; (4) the loss of interest in science and technology; and (5) no limitations on L at all. Von Hoerner believes that condition (5) is entirely inconceivable, ▽ although it does not appear inconceivable to us. △ He also believes that in cases (2) and (3), a new civilization might arise on the same planet, out of the ashes of the old, or from unaffected lower forms of life. The time required for such a reestablishment of civilization would probably be short compared with T_0. ▽ Fred Hoyle has suggested that the reestablishment of civilization may not be as easy as it sounds. Our civilization developed using fossil fuels as an energy source. The coal and oil in the Earth's crust are the residues of hundreds of millions of years of biological evolution and decay. At the present rate of growth, in another 50 or 100 years we will have exhausted all fossil fuels on Earth. If our civilization were to destroy itself at that time, the absence of fossil fuels would make the development of a successor civilization unlikely, at least for a few hundreds of millions of years. △

We shall denote the average lifetime on these five hypotheses as L_1, L_2, L_3, L_4, and L_5; and the likelihood, or probability of realization, of each hypothesis as P_1, P_2, P_3, P_4, and P_5, respectively. Thus,

$$\nu = (\nu_0/T)P_1L_1 + P_2L_2 + P_3L_3 + P_4L_4 + P_5(T - T_0)Q,$$

where Q, equal to $[1 - (P_2 + P_3)] - 1$, takes into account the possibility of the reestablishment of a destroyed civilization. Since $L = P_1L_1 + P_2L_2 + P_3L_3 + P_4L_4 + P_5(T - T_0)$ is the average lifetime of a technical civilization, this expression may be simplified to

$$\nu = QL\nu_0/T.$$

What is the probable age of the first extraterrestrial civilization with which we might make contact? A simple discussion by von Hoerner shows that this time is

$$\tau = [P_1L_1^2 + P_2L_2^2 + P_3L_3^2 + P_4L_4^2 + P_5L_5^2]/2L,$$

and the probability that there was at least one previous civilization on a given planet is

$$P_2 = (Q - 1)/Q.$$

To obtain concrete numerical estimates from these general formulae, it is necessary to assign values to the various L_i and P_i. Von Hoerner's estimates for these quantities, ▽ like anyone else's, △ are quite subjective. But note that if we combine our expressions for d and ν, we find

$$d = d_0(\nu_0QL/T)^{-\frac{1}{3}}$$

except for extremely long-lived civilizations. Thus, our principal unknown, L, appears with an exponent $-\frac{1}{3}$, and the uncertainty of our estimated L will not strongly influence our estimate of d.

Table VI gives von Horner's estimates of the probable lifetime of an

TABLE VI

AN ARBITRARY SET OF VALUES FOR THE LIFETIMES AND PROBABILITIES OF DESTRUCTION OF TECHNICAL CIVILIZATIONS

(after von Hoerner)

Alternative	*Estimated range for L_i, years*	*Value adopted* L_i, *years*	*Value adopted* P_i	P_iL_i, *years*
Complete destruction	0–200	100	0.05	5
Destruction of higher life	0–50	30	0.60	18
Degeneration	10^4–10^5	3×10^4	0.15	4500
Loss of interest	10^3–10^5	10^4	0.20	2000
No limitation	—	—	0.00	0

advanced technical civilization under each of his five hypotheses. It also gives his estimates of the likelihood, or probability of realization, of each of these modes for the termination of a civilization.

In my opinion, it is logical to assume that the era of technical development on any planet is finite. However, any attempt to estimate the probabilities connected with this idea are subjective and may lead to paradoxical conclusions, a problem which we discuss in some detail later. For the values of L_i and P_i selected by von Hoerner in Table VI, the average lifetime of a technical civilization becomes $L = 6500$ years, and the mean number of reestablishments of destroyed civilizations becomes $Q = 4$. ▽ Note, however, that von Hoerner has assigned a zero probability to an extremely long-lived civilization such as we described earlier in this chapter. Even a very low probability for the occurrence of such a civilization would, in von Hoerner's theoretical development, lead to a very large value of the mean lifetime of a technical civilization. For example, if $L_5 = 10^9$ years, and $P_5 = 10^{-2}$, we find $L = 10^7$ years. △ But with von Hoerner's numbers and $T = 10^{10}$ years, $\nu_0 = 0.06$, and $d_0 = 2.3$ parsecs, the average distance between the Sun and nearest stars, we find that $\nu = 2.6 \times 10^{-7}$. This means that within the framework of von Hoerner's assumptions, only about one out of every three million stars has a planet which currently sustains intelligent life. The average distance between Galactic civilizations is then $d = 360$ parsecs, or a little over 1000 light years. ▽ Considering the differences in analytic treatments and choices of numerical values in our earlier discussion and in the present discussion of von Hoerner, the agreement of final results is somewhat gratifying. △ The most probable age of a technical civilization when we first contact it is $\tau = 12{,}000$ years. ▽ The level of technical development of such a civilization is difficult for us to imagine. But if it corresponds to the technical civilization of the Earth in the year 14,000 A.D., continuously developed from the present, it must be a civilization different not in degree, but in kind, from our own. △ There is a 75 percent probability that this civilization is the successor to an older civilization which previously flourished on the same planet, but which was subsequently destroyed. The calculations indicate that there is only a small probability—about 0.5 percent—that any given interstellar contact would be with a civilization at the same phase of development as our own. ▽ Thus, in any interstellar contact, we very likely have much more to learn than to teach. △ We again emphasize that all the foregoing numerical estimates are valid only to the extent that the initial values for L_i and P_i are valid, and these values are necessarily arbitrary.

If these estimates are at all accurate, however, we can conclude that it would be useful to attempt to detect interstellar radio signals by the methods of Project Ozma [see Chapter 27]. If the nearest technical civilization were 1000 light years away, how could the inhabitants single out our Sun from among the millions of stars within 1000 light years of them, and convey information or inquiries in our direction? It is more reasonable to suppose that the signals would be sent out in all directions, and would initially be designed to make the existence of their technical civilization known, an announcement signal. ▽ Only after a similar signal had been received would two-way conversation be initiated. △ Since $d = 1000$ light years in this case, the time interval between inquiry and answer, t_0, would be greater than 2000 years. It would hardly be a hurried conversation. Since the lifetime of the technical civilization would be limited, the number of possible conversations would also be limited. With the results of von Hoerner's calculations, there would be time for only about ten two-way conversations, and the exchange of information would be limited. ▽ But while limited, the amount of information transmittable would not be small [see Chapter 27]. △

The situation would be radically different if we were to take into account what von Hoerner calls the "feedback effect." This effect, also considered by the Australian-American radioastronomer Ronald Bracewell of Stanford University, may be understood as follows: If the waiting time, t_0, were significantly greater than the lifetime, L, of the technical civilization, answers to the transmitted inquiries would of course never be obtained, and interest in communication would eventually dissipate. But if t_0 were significantly less than L, it is entirely possible that a fruitful and productive exchange of information could take place. ▽ It would in fact be to the advantage of the communicating civilizations to increase the lifetime of their communication partners, if they wished to continue the conversation. △ The various civilizations, distributed through the Galaxy, could be of mutual benefit and assistance from the radio or optical contacts. As a consequence, the local value of L in any given system would undoubtedly increase, perhaps by a significant factor. Von Hoerner calls this the feedback effect.

We believe, however, that even if t_0 were greater than L, and the conversations turned out to be monologues, feedback would still take place. Any information at all received by a planetary civilization could assist the society in overcoming difficulties which impede its further development. The result would be the lengthening of L.

In the case that $t_0 > L$, where L is the average lifetime of a technical civilization, the quantity $K = L/t_0$ is of significance. Note, incidentally, that $t_0 = 2d/c$, where c is the velocity of light.

Taking von Hoerner's estimates of the most probable values of L and d from Table VI, one finds that $K = 10$. This quantity can also be written as

$$K = (L/L_0)^{\frac{4}{3}},$$

where

$$L_0 = (8d_0T/c^3\nu_0Q)^{\frac{1}{4}}.$$

If we assume that $d_0 = 2.3$ parsecs, $T = 10^{10}$ years, $\nu_0 = 0.06$, $c = 3 \times 10^{10}$ cm sec^{-1}, and $Q = 4$, then $L = 4500$ years, comparable to von Hoerner's previous estimates. When $K > 1$, feedback can occur. Thus, if the lifetime of a technical civilization, L, is unaltered by feedback, $L_0 \simeq 5000$ years. We note that L_0 is determined with a relatively high level of confidence, since all the quantities entering into it appear to the $\frac{1}{4}$ power. Therefore, even very large errors in the estimates of d_0, ν_0, and Q would not lead to a substantial error in the estimate of L_0. If L is significantly greater than 5000 years, then, due to feedback, L would increase substantially. It is difficult—perhaps impossible—to estimate by how much L would increase. Von Hoerner himself assumes that there is only a small probability that L would increase, for example, to one million years. However, we must emphasize again that von Hoerner's estimates are purely subjective.

Fluctuations in the space-time distribution of extraterrestrial civilizations, even in the case where $t_0 > L$, could have very important consequences for the feedback effect. If the feedback results in a substantial local increase in L, due to such fluctuations, the further development of many technical civilizations could be significantly enhanced. For example, the lifetime of our own technical civilization might increase substantially, and then the lifetimes of technical civilizations in general could increase throughout the entire Galaxy. The rapid multiplication of microorganisms inoculated into a suitable medium is an analogous phenomenon.

It is evident that feedback could have a decisive significance for intelligent life in the universe. Ultimately, it could be the basic method for the development and propagation of knowledge throughout the Galaxy and metagalaxy, a subject we consider in more detail in Chapter 34.

▽ The very tentative conclusions of this chapter may now be summarized: The number of extant civilizations substantially in advance of our own in the Galaxy today appears to be perhaps between 50 thousand and one million. The average distance between technical civilizations is between a few hundred light years and about 1000 light years. The average age of a communicating technical civilization is 10,000 years or more. And the information transmitted by interstellar contact may serve to substantially increase the lifetime of the participating civilizations. △

30

Interstellar radio contact: the character of the signals

But if we allow these Planetary Inhabitants some sort of Reason, must it needs, may some say, be the same with ours? Certainly it must; whether we consider it as applied to Justice and Morality, or exercised in the Principles and Foundations of Science. For Reason with us is that which gives us a true Sense of Justice and Honesty, Praise, Kindness, and Gratitude: 'tis That that teaches us to distinguish universally between Good and Bad; and renders us capable of Knowledge and Experience in it. And can there be any where any other Sort of Reason than this? or can what we call just and generous, in Jupiter or Mars be thought unjust Villany?

Christianus Huygens, *New Conjectures Concerning the Planetary Worlds, Their Inhabitants and Productions* (c. 1670)

Let us now discuss the anticipated character of radio ▽ or optical laser △ signals which we might receive from another civilization. Von Hoerner has suggested the nature of the signals would be determined ultimately by (a) the purpose they are to serve; and (b) the most economical transmission channel. There are three general types of signals which we might anticipate: (1) local broadcast, that is, radiation due to local communications on a planet such as from domestic television transmitters. ▽ Eavesdropping on such calls is, under some circumstances, feasible; △ (2) long distance calls, that is, specifically directed radio contact between two particular civilizations; and (3) announcement signals, that is, signals transmitted for the purpose of attracting the attention of any civilization which has not yet been contacted.

Local broadcasting was discussed in Chapter 27. We have noted that due to the activities of mankind, the power of the Earth's radio spectrum at meter wavelengths is approximately 1 watt $(\text{c.p.s.})^{-1}$, and the brightness temperature of the Earth at these wavelengths is some 100 million degrees. If a hypothetical observer were at the distance of the nearest stars, some 10 light years away, the meter radiation flux from the Earth would be about 10^{-35} watts meter^{-2} $(\text{c.p.s.})^{-1}$, a negligible amount. For this radiation to be detected by conventional techniques over interstellar distances, the power would have to be increased some 10^8 times. ▽ However, as discussed in Chapter 27, if cross-correlation techniques are used with a very large frequency bandpass, eavesdropping becomes possible even though the signal may be much less than the noise. △

A long distance call intended for another civilization might be detected on the Earth only if our planet were accidentally interposed in the direct radio path between two communicating Galactic civilizations.

Von Hoerner estimates the probability of such accidental interception as $(\pi/120)q^3\beta^2n^2$, where β is the beam width of both the transmitting and receiving antennas (assumed identical), n is the number of neighbors with which each civilization maintains contact, and q is the ratio of the distance at which the signal can be detected to the distance at which it can be positively interpreted. The quantity q is always > 1, because it is simpler to detect a signal than to decipher it. Curiously, the interception probability does not depend on L or on d.

Assuming that the interception probability is sufficient to warrant the organization of an interception service (if, for example, this probability is $\frac{1}{2}$), that $q = 5$, and that $\beta = 1$ minute of arc (corresponding to the beam width of current large radiotelescopes), then n would equal 1300. In other words, the signals would be accidentally intercepted only if each civilization was attempting to converse simultaneously with 1300 neighbors. This seems highly improbable. If we require the probability of interception to be

½, and assume n to be as small as 50, we must have $q = 10$ and $\beta = 10$ minutes of arc, which is again highly improbable.

We can surmise that the probability of accidental interception of interstellar long distance communication signals is very small.

An announcement signal is designed to attract the attention of an unknown civilization. ▽ One such announcement signal might be the atomic markers in stellar spectra, discussed in Chapter 28. △ There is today increasing interest in the most likely character of interstellar signals. Such signals must fulfill two requirements: They must attract attention, but at the same time they must be economical. The consumption of energy and other resources must be a minimum, while the distance over which it is detectable must be a maximum. Of course, the criteria for economy which might seem natural to us as members of a terrestrial civilization may not be identical with the estimates of other advanced societies.

There are several methods which might be used for such an announcement signal. For each method, it is possible to estimate a certain equivalent cost, C, the price which must be paid in order that the probability, P_d, of detecting the signal at the distance d during the time t_d be sufficiently large. We can assume, for example, that $P_d = \frac{1}{2}$, $d = 1000$ light years, and t_d is of the order of several hundred years. One then chooses from among those methods which give acceptably small values for the cost, C.

Von Hoerner has assumed that the quantity C would be a minimum if all the power is sent in a narrow beam at a specific frequency interval which the unknown receiving civilization could reliably guess beforehand. In Chapter 27, we considered the suggestion of Cocconi and Morrison that the most supremely rational frequency for interstellar communication is the natural frequency of the 21 cm radio frequency line of hydrogen. ▽ We also considered objections to this choice of frequency, and alternative frequency selections. △

In order to minimize C, we must also choose an optimum distribution for the transmitted power, both in space and in time. The communication mode might provide for modulation of the signals, and would probably be elegantly simple, rational, and easily understood by the unknown receiving civilization. Since the waiting time for a reply will be quite long, the initial messages will probably contain significant quantities of information, as well as the cynosures of the announcement signals. The information content could be included either in the entire transmitted signal spectrum—for example, through modulation—or by an indication of a separate frequency channel on which the information is being sent.

Attention might be directed to the information channel as follows: The announcement signal could consist of a large number of signals transmitted at various fixed frequencies which are symmetric with respect to a certain central frequency. Approaching this central frequency, the spacing between neighboring signals might become narrower and narrower, and the signals themselves could have much narrower frequency bandpasses. In this way, attention would be drawn to the fact that the central frequency has special significance. ▽ (Cf. the discussion of CTA 102 in Chap. 27.) △ Information could be transmitted at this frequency at definite time intervals, perhaps once every several years, although the time intervals need not necessarily be multiples of terrestrial years, months, or days. The first transmitted information would probably contain an introduction to interstellar linguistics, the language which the transmitting civilization has selected for the clear communication of information.

▽ But how is this possible? Suppose we were to identify an announcement signal and correctly identify the frequency of the communications channel. We might find a modulated signal there of clearly intelligent origin—for example, we might represent it as a sequence of zeros and ones, or dots and dashes. A zero and a one might represent the signals of two neighboring frequencies; the difference between a dot and a dash might be, as in Morse code, the length of the pulse. Zeros and ones might be coming at us at an extremely rapid rate, since the transmitting civilization is likely to be vastly in advance of our own. We would record the information, perhaps on magnetic tape, slow the signals down, and display them in some conventional representation as, for example, zeros and ones. Due to the rotation of the Earth, the area of the sky from which the signal comes would not always be accessible to our largest radio or optical telescopes used for the detection of this hypothetical interstellar transmission. We would receive a long message, but a fragmented one, abruptly terminated when the radio or optical source set below the observatory's horizon. The next day, the source would reappear, and the message would be picked up again in the midst of transmission. With some effort in data-gathering and preliminary analysis, we might note that, for example, a common sequence of zeros and ones is frequently present—for example, the sequence of 551 zeros and ones in Figure 30–1.

▽ An advanced technical civilization is trying to communicate with us. But how can we possibly understand what they are saying? They are not likely to speak English or Russian. They have had a different evolutionary history. They are on a planet with perhaps an entirely different physical environment. Their thought

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0 0 1 0 0 0 1 1 1 1 0 0 1 0 1 1 1 1

FIGURE 30–1. *A hypothetical interstellar message due to Frank Drake. The 551 zeros and ones are representations of the two varieties of signals contained in the message. The problem is to convert this sequence of 551 symbols into an intelligible message, knowing that there has been no previous communication between the transmitting and receiving civilizations.*

patterns, conventions, and cultural values may be entirely alien to our own. At first sight, it seems no more likely that we might understand their transmission than that the content of the first message directed at us is "Are you chaps Presbyterians?"

▽ If you ponder this problem briefly, it will soon become apparent that the initial transmission of words, no matter how simple, in the language of the transmitting civilization, will not be useful for interstellar communication. What we desire is a picture. The adaptive value of vision is very high, and, as we discussed in Chapter 24, there are good reasons for supposing that extraterrestrial biological radiation receptors will work at visible frequencies. Since both transmitting and receiving civilizations are very likely to "see" in some sense, the initial messages must be pictures.

▽ After the first scientific meeting held in the United States on intelligent extraterrestrial life [see Chapter 29], Frank Drake sent through the mails to each of the participants the hypothetical interstellar message of Figure 30–1 and asked us to propose a solution. We had not discussed the probable content of the first interstellar messages, and had not even agreed yet that a picture would be the most likely initial message. The participants met this challenge with varying degrees of success, although all participants did not decode the message. In order to represent more realistically the probable circumstances attending the reception of the first interstellar message, I prepared a message identical to Drake's, but with one of the zeros missing. The radio or optical channels are noisy, and perfect fidelity after transmission over interstellar distances cannot be expected. If the same message is repeated many times, intercomparison will rapidly indicate the points of error, a technique, incidentally, probably used by the cell in decoding the instructions of the genetic material (cf. Chapter 14). This altered message was pondered by a distinguished group of physicists, chemists, and biologists assembled for a private party in Cambridge, Massachusetts. Although several hours were spent in the attempt to decode the message, and despite the fact that the idea of transmission of a visual image was agreed upon early, the altered message was not decoded. The longer the message, the more danger there is that an error in transmission or detection will obscure a major fraction of the message. Thus, both to insure fidelity of content and to allow for the fact that the telescopes of the receiving planet are unable to observe the transmitted signal for an entire period of rotation, all messages should be repeated several times.

▽ With this warning, the reader is invited to inspect the decoded message in Figure 30–2. An explanation of the rationale of the message and its contents, prepared by Drake, follows:

The first step in the solution of this message is to determine, if possible, the number of dimensions in which the message is written. If one dimensional, it will be similar to an ordinary telegram; if two dimensional, it will be similar to a conventional TV picture, although other than Cartesian coordinates might be employed, etc. We would not expect the number of dimensions to be large, simply because ease of decipherment calls for few dimensions. To make headway in this, one may see what factors may be divided into 551. This test reveals that 551 is the product of only two factors, 19 and 29, both prime

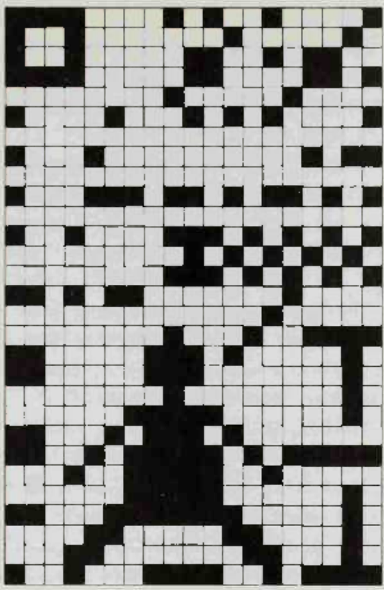

FIGURE 30–2. *The correct decoding of the message in Figure 30–1. The ones have been represented as dark spaces, the zeros as light spaces, and the 551 characters have been arranged into an array of 29 groups of 19 characters.*

numbers, of course. This is a good indication that the message is two dimensional. Trial and error with Cartesian coordinates shows that breaking the message into 29 groups of 19 characters, and arranging these as in a conventional TV raster, gives a clearcut picture, which is obviously the correct decipherment of the message. ▽ Arrangement into 19 groups of 29 characters gives the meaningless result shown in Fig. 30–3. △

The interpretation of the picture is as follows:

1. The figure of the manlike creature at the bottom of the picture is obviously a

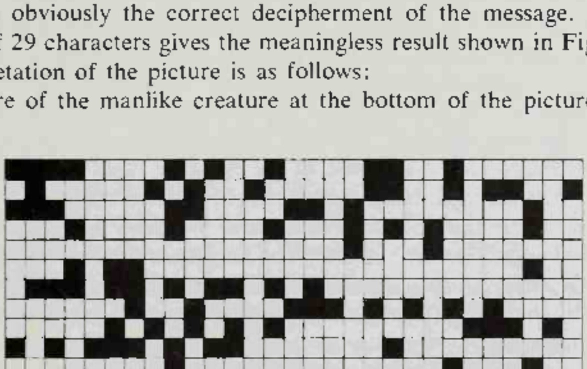

FIGURE 30–3. *An incorrect deciphering of Figure 30–1. Here the zeros and ones have been arrayed into 19 groups of 29 characters.*

drawing of the being sending the message. We see that it resembles a primate, with a heavier abdomen than we have, and that it carries its legs more widespread than we do. Its head is also more pointed than ours (or else it has a single antenna). One may speculate from this physiognomy that the gravitational acceleration is greater on the home planet of this creature than it is on earth.

2. The large square in the upper left-hand corner, accompanied by nine smaller objects strung along the left-hand margin, is a sketch of the planetary system of the creature. We see that there are four small planets, a larger planet, two large planets, another intermediate planet, and one last small planet. The system thus resembles our own in basic morphology.

3. The two groups in the upper right-hand corner may be recognized as schematic drawings of the carbon and oxygen atoms. We deduce from this that the creature's biochemistry is based on the carbon atom, as ours is, and that the oxidizer used in its chemistry is oxygen, also as with terrestrial animals.

4. A key group of symbols are those occurring just to the right of the four minor planets and the fifth planet. Inspection of these symbols shows that they are simply a modified binary representation of 1, 2, 3, 4, 5, written in sequence alongside the first five planets. The modification made to the basic binary numbers is the addition to the ends of the numbers of parity bits, where necessary, so that the number of 1's in every binary number is odd. This is similar to computer practice on earth. It is apparently not used here as a check on transmission, but rather to designate a symbol as a number. In future communications, symbols will certainly also be used for words of language. We may deduce from the creature's careful setting down of the binary number system that he will use this, with parity bits, for numbers henceforth. It follows that we may expect words of language to have even numbers of 1's. In this way, the creature has established a number system and has enabled us to recognize words of language.

5. Knowing this, we may interpret the portions of the message located above the creature and below the atoms. We note that there are three groups of characters all having an odd number of 1's. These are then numbers. The lower group is connected to the creature by a diagonal line, signifying that it has something to do with him. We further note that the arrangement of these groups are mutually consistent only if no parity bits are present. The lower group, which was too long to place on one line, is about 7×10^9 in decimal notation. The next is about 3000, and the upper group is 11. Noting that these groups are connected to the creature, and written alongside planets 2, 3, and 4, we reach the apparent interpretation that these numbers are the population of the creature on those planets. There are about 7 billion creatures on planet 4, evidently the home planet. There are about 3000 on planet 3, from which we can deduce the fact that astronautics is more developed than on earth, and there is a sizable colony on planet 3. Lastly, there are 11 of the creatures on planet 2, evidently a small scientific or exploratory group.

6. The figure to the right of the creature contains one binary number, and a symmetric configuration of symbols of even parity, probably not words, and certainly not numbers. One symbol is level with the top of the creature's head, and the other his feet. This is apparently telling us the size of the creature—it is 31 somethings tall. The only unit of length our two civilizations have in common is the wavelength at which the message was sent, so we conclude that the creature is 31 wavelengths tall.

7. Lastly, there is a symbol of even parity, with four 1's, underneath the creature. This is evidently an effort by the creature to use up all the "words" allotted him in his

message. We may suspect, in keeping with the discussion in (4), that this is a word of language, and is very likely the symbol that the creature will use for himself in future messages. This behavior would seem to reinforce the conclusions of (4), but we will have to wait for future messages for proof that this conclusion is correct.

A few remarks:

The content of the message was designed to contain the data we would first like to know about another civilization, at least in the opinion of many scientists who have thought about this problem.

In preparing the message, an attempt was made to place it at a level of difficulty such that a group of high quality terrestrial scientists of many disciplines could interpret the message in a time less than a day. Any easier message would mean that we are not sending as much information as possible over the transmission facilities, and any harder might result in a failure to communicate. In trying this puzzle on scientists, it has been true so far that scientists have understood the parts of the message connected with their own discipline, but have usually not understood the rest. This is consistent with the philosophy behind the message.

The use of two dimensions has made possible the transmission of a great deal of information with few bits. This is because it is possible to arrange the symbols of the message in positions relative to one another such that even the arrangement carries information, when we employ logic and our existing knowledge of what may possibly occur in another planetary system. Thus the 551 bits are equivalent to approximately 25 English words, but the information content of the message appears much greater than that. This is because much of the message tells us, by the placement of a single symbol, which of several complicated possibilities is the one that has occurred in the other planetary system, without using bits to spell out precisely the possibility that has occurred.

▽ Each of the zeros and ones in the message of Figure 30–1 is called a "bit"—a unit of binary information. It is a "yes" or "no" answer to a specific question—the absence or presence of a dark picture element against a white background at a specific place in the illustration. △ It is amazing that such a large amount of information is contained ▽ within 551 bits. △ This example vividly illustrates the possibility of exchanging vast quantities of information by transmitting pictures over interstellar distances. This small number of elements could be transmitted in a very narrow frequency band, and over a short period of time. If the frequency band were sufficiently broad, and the period of transmission were lengthy, the amount of information could exceed the entire aggregate knowledge of mankind.

In order to clarify this last statement, let us give an example. Let us assume that the essentials of the knowledge of mankind are contained in one million books composed of ten chapters each. There are in general some 40,000 printed signs per chapter. The total number of such signs in one million books is then 4×10^{11}. ▽ If each symbol were one of two possibilities, this would correspond to 4×10^{11} bits. But terrestrial language is not written in zeros and ones, although it might be; instead, each alphabetical terrestrial language uses perhaps 100 symbols. This corresponds to slightly less than 7 bits, because $2^7 = 128$. △ If each sign is coded in a binary system, and the transmission of information is prefaced even by a vast linguistic introduction, the total number of binary bits transmitted would be $\sim 3 \times 10^{13}$. Let the frequency bandpass transmitting the signal be 100 megacycles sec^{-1}, a value easily obtained at 21 cm wavelength. ▽ Thus, with 10^8 cycles per second, it would take only 3×10^5 seconds for the 3×10^{13} bits to be transmitted. In less than 4 days, the knowledge of mankind could be transmitted.

▽ The transmission of this core knowledge would be preceded by a linguistic introduction which itself would be preceded by an announcement signal. Preliminary information could be transmitted graphically, as our illustration with the 551-bit message showed. Let us now consider how a non-graphic interstellar vocabulary could be developed for the expression of more abstract ideas. As an example, let us consider the artificial language Lincos, recently devised by the Dutch mathematician Hans Freudenthal. △ Lincos is ▽ designed as △ an entirely logical language, free from inconsistencies such as exceptions to grammatical rules, and other irregularities found in the spoken languages of the world. While the study of terrestrial languages includes grammar, syntax, and phonemics, Lincos is devised entirely in terms of semantics.

Lincos cannot be spoken. It consists of a coded system of units. The individual parts of the message are clearly enumerated into chapters, paragraphs, and so forth. This facilitates the interpretation of the message, because the semantic content of the language must be derived from logic external to the linguistic system itself. The clearcut differentiation into separate parts also aids the recipient in deciphering transitions, for example, from a mathematical chapter to a biological chapter.

A transmission in Lincos begins with the most elementary concepts of mathematics and logic. This is because the language must define itself before it can become a system of communication. In other words, it is *progressively synthetic*. The first transmissions might consist of very small units—for example, paragraphs preceded by captions. An introductory transmission might be as follows:

Chapter I. A course in basic mathematics.

PARAGRAPH 1. A series of natural numbers.

▽ (So far, of course, the recipient civilization, having not yet deciphered Lincos, does not know the significance of these captions.) △ The lesson would consist of a series of simple radio pulses, not coded—first one pulse, then two pulses, etc.

PARAGRAPH 2. Code numbers

- = 1
- - = 2
- - - = 3 etc.

From this transmission, the receiving civilization would learn the symbols for equality, and the designations of the ordinal numbers in Lincos. Could the receiving civilization actually make sense of such a transmission? We believe that if an extraplanetary civilization were able to build the apparatus to receive such signals, it would certainly be able to decode a passage based on so simple a language system. Any residual confusion about the contents of the first two paragraphs would tend to be resolved by the next paragraph:

PARAGRAPH 3. Addition

$$1 + 2 = 3$$
$$1 + 3 = 4$$
$$2 + 3 = 5 \qquad \text{etc.}$$

Lessons on subtraction, multiplication, and division would be transmitted in the same way. Gradually, the more complicated areas of mathematics could be covered—the transcendental number pi, the base of natural logarithms, algebra, the differential and integral calculus, and all of analysis. Geometry could be transmitted by images in combination with the Lincos words.

During such a course in mathematics, the receiving civilization would find itself introduced to a number of important concepts such as "similar to," "more than," "less than," "different from," "it is true that," "it is not true that," "as an example," "maximum," "minimum," "increase," "decrease," and even that invaluable mathematical phrase, "it is easy to prove that." Each of these concepts would be useful to the recipient civilization in the deciphering of subsequent information.

According to Freudenthal, Lincos could also transmit more complex ideas which characterize human nature—for example, "quick wit," "cowardice," "anger," or "altruism"—by transmitting short theatrical performances among imaginary characters, ▽ a sort of cosmic Mickey Mouse. △ At first, such performances would be only mathematical in character. Let us illustrate:

COURSE: Fundamentals of human behavior.

SUBJECT: Differences in mathematical abilities.

(One man speaking to another is denoted symbolically by →.)

A → B: How much is 2 + 3?
B → A: 2 + 3 = 5.
A → B: Correct.

In a series of analogous scenes, Man C appears.

A → B: How much is 15 × 15?
B → A: 15 × 15 = 220.
A → B: False.
A → C: How much is 15 × 15?
C → A: 15 × 15 = 225.
A → C: Correct.
C is more intelligent than B.

▽ This last is presumably an aside to the cosmic reader. △

After this transmission, a series of more complicated interactions could be portrayed. Sooner or later, the recipient civilization would realize that more than just mathematics was being discussed; that theatrical representations conveying the concepts of emotions, ▽ social conventions, and a wide range of philosophical postures △ were being transmitted into space.

We have already mentioned that linguistic information could be transmitted alternately with pictorial information. Especially in transmitting scientific data, this coupling could be very effective. For example, Mendelyeev's periodic system of the elements could be pictured, accompanied by the corresponding words in Lincos. ▽ We saw in Figure 30–2 how the conventional representations of nuclei with associated electrons could be transmitted into space. The number and distribution of electrons, of course, would indicate the nature of the atom. △ Then, a graph of the number of protons in the nucleus versus the number of neutrons could be transmitted. ▽ By this time, the cosmic discourse is well along into atomic and nuclear physics. △

It would be relatively simple to transmit physical, astronomical, and chemical constants. The unit of length could be expressed in terms of the wavelength of transmission, and all other linear units would be either fractions or multiples of this basic unit. The unit of mass could be the mass of the electron; the unit of time could be defined in terms of the velocity of light (▽ for example, the time for light to cross a distance equal to the wavelength of transmission △). Thus, very complex scientific information could be transmitted economically.

We wish to emphasize that a linguistic system based upon these fundamentals would be far easier to decipher than many of the written languages of ancient civilizations which have been deciphered by archaeologists.

31

Interstellar contact by automatic probe vehicles

. . . So deep is the conviction that there must be life out there beyond the dark, one thinks that if they are more advanced than ourselves they may come across space at any moment, perhaps in our generation. Later, contemplating the infinity of time, one wonders if perchance their messages came long ago, hurtling into the swamp muck of the steaming coal forests, the bright projectile clambered over by hissing reptiles, and the delicate instruments running mindlessly down with no report.

Loren Eiseley, *The Immense Journey* (1957)

In the consideration of contact with advanced extraterrestrial civilizations, the average distance among civilizations is clearly critical. If the average distance to the nearest civilization is approximately 10 light years, as assumed by Cocconi and Morrison, and by Townes and Schwartz, we have seen in Chapters 27 and 28 that contact by participating civilizations at the contemporary level of terrestrial technology appears feasible. ▽ But we also saw, in Chapter 24, that there are only five star systems of approximately solar spectral type within 15 light years—namely, Alpha Centauri, Epsilon Eridani, 61 Cygni A, Epsilon Indi, and Tau Ceti. △ Thus, it would be relatively easy to establish whether any one of these stars were sending artificial radio or optical signals in our direction.

On the other hand, assume (as seems much more likely, on the basis of our discussion in Chapter 29) that the average distance among technical civilizations is some hundreds of light years. The situation is then radically different. There are now many thousands of stars with possible populated planets. It seems probable that many stars would have to be observed over a long period of time, in order to determine which, if any, were transmitting artificial signals. An extensive "Operation Starwatch" would have to be performed. The detection of artificial signals, even in the simplest situations, is a difficult and intricate task ▽ at our present level of advance, provided that we are not listening to a vastly more advanced civilization. △ But it would become incommensurately more difficult if, over many centuries or millennia, we must direct beams of electromagnetic radiation with great precision at tens of thousands of stars, while patiently waiting, perhaps in vain, for a reply. And we must remember that intelligent extraterrestrial civilizations may not even be sending radio or optical impulses in the direction of our solar system. Perhaps, for reasons of their own, they have excluded our Sun from the vast numbers of stars which they believe might possess inhabited planets . . .

▽ We saw in Chapter 29 how the number of technical civilizations in the Galaxy, and therefore the distances between them, is fairly sensitively dependent upon L, the lifetime of the technical civilization. We concluded, by two different analyses, that the probable distance to the nearest technical civilization lies between several hundred light years and perhaps 1000 light years from the Earth. But the range of uncertainty, we again emphasize, is very great. If the average lifetime of a technical civilization is comparable to the lifetime of its star, there may be a billion intelligent civilizations in our Galaxy. If the average lifetime of a technical civilization is only a few decades, ours may be the only civilization in the Galaxy, and even a massive effort to detect signals from an extraterrestrial civilization—in the few decades remaining to us—would prove fruitless.

▽ But let us assume that the nearest civilization is 1000 light years away. The average separation between stars in the solar neighborhood is $d_0 \simeq 2.3$ parsecs, or $2.3 \times 3.26 =$ some 7.6 light years. The number of stars in a volume of radius 1000 light years is therefore $(4\pi/3)$ $(1000/7.6)^3$, or about 10 million. Even if we restricted our search to stars of approximately solar spectral type, there would be more than a million candidates. △ How could we possibly predict which one of these stars has a habitable planet supporting intelligent life? In view of this situation, Ronald Bracewell has suggested another means of establishing contact.

Bracewell assumes that in general, the development of a technically advanced civilization will be accompanied by great progress in rocketry and other space vehicle technology. Relatively early in its lifetime, the civilization would be capable of sending small, automatically controlled interstellar probes to the nearest stars, and of placing them automatically into almost circular orbits about their objectives.

Great advances in space technology are already occurring on the Earth. ▽ Guidance systems have been developed which have permitted a close flyby of the Moon by Luna III and Zond III, accurate lunar impacts by, for example, Ranger IX and Luna IX, close flybys of Venus and Mars by Mariners II and IV, and an entry into the atmosphere of Venus by a capsule from Venus III △ Guidance systems exist which enable us to put artificial satellites, ▽ like Luna X, △ in orbit about the Moon. The guidance techniques include the transmittal of in-flight commands for midcourse corrections of the space vehicle's trajectory. Some day, ▽ perhaps fairly soon, △ this technology will also be applied to the orbiting of artificial satellites about the planets—perhaps Venus first, and then Mars. Eventually, automatic probe vehicles could be sent to the nearest stars, where they would become artificial planets.

After the initiation of such an interstellar exploration program, only a few more centuries would be required to place such vehicles in orbit about all stars which are likely to have habitable planets within a radius of 100 light years of the Sun. The velocities of such probes might reach 1 or 2×10^5 km $\sec^{-1}$. Such velocities are very great, but they would still be short of the speed of light, and avoid the effects due to relativity, ▽ described in Chapter 32. △ The probes would, of course, contain exceptionally long-lived radio receiving and transmitting apparatus. The energy required to power this apparatus could come from the light of the star about which the satellite is in orbit.

There are a number of distinct advantages of contacts of this type. ▽ Once in orbit about the local star, the probe would then automatically attempt contact with habitable planets in its vicinity. △ Since the instrumentation of the probe is powered by the local star, its transmitted signal would be much more powerful than a signal sent directly from the Earth. Second, the signal from the probe to the inhabited planet would travel a much shorter distance than if it were sent directly from the Earth. ▽ In the case of optical contact, this might avoid the difficulty we discussed in Chapter 28 (that is, the need for the laser beam to fill a significant fraction of the local solar system for there to be a sizable probability of detection). △ Third, such interstellar exploration need not assume that intelligent extraterrestrial societies are conducting an extensive, continuous survey of the heavens in search of signals from suitable stars. Finally, this program does not depend on a specific choice of wavelengths, such as the 21 cm band.

This program, suggested by Bracewell, could be implemented as follows: At the destination star, the probe would investigate the surrounding regions of space, searching for monochromatic radio transmission. Such a search would cover a wide range of frequencies. Should signals be detected, the probe would record them and immediately transmit them back to their original source without change. A repeated playback would undoubtedly attract the attention of the planetary inhabitants. ▽ The reception of a housewife's daytime television serial, from interplanetary space, would undoubtedly interest terrestrial radioastronomers. △ As a result, a very important goal would be achieved: The extraterrestrial society would discover the presence of a messenger from a distant civilization.

After two-way contact with the probe had been established, the probe would transmit a previously-arranged program of more complex information. Television could be used to great advantage—for example, the probe could transmit to the planet a televised image of the constellation in which the probe's star of origin is located, ▽ that is, in this case, the Sun. △ We would of course have to know beforehand how the Sun would appear in the sky of the planet of destination. ▽ Subsequently, a very large volume of information could be transmitted from the probe to the planet, along the lines suggested in Chapter 30. △

As soon as the inhabitants of the contacted planet learn of the presence of intelligent beings near a particular star in their sky, they could begin their own intensive investigation. They might send modulated optical and radio transmission, and also their own automatic probe vehicles, in the direction of this star. It is conceivable that after several centuries, a lively two-way contact could be established between these civilizations, separated by a distance of, say, some tens of light years.

▽ Note that for contact to be established, it is not necessary that the initial probe inform us of the success of its mission. If its mission is successful, the contacted civilization will make its own contact. △ The volume of information contained in such a probe could be so great that even a simple one-sided contact would be valuable.

It is also possible to conceive of a system of relay stations for the retransmission of signals obtained by the probe vehicle. The interstellar space vehicles used as relay stations would sequentially transmit the acquired information to the Earth.

▽ At first, only civilizations relatively close to one another could be investigated by interstellar probes. △ However, we can assume that highly developed civilizations would investigate the universe in a systematic manner, without unnecessary duplication of contacts. As an end result, it is possible to postulate the existence of a vast network of intelligent civilizations in productive mutual contact.

▽ Such a universe, in which physical contact was effected only by relatively short-range automatic interstellar probe vehicles, would have some interesting properties. For example, it is certainly conceivable that physical objects could be transported in such vehicles to civilizations on neighboring stars. The exchange of cultural artifacts—for example, works of art—would have a salutary influence on the maintenance of contact. Such artifacts might in fact be relayed over substantial distances by the automatic interstellar ferries of a multitude of civilizations. Over long periods of time, such objects would tend to diffuse over large distances within the Galaxy, but the likelihood of encountering them far from their source would be small. If the useful range of interstellar space vehicles were only some tens of light years, one would not expect to find terrestrial artifacts near the Galactic center. If interstellar voyages over distances greater than some tens of light years are undertaken, then this artifact diffusion will tend to loosely connect civilizations of greatly differing levels of technical and artistic development. There would occasionally come our way an object of incredible beauty or devastating power that we were unable either to understand or reproduce. Even in a technical civilization such artifacts might evolve into objects of worship. Similar circumstances and an entire associated mythology have developed under analogous conditions in the contemporary cargo cults of New Guinea—an example of artifact diffusion contact between civilizations at greatly differing levels of technical advance. △

Because of the real possibility that such interstellar probes actually exist, Bracewell believes that it is very important for us to investigate carefully all radio signals of cosmic origin. There is some possibility that probes from distant Galactic civilizations are already present within our solar system. In this connection, Bracewell has called attention to certain phenomena which have been known for many years but never explained in a satisfactory manner. For example, during the 1930's, Störmer and van der Pol, ▽ in pioneering work on the atmospheric propagation of radio waves, △ detected several instances of an unexplained radio echo. The time lag in the reflected signal reached many seconds, and at times as long as a minute, suggesting that the signal was reflected from some object removed a distance of about one million kilometers from the Earth, ▽ a respectable interplanetary distance. △ Might these curious echoes be the transmissions of some automatic vehicle from a distant world? We must not forget that in the past, cosmic radio signals of very great intensity have been missed by terrestrial observers. For example, strong radio emission from the planet Jupiter, with a power $\sim$ 1000 watts $(\text{c.p.s.})^{-1}$ were detected many times during the last decades, but were not identified as Jovian emission until 1954.

If a careful search over a number of years does not lead to the detection of a source of artificial radio signals, we can come to the conclusion that the nearest technically advanced society is so far away that it cannot establish contact with us. For example, it might be that the average lifetime of a technical civilization is $\sim$ 1000 years, and the mean distance between civilizations is about 2000 light years. It is clear that under these circumstances, ▽ two-way △ contact between civilizations would be very unlikely. On the other hand, the situation would be entirely different if the average lifetime of a technical civilization were $\sim 10^7$ years, and the average distance between civilizations approximately 100 light years. Then, after some millions of years of technical development, a civilization would reach a peak from which it could easily investigate several thousand neighboring stars, among which at least one would be inhabited by an advanced technical society.

In the case that the lifetime of a technical civilization is long, it may have reached an exceptionally advanced level of competence and be able to establish contact with civilizations which are thousands of light years distant. Even the most remote regions of the Galaxy might be investigated by direct means. We cannot say what methods of investigation such highly developed civilizations might use—there would be too great a difference between their level of development and ours. Perhaps such embryonic civilizations as those of our own world would be of little interest to them. They might pass us by, deeming it unnecessary to investigate all primitive civilizations which, like butterflies, run the gauntlet from birth to death in a single instant.

(▽ At this point in the Russian edition of the present work, Shklovskii expresses his belief that civilizations are not inevitably doomed to self-destruction, despite his description of contemporary Western literature as filled with details of atomic holocaust. He expresses his belief that as long as capitalism exists on Earth, a violent end to intelligent life on the planet is probable. There is reason to assume, he asserts, that future peaceful societies will be constructed on the basis of Communism. I am able to imagine alternative scenarios for the future. No one today lives in a society which closely resembles Adam Smith capitalism or Karl Marx communism. The political dichotomies of the twentieth century may seem to our remote descendants no more exhaustive of the range of possibilities for the entire future of mankind than do, for us, the alternatives of the European religious wars of the sixteenth and seventeenth centuries. As Shklovskii says, the forces of peace in the world are great. Mankind is not likely to destroy itself. There is too much left to do.) △

32

Direct contact among galactic civilizations

"There is no use trying," she said: "one *can't* believe impossible things."

"I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

Lewis Carroll, *Alice in Wonderland*

"What matters it how far we go?" his scaly friend replied,
"There is another shore, you know, upon the other side.
The farther off from England, the nearer is to France;
Then turn not pale, beloved snail, but come and join
the dance."

Lewis Carroll, *The Lobster Quadrille*

▽ Among the possible ways of effecting interstellar communication, we have considered automatic interstellar probe vehicles of rather limited range, and methods of electromagnetic communication over somewhat greater ranges. The difficulties in electromagnetic communication over interstellar distances are serious. A simple query and response to the nearest postulated technical civilization would require periods approaching 1000 years. An extended conversation—or even a one-way transmission to a particularly interesting community on the other side of the Galaxy—would occupy much greater time intervals, 10^4 to 10^5 years. Electromagnetic communication assumes that the choice of signal frequency will be obvious to all communities. We saw in Chapter 27 that there has been considerable disagreement about interstellar transmission frequency assignments even on our own planet. Among Galactic communities, we may expect even greater differences of opinion about what is obvious and what is not. △

If there were indeed a lack of coordination in the standard wavelength—even if the wavelength were an integral fraction or multiple of 21 cm—the extraterrestrial societies would find it very difficult to detect the signals. Furthermore, if radio contact were attempted between civilizations separated by more than 2000 or 3000 light years, and if the communication radiation would have to pass relatively close to the Galactic plane, the artificial signal would be absorbed by the interstellar medium. Such absorption could be significantly decreased if we depart slightly (1 to 2 megacycles per second) from the neutral hydrogen frequency (1420 megacycles sec^{-1}); but this would again complicate the search.

▽ No matter how ingenious the method, there are certain limitations on the character of the communication effected with an alien civilization by electromagnetic radiation. With billions of years of independent biological and social evolution, the thought processes and habit patterns of any two communities must differ greatly. While it seemed likely to us, in Chapter 30, that the transmission of pictorial representations and artificial languages such as Lincos would be easily understood by alien civilizations, this is really a conjecture. We do not know what hidden assumptions lie in our proposed communication channel, assumptions which we are unable to evaluate because they are so intimately woven into the fabric of our thinking.

▽ There is a famous story in the anthropological community which illustrates this point:

> ▽ A husband-and-wife team of anthropologists was studying adjacent villages in a remote Pacific island. Despite their proximity, different languages were spoken in the two villages. One day, the woman anthropologist received an urgent message by bearer from her husband, asking her to come at once. She arrived in

haste and found her husband in an ecstasy of anthropological exhilaration. "My dear," he said, "I have stumbled upon a marvelous philosophical insight of the inhabitants of this village." Approaching one of the villagers, he pointed to a palm tree and asked, "What is this?"

The native promptly replied, let us say, "Unga munga." Next, the anthropologist pointed to a pig wallowing in the mud, and illuminated by the late afternoon sun. "What is this?"

"Unga munga," again replied the informant, with identical inflection.

Finally, in triumph, the anthropologist pointed to the village chieftain, and once again, asked "What is this?"

The respondent replied again—this time, somewhat dejectedly, it seemed—"Unga munga."

"You see—they do not make distinctions among different forms of life. Their language incorporates the unity of all living things," exclaimed the anthropologist.

"Dear," suggested his wife gently, "ask him what the word for index finger is."

▽ I can imagine such difficulties amplified by many orders of magnitude, were we to establish tomorrow interstellar radio contact.

▽ As an example of the potential difficulties of a less subtle sort, we can consider the case of Egyptian hieroglyphics. This language was deciphered only after the discovery of the Rosetta Stone, in effect a selective dictionary in two other known languages, Demotic and Greek. But earlier, several generations of European linguists had attempted to decipher the large body of hieroglyphic writing available even then. What is noteworthy is not so much that their efforts were almost uniformly unsuccessful, but rather, that some thought they had succeeded. While the hieroglyphics are mainly syllabic, some of the early linguists thought that they were ideographic, and constructed marvelously fanciful translations in which birds of course played a leading part. The Egyptians did not write their inscriptions for the benefit of another civilization ignorant of their language. In interstellar communication, there will be conscious attempts to make the contents clear. But our partners in the cosmic discourse will not be human beings, and it remains to be seen whether mathematics is the interstellar Rosetta Stone.

▽ Electromagnetic communication does not permit three of the most exciting categories of interstellar contact:

▽ (1) Contact between an advanced civilization and an intelligent but pre-technical society. △ Such contact would be particularly valuable, because the lifetime of the pre-technological era on many planets may be quite long, and the number of pre-technical civilizations in the Galaxy may greatly exceed the number of technically advanced societies.

▽ (2) Direct exploration of alien nonintelligent biologies, of the interstellar medium, of exotic star systems, and of the wide range of physical phenomena unobservable from the solar neighborhood.

▽ (3) The direct exchange of material objects, including biological specimens, among distant civilizations.

▽ If effective interstellar electromagnetic communication is feasible, there is the possibility of a kind of surrogate exchange of material goods, despite the fact that only photons would be exchanged. We might receive, for example, detailed instructions for the construction of material objects, a scale model of the capital of Delta Pavonis 3, a household appliance of Beta Hydri 4, or perhaps a novel scientific device developed on 82 Eridani 2. It is even possible, as Fred Hoyle has suggested, that we should receive detailed instructions for assembling the genetic material of an extraterrestrial organism, even an intelligent extraterrestrial organism. △ But even then, the demand for actual physical exchange would soon arise.

▽ In electromagnetic interstellar communication, the communicants are far distant, the learning vicarious, and the duration of the discourse long. But if direct interstellar spaceflight were possible, it would sweep away these difficulties; it would reopen the arena of action for civilizations where local exploration has been completed; it would provide access beyond the planetary frontiers. We have already discussed the possibility of automatic interstellar spaceflight. We must now examine the prospect of interstellar spaceflight, manned—this will not be quite the appropriate word—by intelligent beings.

▽ There are two basic methods of achieving interstellar spaceflight within characteristic human lifetimes. One involves the slowing down of human metabolic activities during very long flight times. Let us imagine that society has advanced to the stage where fast non-relativistic interstellar spaceflight is possible, with velocities of, say, 100,000 km sec^{-1}, one-third the speed of light. A one-way voyage to a destination planet 1000 light years distant would take some 3000 years, or slightly longer, allowing for acceleration and deceleration. A round-trip to the Galactic center would take about 60,000 years. If such voyages are to be feasible, the lifetime of our civilization should perhaps exceed the length of the voyage. Otherwise, there will be no one to come home to. Work on metabolic inhibitors is just beginning on our planet. As we discussed in Chapter 19, it is possible to preserve a variety of microorganisms for extended periods of time—perhaps indefinitely—by quick-freezing them to fairly low temperatures. Low-temperature preservation of human blood and sperm is now routine. But the preservation of a whole human being at low temperatures for extended periods of time has never been accomplished. The reason is essentially this: The density of ice is lower than the density of water. (This is why ice floats on ponds in winter.) Therefore, ice occupies a larger volume than the same mass of water. (For this reason, milk bottles placed outdoors on cold days undergo sometimes spectacular distortions.) Consequently, on freezing an animal such as a human being, composed largely of water, serious damage is done to his cells, both during freezing and during thawing. During freezing, the volumes of the cells increase; they encroach upon each other, and their internal structure is disrupted. During thawing, comparable contractions occur. Antifreezing chemicals are, of course, known, but it is difficult to saturate adequately a human being with such antifreezes without killing him first.

▽ But there do exist possibilities which have not yet been explored. As one example, we consider the following idea, developed jointly in conversation between myself and the Swedish biologist Carl-Gören Hedén, of the Karolinska Institute, Stockholm. While freezing preserves, it also kills, as we have just discussed, because of the difference in density between water and ice. But at high pressures, there are other kinds of ice, with different crystal structures and different densities from those of ordinary ice. At pressures of about 3000 atm and temperatures of $-40°C$ ($-40°F$) or less, ordinary ice, called ice I, becomes ice II, a variety of frozen water which has very nearly the same density as the liquid. If a human being could be safely brought to and maintained at an ambient pressure of several thousand atmospheres, and then quickly and carefully frozen to very low temperatures, it might be possible to preserve him for long periods of time. This is only one of many possible alternatives. It seems possible that by the time interstellar space vehicles with velocities of 10^{10} cm sec^{-1} are available, techniques for long-term preservation of a human crew will also be available. From the same considerations which we developed in Chapter 15, in our discussion of the survival of interstellar panspermia, it follows that even for very long journeys—say, approaching 10^5 years in duration—the background cosmic radiation will not prove a very serious hazard to the survival of the sleeping crew.

▽ There is another possible means of establishing manned interstellar spaceflight over long distances, which does not necessarily involve metabolic inhibitors. This is relativistic interstellar spaceflight.

▽ It has been known for some time that there is a remarkable effect, due to the theory of relativity, which would play a major role in spaceflights at velocities close to *c*, the velocity of light. The passage of time, as measured by the crew of the space vehicle, would be very slow when compared with the passage of time measured by their friends, relatives, and colleagues on their home planet. As the passengers would travel over immense distances of thousands of light years or more at relativistic velocities, they would become only slightly older. This phenomenon of relativistic time dilation is a specific consequence of the theory of special relativity formulated by Albert Einstein, a theory whose other predictions have been repeatedly verified. Direct experimental confirmations of time dilation itself also exist. For example, the time for an elementary particle called a mu meson to decay at non-relativistic velocities is well known. If, as a result, for example, of the cosmic ray bombardment of the upper atmosphere, a mu meson were to enter the atmosphere of the Earth traveling at a velocity close to the speed of light, but with its ordinary lifetime, it would never reach the surface of the Earth, and would never be detected there. Instead, mu mesons are commonly detected at the surface of the Earth, because the time for them to decay when moving at relativistic velocities is much longer than the time for them to decay at slower velocities. There is no essential difference between biological time and physical time; both are subject to the same physical laws. Aboard a relativistic interstellar space ship, not only would the passengers' clocks move more slowly than their counterparts' on Earth, but they themselves would move more slowly, their hearts would beat more slowly, their awareness of the passage of time would be retarded. Relativistic interstellar spaceflight is in fact a kind of metabolic inhibitor, but one that works on the entire spacecraft.

▽ Let us illustrate the time dilation phenomenon with a concrete example. Let us consider a spacecraft which moves with a constant acceleration as far as the midpoint of its journey, and then decelerates at the same rate to its destination. The acceleration chosen for the trip would very likely be the same as the acceleration due to gravity on the home planet. For example, on the planet Earth, the acceleration due to gravity, that is, the acceleration experienced by any falling body, is 980 cm sec^{-2}, or 32 feet sec^{-2}. If the spacecraft were to move with this same acceleration, called 1 *g*, the human passengers would feel quite at home, and would experience neither any sense of motion nor any untoward lightness or ponderousness. The inhabitants of a Jovian-type planet would choose accelerations of perhaps 2 *g* or 3 *g*. At an acceleration of 1 *g* it would take only about a year to be traveling close to the speed of light. However continued acceleration would not carry the spacecraft faster than the speed of light but only closer and closer to its value of 300,000 km/sec. This ultimate limit on velocity while unfortunate in the present context is inexorable. The impossibility of information or material objects travelling faster than light is one of the firmest foundations of contemporary physics.

▽ With the above flight plan, it is then possible to compute the elapsed time in years, as measured on board the spacecraft, for a trip to a destination distant *S* light years from the Earth. These computations are displayed in Figure 32–1 for three choices of on-board acceleration—1 *g*, 2 *g*, and 3 *g*. We see that at an acceleration of 1 *g*, it takes only a few years, ship time, to reach the nearest stars; 21 years to reach the Galactic center; and 28 years to reach the nearest spiral galaxy beyond the Milky Way. With accelerations of 2 or 3 *g*, these distances can be negotiated in about half the time. Of course, there is no time dilation on the home planet. The elapsed time in years there approximately equals the distance of the destination in light years plus twice the time required to reach relativistic velocities. This time, at an acceleration of about 1 *g*, is close to one year. For distances beyond about 10 light years, the elapsed time on the home planet in years roughly equals the distance of the destination in light years. Thus, for a round-trip with a several-year stopover to the nearest stars, the elapsed time on Earth would be a few decades; to Deneb, a few centuries; to the Vela cloud complex, a few millennia; to the Galactic center, a few tens of thousands of years; to M 31, the great galaxy in Andromeda, a few million years; to the Virgo cluster of galaxies, a few tens of millions of years; and to the immensely distant Coma cluster of galaxies, a few hundreds of millions of years. Nevertheless, each of these enormous journeys could be performed within the lifetimes of a human crew, because of time dilation on board the spacecraft.

▽ It is at these immense distances that another curious feature of relativistic interstellar spaceflight emerges. If for some reason we were to desire a two-way communication with the inhabitants of some nearby galaxy, we might try the transmission of electromagnetic signals, or perhaps even the launching of an automatic probe vehicle. With either method, the elapsed transit time to the galaxy would be several millions of years at least. By that time in our future, there may be no civilization left on Earth to continue the dialogue. But if relativistic interstellar spaceflight were used for such a mission, the crew would arrive at the galaxy in

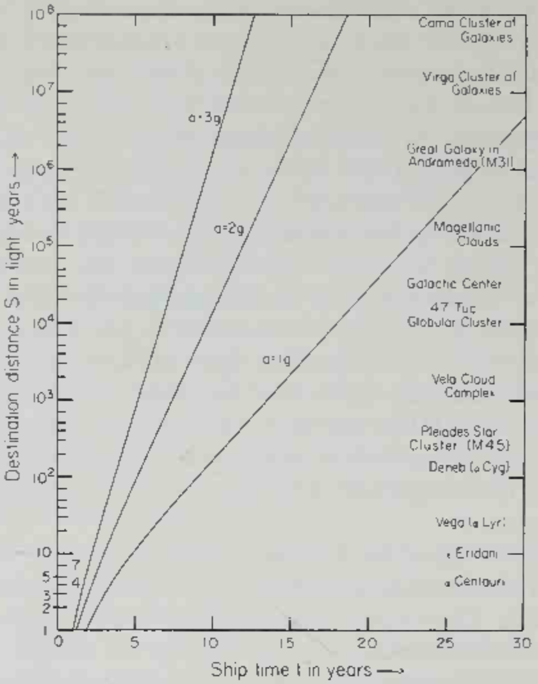

FIGURE 32–1. *An illustration of the potentialities of time dilation in interstellar space flight. A space vehicle is imagined which has uniform acceleration of 1g, 2g, or 3g to the midpoint of its voyage and a uniform deceleration thereafter. It is seen that immense distances —million of light years and more—could be reached by such vehicles during the lifetime of its crew. Yet the time passed on their home planet during the same voyage would amount to millions of years as measured by clocks there. (Courtesy of* Planetary and Space Science, *Pergamon Press, London)*

question after perhaps 30 years in transit, able not only to sing the songs of distant Earth, but to provide an opportunity for cosmic discourse with inhabitants of a certainly unique and possibly vanished civilization. Despite the dangers of the passage and the length of the voyage, I have no doubt that qualified crew for such missions could be mustered. Shorter, round-trip journeys to destinations within our Galaxy might prove even more attractive. Not only would the crews voyage to a distant world, but they would return in the distant future of their own world, an adventure and a challenge certainly difficult to duplicate.

▽ It is clear that the ships and engines which we are now barely developing for the exploration of our provincial solar system are but pale shadows of the mighty starships required for relativistic interstellar spaceflight. The primary problem is the construction of a space ship capable of carrying a substantial payload at extremely high velocities over a long period of time. A propulsion system based on contemporary design with the fuel carried on board the spacecraft at launch would require a fantastic quantity of fuel, even if complete conversion of the mass of the fuel into energy were attainable and all the energy so released could be utilized for thrust. At relativistic velocities and with the above flight plan, the ratio of payload mass to the initial total mass of the spacecraft must be about $2/(1-v/c)$, where v is the maximum velocity. To reach the great galaxy in Andromeda, M 31, during the lifetime of a human crew would require $v = 0.99999\ c$. The initial mass of this ideal fuel would then have to be some 200,000 times greater than the mass of the remainder of the spacecraft. Complete conversion of mass into energy could be obtained only if half the rocket fuel were anti-matter—that is, a form of matter in which our familiar positively charged protons are replaced by negatively charged anti-protons, and in which conventional negative electrons are replaced by positively charged positrons. Anti-matter is uncommon on the Earth for a reason: When it is brought into physical contact with ordinary matter, both become annihilated, in a violent, blinding conversion of mass into energy, often in the form of gamma rays. It is just such an annihilation which would be used to power a hypothetical anti-matter space drive.

▽ The containment of the anti-matter—to say nothing of its production in the quantities required—is clearly a very serious problem. We would not want it to accidentally come into contact with the walls of the spacecraft, themselves composed of ordinary matter. △ Surprisingly, a number of interesting ideas have been put forward which might lead to a successful circumvention of this difficulty. For example, perhaps a special type of non-material, magnetic bottle, employing an intense magnetic field, could be used. Such magnetic bottles are now being investigated in connection with experiments on controlled thermonuclear reactions. ▽ But an interstellar space vehicle powered by anti-matter and requiring a mass ratio of 200,000 does not seem to be an elegant solution to this problem.

▽ A way out of these difficulties which approaches elegance in its conception has been provided by the American physicist Robert W. Bussard, of the TRW Corporation, Los Angeles. Bussard describes an interstellar ramjet which uses the atoms of the interstellar medium both as a working fluid (to provide reaction mass) and as an energy source (through thermonuclear fusion). There is no complete conversion of matter into energy. Such a fusion reactor is certainly not available today, but it violates no physical principles. Its construction is currently being very actively pursued in research on controlled thermonuclear reactions, and there is no reason to expect it to be more than a century away from realization on this planet.

▽ Such an interstellar ramjet would require a large surface area, in order to draw in sufficient interstellar gas to propel the craft. The calculations of Bussard indicate that if there were one atom of hydrogen per cm^3 in the interstellar medium, the surface density of the ramjet would have to be 10^{-8} gm cm^{-2}. In general, the intake surface area of the ramjet is inversely proportional to the concentration n_H of the interstellar gas. If, for example, the mass of the rocket were 100 tons, and n_H equalled 1 atom cm^{-3}, the surface area of the ramjet intake would have to be 10^{15} cm^2, corresponding to a radius of about 700 km. △ In metagalactic space, where $n_H \leq 10^{-5}$ atoms cm^{-3}, the intake radius would have to be 100 times greater.

▽ These frontal loading areas seem, of course, enormously large by contemporary standards, and perhaps remain absurdly large even when we project the progress of future technology. But we should emphasize that the collecting areas need not be material. Intense magnetic fields are now routinely generated in the laboratory, and even in commercial applications, through the use of what are called superconducting flux pumps. Magnetic fields guide charged particles along a specified trajectory, and if the magnetic lines of force are cleverly arranged, through the design of the flux pumps, the charged particles can be conveyed to any desired region within the magnetic field. Thus, it seems at least possible that the collection of atoms of the interstellar medium by ramjet starships will be accomplished by ionizing the medium ahead of the spacecraft, and guiding the ions into the intake area through the use of intense magnetic fields. △

Should the Bussard ramjet become a reality, our descendants will witness a return, in the interstellar context, of the flight principles used by their ancestors for jet aircraft. The surrounding medium would be necessary for flight.

▽ There is still another very serious difficulty which must be overcome before relativistic interstellar spaceflight can be considered feasible. The ramjet is moving through the interstellar medium with a velocity just short of the velocity of light. This is equivalent to the spacecraft sitting motionless, and the dust grains and atoms of the interstellar medium rushing into it with a velocity almost equal to the velocity of light.

▽ With our previously described flight plan, the maximum velocity of the ramjet would be

$$v = c\,[1 - (1 + aS/2c^2)^{-2}]^{\frac{1}{2}}$$

where S is the destination distance, and a is the constant acceleration and deceleration chosen. If S equalled 10,000 parsecs—the distance to the Galactic center—v would differ from c by only one millionth of a percent. At this velocity, each atom of the interstellar medium colliding with the ramjet would appear as a component of the cosmic rays having an energy of 10^{13} electron volts. For 1 atom of hydrogen cm^3 in interstellar space, the spacecraft encounters 10^{13} electron volts cm^{-3}. Since the spacecraft is moving almost with the velocity of light, the flow of equivalent cosmic radiation striking the frontal loading area of the ramjet would be 10^{13} electron volts cm^{-3} $\times$ (3×10^{10} cm sec^{-1}) $= 3 \times 10^{23}$ electron volts cm^{-2} sec^{-1}, or 2×10^{11} erg cm^{-2} sec^{-1}. This is penetrating radiation, with an intensity 100,000 times greater than the intensity of sunlight at the surface of the Earth.

The crew would be fried, even on flights to the nearest stars, unless careful precautions were taken.

▽ It is evident, from the large mass ratios already required for "boosted" interstellar flight (for example, using anti-matter), and from the very low frontal loading area surface densities required for an interstellar ramjet, that material shielding would probably never be a practical solution. But it is possible that the same magnetic deflection techniques used to guide interstellar particles to the ramjet's thermonuclear reactor could also be used to deflect particles away from the living quarters and other sensitive areas of the spacecraft. △

These difficulties seem colossal today, but we must remember that a century ago, the prospect of flight in a heavier-than-air vehicle seemed remote ▽ or impossible. △ Now, of course, we take the airplane for granted. Experience in the development of science and technology teaches us that if the basic requirements for an idea do not contradict known scientific principles, sooner or later the problem will be solved. The tempo of scientific and technological development seems to be increasing with each decade. Considering all the possibilities for establishing contact among Galactic civilizations, we cannot exclude direct contact by means of interstellar spaceflight. ▽ Bussard's own concluding remarks on the magnitude of the effort involved in relativistic interstellar spaceflight are worth quoting:

> . . . On any account interstellar travel is inherently a rather grand undertaking, certainly many magnitudes broader in scope and likewise more difficult than interplanetary travel in the solar system . . . The engineering effort required for the achievement of successful short-time interstellar flight will likely be as much greater than that involved in interplanetary flight as the latter is more difficult than travel on the surface of the Earth. However, the expansion of man's horizons will be proportionately greater, and nothing worthwhile is ever achieved easily. △

33

Possible consequences of direct contact

Where are they?

Enrico Fermi (1943)

. . . Were we to meet with a Creature of a much different Shape from Man, with Reason and Speech, we should be much surprised and shocked at the Sight. For if we try to imagine or paint a Creature like a Man in every Thing else, but that has a Neck four times as long, and great round Eyes five or six times as big, and farther distant, we cannot look upon't without the utmost Aversion, altho' at the same time we can give no account of our Dislike . . . For 'tis a very ridiculous Opinion, that the common People have got, that 'tis impossible a rational Soul should dwell in any other Shape than ours . . . This can proceed from nothing but the Weakness, Ignorance, and Prejudice of Men.

Christianus Huygens, *New Conjectures Concerning the Planetary Worlds, Their Inhabitants and Productions* (c. 1670)

▽ In the previous chapter, we argued that manned interstellar spaceflight, either at sub-relativistic velocities using metabolic inhibitors, or at relativistic velocities with the Bussard ramjet, is possible without appeal to as yet undiscovered principles. Especially allowing for a modicum of scientific and technological progress within the next few centuries, I believe that efficient interstellar spaceflight to the farthest reaches of our Galaxy is a feasible objective for humanity. If this is the case, other civilizations, aeons more advanced than ours, must today be plying the spaces between the stars.

▽ If interstellar spaceflight is technically feasible, even though an exceedingly expensive and difficult undertaking from our point of view, it is likely to be developed by a civilization substantially in advance of our own. Even beyond the exchanges of information and ideas with other intelligent communities, the scientific advantages of interstellar spaceflight are innumerable. There are direct astronomical samplings—of stars in all evolutionary stages, of distant planetary systems, of the interstellar medium, of very ancient globular clusters. There are cooperative astronomical ventures, such as the trigonometric parallaxes of extremely distant objects; there is the observation and sampling of a multitude of independent biologies and societies. These are undertakings which could challenge and inspire even a very long-lived civilization.

▽ For the civilization lifetimes, *L*, previously adopted, we see that interstellar spaceflight to all points within the Galaxy, and even to other galaxies, is possible in principle. The voyagers will return far in the future of their departure, but we have already anticipated the civilization will be stable over these immense periods of time. There will still be a record of the departure, a repository for the information collected, and a community interested in results obtainable in no other way. To avoid unnecessary duplication in interstellar exploration, the communicative societies will pool information and act in concert, as Bracewell has already pointed out. Direct contacts and exchange of information and artifacts will exist among most spacefaring societies possessing starships. In fact, over large distances, starship communication will occur very nearly as rapidly as, and much more reliably than, communication by electromagnetic radiation. The situation bears some similarity to the post-Renaissance seafaring communities of Europe and their colonies before the development of clipper ships and steamships. If interstellar spaceflight is feasible, the technical civilizations of the Galaxy will be an intercommunicating whole. But the communication will be sluggish.

▽ It is of some interest to estimate the mean time interval between contacts for a given planetary system. Although the shipboard transit times at relativistic velocities are very roughly the same to any place in the Galaxy, the elapsed time on the home planet is, of course, approximately proportional to the distance of the voyage. Interstellar contact using either metabolic inhibitors or relativistic velocities should be most frequent among neighboring communities, although we can anticipate that occasional very long journeys will be attempted.

▽ Let each of the N planets in the communicative phase launch q starships per year. These vehicles each effect at least one contact per journey, and are most often gone some 10^3 to 10^4 years from the home planet per mission. In the steady state, there are then q contacts per year effected by each of N planets, and about qN contacts per year for the Galaxy as a whole (the units of time here are Earth years). Relative to the economic capacity of such advanced civilizations, a value of $q = 1$ yr^{-1} seems modest. Other choices of q will modify the results in an obvious manner. Thus, each civilization makes about one contact per year, and an average of L contacts during its lifetime. Let us assume, following the discussion at the beginning of Chapter 29, that $N = 10^6$ and $L = 10^7$ years. △ In my opinion, these estimates of Sagan are slightly too optimistic. ▽ Then, each civilization makes an average of 10^7 contacts during its lifetime. The number of contacts per year for the Galaxy as a whole is 10^6, a sizable fraction of which should be between two advanced communities. The mean number of starships on patrol from each technical civilization at any given time is $\sim 10^3$ to 10^4.

▽ If contacts are made on a purely random basis, each star should be visited about once each 10^5 years. Even the most massive stars will then be examined at least once while they are on the main sequence. Especially with a central Galactic information repository, these advanced civilizations should have an excellent idea of which planetary environments are most likely to develop intelligent life. With an average contact frequency per planet of 10^{-5} yr^{-1}, the origin and evolution of life on every planet in the Galaxy can be monitored efficiently. The successive development of metazoa, of cooperative behavior, of the use of tools, and of primitive intraspecific communication schemes would each be noted, and might each be followed by an increase in the interstellar sampling frequency. If the fraction of inhabited planets which have intelligent beings on them, f_i, is about 10^{-1}, then, biasing by rarity, the frequency of contact with intelligent pre-technical planetary communities should be $\sim 10^{-4}$ yr^{-1}. Once a technical civilization has been established, and especially after interstellar contact has been established—for example, by radio—the frequency of direct contact should again increase. If the fraction of planets inhabited by intelligent beings which are also in the communicative phase is $f_c \sim 10^{-1}$, the contact frequency with technical societies should be increased to about 10^{-3} yr^{-1}. Planets of extraordinary interest will be visited even more frequently.

▽ Under the preceding assumptions, each communicative technical civilization should be visited by another such civilization about once every thousand years. The survey vehicles of each civilization should return to the home planet at a rate of about one a year, and a sizable fraction of these will have had contact with other communities. The wealth, diversity, and brilliance of this commerce, the exchange of goods and information, of arguments and artifacts, of concepts and conflicts, must continuously sharpen the curiosity and enhance the vitality of the participating societies.

▽ If these estimates are even approximately correct, we may anticipate extensive interstellar colonization by technical civilizations of planets previously uninhabited. In Chapter 29, we estimated crudely the probability that a given planet suitable for life actually possesses a technical civilization as $f_c f_i \sim 1$ percent. Thus habitable planets lacking technical civilizations will frequently be encountered by spacefaring civilizations. It is not clear what their response will be. They may wish to leave such worlds strictly alone and permit them to slowly evolve their own unique life forms, through the inexorable sieve of natural selection. Direct contact may be delayed until the life forms on a planet develop a technical society at their own pace. Perhaps strict injunctions against colonization of populated but pre-technical planets is in effect in some *Codex Galactica*. But we are in no position to judge extraterrestrial ethics. Perhaps attempts are made to colonize every habitable planet without regard for the indigenous inhabitants, for purposes of prestige, or exploitation, or some non-human motivation which we cannot even guess. A whole spectrum of intermediate cases can also be imagined, in which small colonies are planted on pre-technical planets, not to interfere with or direct the evolutionary development of the local life forms, but merely to observe them. Note that if colonization is the rule, then even one spacefaring civilization would rapidly spread, in a time much shorter than the age of the Galaxy, throughout the Milky Way. There would be colonies of colonies of colonies, such as arose at many sites in the Western Mediterranean during classical times.

▽ But then, every habitable planet would have a technical civilization, and $f_i f_c$ would equal 1. Using our analysis of the beginning of Chapter 29, it would then follow that the number of technical civilizations in the Galaxy at the present time, $N = 10\ L$, where L is the mean lifetime per civilization. If we were to take $L = 10^7$ years, there would be 10^8 technical civilizations in the Galaxy, or on planets orbiting about 0.1 percent of the stars in the sky. The mean distance between technical civilizations would then be, instead of hundreds of light years, tens of light years. If instead we selected von Hoerner's estimate of $L \sim 10^4$ years, the mean distance would remain at several hundreds of light years.

▽ The preceding discussion has two curious applications to our own planet, one to our past, and the other to our future. Figure 33–1 shows a recent reconstruction of the ancestral tree of contemporary man, compiled from painstaking paleontological, archeological, and anthropological analyses. We see that some 25 million years ago, there existed a creature named Proconsul who was probably ancestral both to Homo Sapiens and to the great apes. Proconsul was erect, bipedal, and tool-using. The subsequent evolution in the line of man has been marked, as all evolutionary tracks are, by fits and starts and dead ends. We see, for example, that late Paranthropus, late Java man, and late Neanderthal man all represent evolutionary dead ends. They were intelligent, communicative, and probably had their own simple cultures, but they left no issue. Had the physical environment been slightly different, had the accidents of daily existence occurred another way, Homo Sapiens might have been an evolutionary dead end, and perhaps today there would have been a technical civilization of Pithecanthropi on the planet Earth; or perhaps no civilization at all.

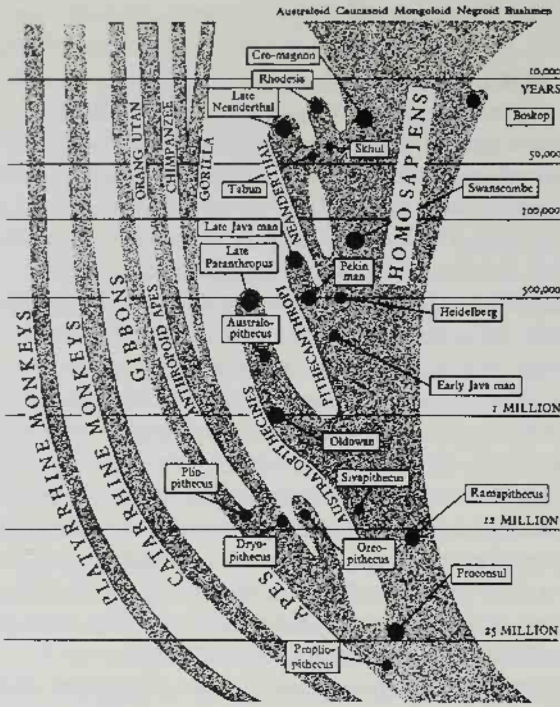

CHART I. The Evolution of Man

FIGURE 33–1. *The evolution of man according to one knowledgable recent view. (Redrawn with slight changes after an illustration in* Pre-History and the Beginnings of Civilization *by Jacquetta Hawkes and Sir Leonard Woolley, Harper and Row, 1963; by permission.)*

▽ But these matters, while difficult for us to reconstruct from a distance of millions of years, would have been much clearer to a technical civilization greatly in advance of the present one on Earth, which visited us every hundred thousand years or so to see if anything of interest was happening lately. Some 25 million years ago, a Galactic survey ship on a routine visit to the third planet of a relatively common *G* dwarf may have noted an interesting and promising evolutionary development: Proconsul. The information would have filtered at the speed of light slowly through the Galaxy, and a notation would have been made in some central information repository, perhaps at the Galactic center. If the emergence of intelligent life on a planet is of general scientific or other interest to the Galactic civilizations, it is reasonable that with the emergence of Proconsul, the rate of sampling of our planet should have increased, perhaps to about once every ten thousand years. At the beginning of the most recent post-glacial epoch, the development of social structure, art, religion, and elementary technical skills should have increased the contact frequency still further. But if the interval between sampling is only several thousand years, there is then a possibility that contact with an extraterrestrial civilization has occurred within historical times.

▽ There are no reliable reports of direct contact with an extraterrestrial civilization during the last few centuries, when critical scholarship and non-superstitious reasoning have been fairly widespread [see Chapter 2]. Any earlier contact story must be encumbered with some degree of fanciful embellishment, due simply to the views prevailing at the time of the contact. The extent to which subsequent variation and embellishment alters the basic fabric of the account varies with time and circumstance. For example, M. Eliade's book *Cosmos and History,* mentions an incident in Rumanian folklore, recorded by C. Brailoiu, where only 40 years after a true romantic tragedy, the real story became elaborately embellished with mythological material and supernatural beings. The actual heroine was still alive at the time that the ballad was being sung and attributed to remote antiquity.

▽ Another incident which is more relevant to the topic at hand is the native account of the first contact of the Tlingit people of the northeast coast of North America with European civilization—an expedition led by the French navigator La Perouse, in 1786. The Tlingit kept no written records; one century after the contact, the verbal narrative of the encounter was related to the American anthropologist G. T. Emmons by a principal Tlingit chief. The story was overlaid with the mythological framework in which the French sailing vessels were initially interpreted. But what is very striking is that the true nature of the encounter had been faithfully preserved. One blind old warrior had mastered his fears at the time of the encounter, had boarded one of the French ships, and exchanged goods with the Europeans. Despite his blindness, he reasoned that the occupants of the vessels were men. His interpretation led to active trade between the expedition of La Perouse and the Tlingit. The oral rendition contained sufficient information for later reconstruction of the true nature of the encounter, although many of the incidents were disguised in a mythological framework—for example, the sailing ships were described as immense black birds with white wings. △

As another example, the people of sub-Saharan Africa, who had no written language until the colonial period, preserved their history primarily through folklore. Such legends and myths, handed down by illiterate people from generation to generation, are in general of great historical value.

▽ The encounter between La Perouse and the Tlingit suggests that under certain circumstances, a brief contact with an alien civilization will be recorded in a reconstructible manner. The reconstruction will be greatly aided if (1) the account is committed to written record soon after the event; (2) a major change is effected in the contacted society by the encounter; and (3) no attempt is made by the contacting civilization to disguise its exogenous nature.

▽ On the other hand, it is obvious that the reconstruction of a contact with an extraterrestrial civilization is fraught with difficulties. What guise may we expect such a contact myth to wear? A simple account of the apparition of a strange being who performs marvelous works and resides in the heavens is not quite adequate. All peoples have a need to understand their environment, and the attribution of the incompletely understood to non-human deities is at least mildly satisfying. When interaction occurs among peoples supporting different deities, it is inevitable that each group will claim extraordinary powers for its god. Residence of the gods in the sky is not even approximately suggestive of extraterrestrial origin. After all, where can the gods reside? Obviously, not over in the next county. It would be too easy to disprove their existence by taking a walk. Until very subtle metaphysical constructs are developed—possibly, in desperation—the gods can only live beneath the ground, in the waters, or in the sky. Except, perhaps, for seafaring peoples, the sky offers the widest range of opportunities for theological speculation.

▽ Accordingly, we require more of a legend than the apparition of a strange being who does extraordinary works and lives in the sky. It would certainly add credibility if no obvious supernatural adumbration were attached to the story. A description of the morphology of an intelligent non-human, a clear account of astronomical realities which a primitive people could not acquire by their own efforts, or a transparent presentation of the purpose of the contact would increase the credibility of the legend. △

Such an unusual occurrence would certainly be described in the legends and myths of the people who came into contact with space voyagers. The astronauts would probably be portrayed as having godlike characteristics and possessing supernatural powers. Special emphasis would be placed on their arrival from the sky, and their subsequent departure back into the sky. These beings may have taught the inhabitants of the Earth useful arts and basic sciences, which would also be reflected in their legends and myths.

In 1959, the Soviet ethnologist M. M. Agrest postulated that representatives from an extraterrestrial civilization have indeed visited our planet. ▽ Despite the great dangers of confusion with legends generated in other ways, △ such hypotheses are entirely reasonable, and worthy of careful analysis. Agrest has boldly conjectured that perhaps a number of events described in the Bible were in reality based on the visit of extraterrestrial astronauts to the Earth. For example, the circumstances surrounding the destruction of Sodom and Gomorrah remind Agrest of a nuclear explosion as it might have been described by an observer living in ancient times. ▽ As another example, Agrest considers the incidents related in the apocryphal book *The Slavonic Enoch* to be in reality an account of the visitation of Earth by extraterrestrial cosmonauts, and the reciprocal visitation of several Galactic communities by a rather befuddled inhabitant of the Earth. However, *The Slavonic Enoch* fails to satisfy several of the criteria for a general contact myth, mentioned above: It has been molded into several different standardized supernatural frameworks; the astronomy is largely incorrect; and there is no transparent extraterrestrial motivation for the events described. The interested reader may wish to consult standard versions of the tale. △

Agrest further suggests that certain monuments of past cultures result from direct contact with an interstellar society. However, this idea, in our opinion, is highly debatable. Although certain claims have been made from time to time, no known ancient artifacts have been unambiguously connected with a cosmic visit. The well-known Soviet journalist G. N. Ostroumov recently announced to the world that the famous steel parallelepiped,—▽ purportedly a machine-tooled product of an unfamiliar alloy, found embedded in an ancient vein of coal— △ kept at the Salzburg Museum, was in reality a fraud. It has also been shown that the famous rust-resistant column in India is not the result of a visit by extraterrestrial cosmonauts, but rather, an outstanding example of primitive powder metallurgy. Much commotion was made over the discovery of the image of a "Martian god," complete with space suit, found in cliffs overlooking the Sahara [see Figures 33–2 and 33–3]. It transpired that these Tassili frescoes represented in fact an ordinary human being in a ritual mask and costume. The press in the Soviet Union and in other countries tends to exaggerate and over-publicize such matters. Such publicity is due, of course, to widespread popular interest in the possibility of contact with intelligent extraterrestrials. ▽ But for this very reason, △ we must examine very critically any purported artifacts uncovered. It is wise to bear in mind the ancient Chinese proverb mentioned in Chapter 23.

▽ Some years ago, I came upon a legend which more nearly fulfils some of our criteria for a genuine contact myth. It is of special interest because it relates to the

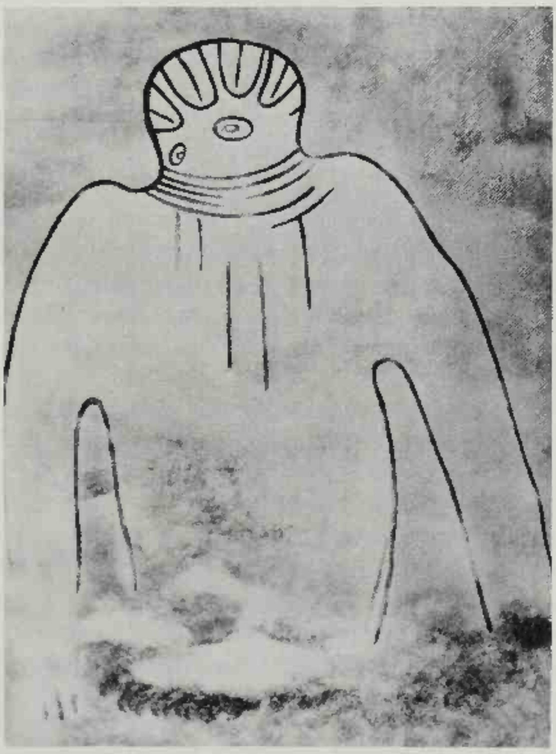

FIGURE 33–2. *A fresco from Tassili-n-ajjer in the central Sahara. Some of these frescoes date to 6000* B.C. *The French archeologist Henri Lhote has called this figure Jabbaren, the "great Martian god," although there is, of course, no evidence to suggest an extraterrestrial origin for the prototype of this illustration. (Reproduced with permission from Henri Lhote,* The Search for the Tassili Frescoes, *E. P. Dutton and Co., New York.)*

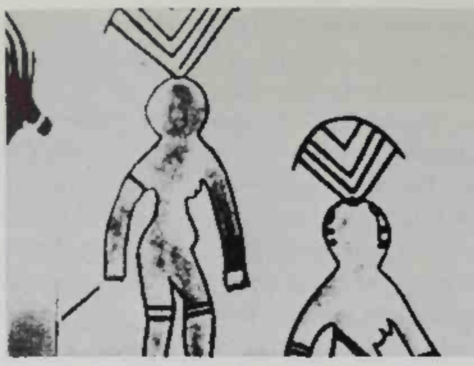

FIGURE 33–3. *A Tassili fresco of apparently a somewhat earlier epoch than that of Figure 33–2. Lhote describes this as the style of the round-headed men, "Martian" phase. The originals are in yellow ochre with red ochre lines. (Reproduced from the Soviet film "Planeta Zagadok".)*

origin of Sumerian civilization. Sumer was an early—perhaps the first—civilization in the contemporary sense on the planet Earth. It was founded in the fourth millennium B.C. or earlier. We do not know where the Sumerians came from. Their language was strange; it had no cognates with any known Indo-European, Semitic, or other language, and is understood only because a later people, the Akkadians, compiled extensive Sumerian-Akkadian dictionaries.

▽ The successors to the Sumerians and Akkadians were the Babylonians, Assyrians, and Persians. Thus the Sumerian civilization is in many respects the ancestor of our own. I feel that if Sumerian civilization is depicted by the descendants of the Sumerians themselves to be of non-human origin, the relevant legends should be examined carefully. I do not claim that the following is necessarily an example of extraterrestrial contact, but it is the type of legend that deserves more careful study.

▽ Taken at face value, the legend suggests that contact occurred between human beings and a non-human civilization of immense powers on the shores of the Persian Gulf, perhaps near the site of the ancient Sumerian city of Eridu, and in the fourth millennium B.C. or earlier. There are three different but cross-referenced accounts of the *Apkallu* dating from classical times. Each can be traced back to Berosus, a priest of Bel-Marduk, in the city of Babylon, at the time of Alexander the Great. Berosus, in turn, had access to cuneiform and pictographic records dating back several thousand years before his time. It is important to quote most of the body of the legend, in the form available today. The manner of presentation is as striking as the content. The quoted translations from the Greek and Latin are taken from Cory's *Ancient Fragments,* in the revised edition of 1876:

The account of Alexander Polyhistor:

> Berosus, in his first book concerning the history of Babylonia, informs us that he lived in the time of Alexander, the son of Philip. And he mentions that there

were written accounts preserved at Babylon with the greatest care, comprehending a term of fifteen myriads of years. These writings contained a history of the heavens and the sea; of the birth of mankind; also of those who had sovereign rule; and of the actions achieved by them.

And, in the first place, he describes Babylonia as a country which lay between the Tigris and Euphrates. He mentions that it abounded with wheat, barley, ocrus, sesamum; and in the lakes were found the roots called gongae, which were good to be eaten, and were, in respect to nutriment, like barley. There were also palm trees and apples, and most kinds of fruits; fish, too, and birds; both those which are merely of flight, and those which take to the element of water. The part of Babylon which bordered upon Arabia was barren, and without water; but that which lay on the other side had hills, and was fruitful. At Babylon there was (in these times) a great resort of people of various nations, who inhabited Chaldea, and lived without rule and order, like the beasts of the field.

In the first year there made its appearance, from a part of the Persian Gulf which bordered upon Babylonia, an animal endowed with reason, who was called Oannes. (According to the account of Apollodorus) the whole body of the animal was like that of a fish; and had under a fish's head another head, and also feet below, similar to those of a man, subjoined to the fish's tail. His voice, too, and language was articulate and human; and a representation of him is preserved even to this day [see Figure 33–4].

This Being, in the day-time used to converse with men; but took no food at that season; and he gave them an insight into letters, and sciences, and every kind of art. He taught them to construct houses, to found temples, to compile laws, and explained to them the principles of geometrical knowledge. He made them distinguish the seeds of the earth, and showed them how to collect fruits. In short, he instructed them in everything which could tend to soften manners and humanise mankind. From that time, so universal were his instructions, nothing material has been added by way of improvement. When the sun set it was the custom of this Being to plunge again into the sea, and abide all night in the deep; for he was amphibious.

After this, there appeared other animals, like Oannes, of which Berosus promises to give an account when he comes to the history of the kings. Moreover, Berosus wrote concerning the generation of mankind; of their different ways of life, and of their civil polity. . .

The account of Abydenus:

So much concerning the wisdom of the Chaldaeans.

It is said that the first king of the country was Alorus, who gave out a report that he was appointed by God to be the Shepherd of the people: he reigned ten sari. Now a sarus is esteemed to be three thousand six hundred years; a neros, six hundred: and a sossus, sixty.

After him Alaparus reigned three sari; to him succeeded Amillarus, from the city of Pantibiblon, who reigned thirteen sari; in his time a semi-daemon called Annedotus, very like to Oannes, came up a second time from the sea. After him Ammenon reigned twelve sari, who was from the city of Pantibiblon; then Megalarus, of the same place, eighteen sari; then Daos, the shepherd, governed

FIGURE 33–4. *A representation of Oannes on an Assyrian cylinder seal of the ninth century* B.C. *The seal was in the Vorderasiatische Abteilung der Staatlichen Museen, Berlin, before the War. (Reproduced from* Cylinder Seals, *by H. Frankfort, Macmillan, London 1939.)*

> for the space of ten sari—he was of Pantibiblon; in his time four double-shaped personages came out of the sea to land, whose names were Euedocus, Eneugamus, Eneuboulos, and Anementus. After these things was Anodaphus, in the time of Euedoreschus. There were afterwards other kings, and last of all Sisithrus (Xisuthrus). So that, in all, the number amounted to ten kings, and the term of their reigns to one hundred and twenty sari. . . .

The account of Apollodorus:

> This is the history which Berosus has transmitted to us: He tells us that the first king was Alorus of Babylon, a Chaldaean; he reigned ten sari; and afterwards Alaparus and Amelon, who came from Pantibiblon; then Ammenon the Chaldaean, in whose time appeared the Musarus Oannes, the Annedotus, from the Persian Gulf. (But Alexander Polyhistor, anticipating the event, has said that he appeared in the first year; but Apollodorus says that it was after forty sari; Abydenus, however, makes the second Annedotus appear after twenty-six sari.) Then succeeded Megalarus, from the city of Pantibiblon, and he reigned eighteen sari; and after him Daonus, the shepherd, from Pantibiblon, reigned ten sari; in his time (he says) appeared again, from the Persian Gulf, a fourth Annedotus, having the same form with those above, the shape of a fish blended with that of a man. Then Euedoreschus reigned from the city of Pantibiblon for the period of eighteen sari. In his day there appeared another personage, whose name was Odacon, from the Persian Gulf, like the former, having the same complicated form, between a fish and a man. (All these, says Apollodorus, related particularly and circumstantially whatever Oannes had informed them of. Concerning these appearances

Abydenus has made no mention.) Then Amempsinus, a Chaldaean from Laranchae reigned, and he, being the eighth in order, ruled for ten sari. Then Otiartes, a Chaldaean from Laranchae, reigned, and he ruled for eight sari.

Upon the death of Otiartes, his son Xisuthrus, reigned eighteen sari. In his time the Great Flood happened. . . .

From the further account of Alexander Polyhistor:

> After the death of Ardates, his son, Xisuthrus, succeeded, and reigned eighteen sari. In his time happened the great Deluge; the history of which is given in this manner. The deity Kronus appeared to him in a vision, and gave him notice, that upon the fifteenth day of the month Daesia there would be a flood, by which mankind would be destroyed. He therefore enjoined him to commit to writing a history of the beginning, progress, and final conclusion of all things, down to the present term; and to bury these accounts securely in the City of the Sun at Sippara; and to build a vessel, and to take with him into it his friends and relations; and to convey on board everything necessary to sustain life, and to take in also all species of animals that either fly, or rove upon the earth; and trust himself to the deep. Having asked the deity whither he was to sail, he was answered, 'To the Gods'. . . .

▽ The preceding four fragments from ancient writers present an account of a remarkable sequence of events. Sumerian civilization is depicted by the descendants of the Sumerians themselves to be of non-human origin. A succession of strange creatures appears over the course of several generations. Their only apparent purpose is to instruct mankind. Each knows of the mission and accomplishments of his predecessors. When a great inundation threatens the survival of the newly introduced knowledge among men, steps are taken to insure its preservation. Thereby, the access of Berosus to antediluvian records is formally explained.

▽ The straightforward nature of this account of contact with superior beings is notable. Oannes and the other Apkallu are described variously as "animals endowed with reason," as "beings," as "semi-daemons," and as "personages." They are never described as gods.

▽ Alexander Polyhistor's description of a sudden transition from chaos to civilization after the appearance of Oannes is in accord with the impressions of some, but by no means all, archeologists. For example, the Danish-American Sumerologist Thorkild Jacobsen, of Harvard University, writes:

> Thousands of years had already passed since man first entered the valley of the Two Rivers, and one prehistoric culture had followed another—all basically alike, none signally different from what one might have found elsewhere in the world. During these millenniums agriculture was the chief means of support. Tools were fashioned from stone, rarely from copper. Villages, made up of patriarchal families, seem to have been the typical form of settlement. The most conspicuous change from one such culture to another, surely not a very profound one, seems to have been in the way pottery was made and decorated.
>
> But with the advent of the Proto-literate period the picture changes. Overnight,

as it were, Mesopotamian civilization crystallizes. The fundamental pattern, the controlling framework within which Mesopotamia is to live its life, formulate its deepest questions, evaluate itself and evaluate the universe, for ages to come, flashes into being, complete in all its main features.

▽ However, since Jacobsen wrote this memorable passage, some evidence has been found for much earlier primitive cities in Mesopotamia, and it now appears possible that the development of Mesopotamian civilization was more gradual than Jacobsen suggested.

▽ Finally, we may mention some relevant ideas of Sumerian mythology. The gods are characterized by a variety of forms, not all human. They are celestial in origin. In general, each is associated with a different star. In fact, in the earliest Sumerian pictographs, which preceded cuneiform writing, the symbols for god and for star are identical. The cosmos is conceived as a state governed by an apparently representative and democratic assembly of the gods, which made the great decisions on the fates of all beings. Within the assembly there was a smaller group of prominent deities called "The Seven Gods Who Determine Destinies." Such a picture is not altogether different from what we might expect if a network of confederated civilizations interlaced the Galaxy.

▽ Some of the astronomical and other ideas of Sumerian and successor civilizations are portrayed on cylinder seals—small cylinders which, when rolled on clay or other impressionable material, left behind the negative of its impression. Unfortunately, the cuneiform notations on each cylinder seal are only very rarely related to the pictorial content of the seal. More often, the cuneiform inscription says something like the Sumerian equivalent of "Joe Williamson: his seal". The illustrations on the cylinder seals have for this reason generally defied attempts to understand them in detail. They refer to mythological material otherwise lost.

▽ In Figure 33–5, we see reproductions of four such cylinder seals, which are now at various museums. In each, there is a clear representation of some celestial object—a central circle, or sphere, surrounded by other, generally smaller circles or spheres. In the upper left-hand illustration of Figure 33–5, we see that the central circle is surrounded by rays and can quite clearly be identified as a sun or star. But what are we to make of the other objects surrounding each star? It is at least a natural assumption that they represent the planets. But the idea of planets circling suns and stars is an idea which essentially originated with Copernicus—although some earlier speculations along these lines were mentioned in ancient Greece.

▽ The cylinder seal in the upper left-hand corner of Figure 33–5 shows, curiously enough, *nine* planets circling the prominent sun in the sky (and two smaller planets, off to one side). The other representations of planetary systems—if we may call them this—show, remarkably, a variation in the numbers of planets per star. In some of the cylinder seals, a star and accompanying planets seem to be associated with a particular deity. An even more enigmatic cylinder seal can be seen in Figure 33–6.

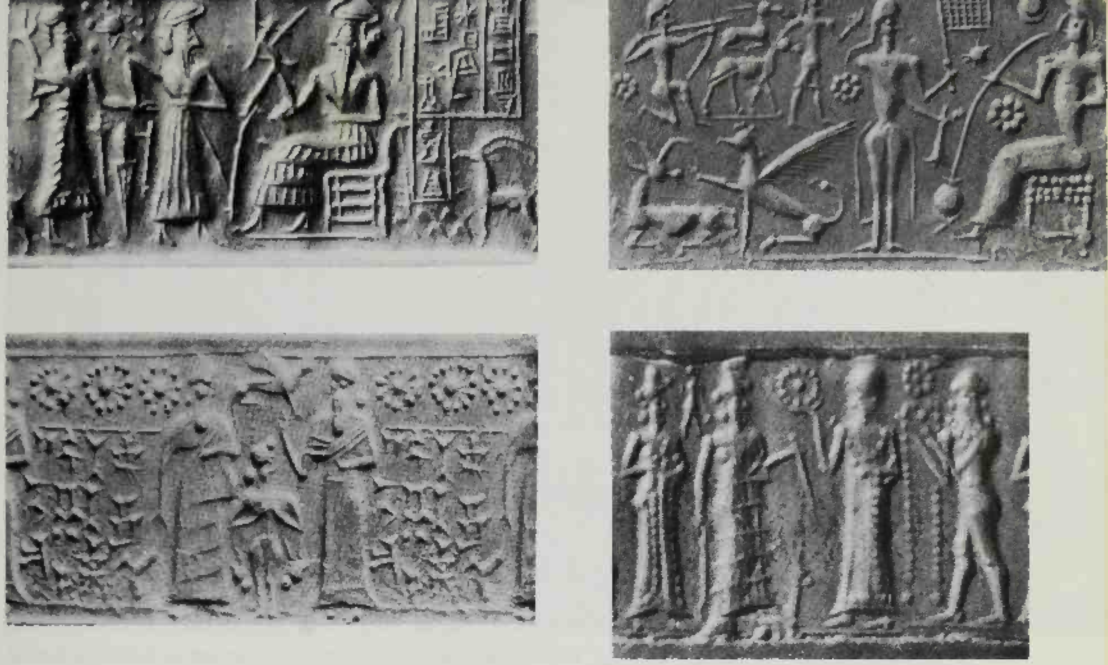

Figure 33–5. *Upper left: an Akkadian cylinder seal showing the god of fertility with plow. The seal was in the Vorderasiatische Abteilung der Staatlichen Museen, Berlin, before the War. Upper right: a Mitannian cylinder seal from the British Museum showing, among other interesting objects, what are conventionally described as a hunter and a drinker. Lower left: a late Kassite cylinder seal, showing influence of Mitannian style. This seal is in the Louvre. Lower right: a cylinder seal from the first Babylonian Empire conventionally described as "Marduk and hero with flowing vase". The seal was in the Vorderasiatische Abteilung der Staatlichen Museen, Berlin, before the War. (Reproduced from* Cylinder Seals, *by H. Frankfort, Macmillan, London, 1939.)*

▽ These cylinder seals may be nothing more than the experiments of the ancient unconscious mind to understand and portray a sometimes incomprehensible, sometimes hostile environment. The stories of the Apkallu may have been made out of whole cloth, perhaps as late as Babylonian times, perhaps by Berosus himself. Sumerian society may have developed gradually over many thousands of years. In any event, a completely convincing demonstration of past contact with an extraterrestrial civilization will always be difficult to provide on textual grounds alone. But stories like the Oannes legend, and representations especially of the earliest civilizations on the Earth, deserve much more critical studies than have been performed heretofore, with the possibility of direct contact with an extraterrestrial civilization as one of many possible alternative interpretations.

▽ There are also other possible sources of information. With the numbers we have discussed, it seems possible that the Earth has been visited by various Galactic civilizations many times (possibly $\sim 10^4$, during geological time). It is not out of the question that artifacts of these visits still exist—although none have been found to date—or even that some kind of base is maintained within the solar system to provide continuity for successive expeditions. Because of weathering and the possibility of detection and interference by the inhabitants of the Earth, it might have appeared preferable not to erect such a base on the Earth's surface. The

FIGURE 33–6. *Assyrian cylinder seal of the ninth century* B.C. *On the left is a scorpion-man and a sun disk with wings, both conventional Mesopotamian symbols. The wistful animal at stage center with the cumbersome apparatus on his back is conventionally described as a dragon. Note the dolphin representation just in front of him. The seal was in the Vorderasiatische Abteilung der Staatlichen Museen, Berlin, before the War. (Reproduced from* Cylinder Seals, *by H. Frankfort, Macmillan, London, 1939.)*

Moon seems one reasonable alternative site for a base. Forthcoming high-resolution photographic reconnaissance of the Moon from space vehicles—particularly, of the back side—might bear these possibilities in mind. △ Agrest has independently made a similar conjecture, ▽ as has the Anglo-Ceylonese science writer, Arthur C. Clarke. △ The cosmic visitors would probably reason that by the time man had developed the technology to explore the far side of the Moon, he would also have attained a certain limited degree of advancement and might be called civilized. ▽ Contact with such a base would, of course, provide the most direct check on the possibility of fairly frequent interstellar spaceflight.

▽ The rate of technical advance of our civilization is very great. It is possible that an extraterrestrial society or federation of such societies might want to contact an emerging technical civilization as soon as possible, perhaps to head off a nuclear annihilation—one possible consequence of intensive technological development—or perhaps for other reasons. A visit every few thousand years would not be nearly frequent enough for such a purpose. Drake and Clarke have suggested that an advanced extraterrestrial civilization might deposit an automatic technology monitor, an alarm which beacons across interstellar space when the local level of technological advance has reached a certain point. For example, such a monitor might analyze the content of radioactive elements in the atmosphere. A substantial increase in atmospheric radioisotopes such as has occurred due to nuclear testing during the last two decades would then trigger the alarm. An extraterrestrial resident agent is an alternative possibility. If such an alarm system exists—although it is of course nothing more than the barest supposition—then it has probably been triggered by now. The message may be winging across interstellar space with the speed of light to the nearest advanced technical civilization. But if civilizations are separated by several hundreds of light years, we will have to wait until A.D. 2300 or 2400 for their response.

▽ However it may not have been considered necessary to introduce such a monitor in a developing society. A technical civilization soon indicates its own existence unintentionally. In Chapter 27 we described the possibility of eavesdropping on radio communication intended for local consumption on a planet. Some 40 or 45 light years from the Earth, at the time of writing, there is a wave front propagating away from the Earth due to the first development of extensive commercial radio broadcasting on Earth. In another few hundred years, it may reach the nearest outpost of the community of Galactic civilizations, and it will be a few centuries further into the future before any response, friendly or unfriendly, could be felt on Earth.

▽ In the discussion of interstellar radio communication in Chapter 27, we mentioned that contact would never be achieved if all advanced civilizations were listening, and none were transmitting signals. Some people have suggested that for the present, we might assiduously listen, but should carefully refrain from transmitting, because we do not know the intentions of a superior Galactic society. This argument deserves a closer examination. What might an advanced extraterrestrial civilization want of us? Most of the conventional nightmares can be dismissed. We would not be useful as slaves, because a society capable of mastering interstellar spaceflight would have adequate machine servants. They could not want us for food, even if human beings were composed of especially tasty proteins. Such a society should be capable of synthesizing them in any desired quantity from the constituent amino acids, after the analysis of a single specimen.

▽ There are other possibilities which cannot be so easily dismissed. One of the primary motivations for the exploration of the New World was to convert the inhabitants to Christianity—peacefully, if possible; forcefully, if necessary. Can we exclude the possibility of an extraterrestrial evangelism? While American Indians were not useful for any concrete task in the courts of Spain and France, they were nonetheless transported there for prestige purposes. Is this an emotion alien to extraterrestrial civilizations? Or perhaps human beings have some relatively uncommon talent, of which they are themselves entirely unaware. J. B. S. Haldane once pointed out to me that sea lions and seals have a remarkable ability to balance a rubber ball on their noses, which is part of the reason we maintain them in captivity. Yet such an ability is probably perfectly useless for a seal in the wild state. While any organism or artifact of the Earth could be duplicated by an advanced extraterrestrial society, the original and the duplicate are still different. The American psychologist Ruth Ellen Galper has pointed out in this connection that we carefully distinguish between natural and cultured pearls. Finally, can we exclude even darker motives? Might an extraterrestrial society want to be alone at the summit of Galactic power, and make a careful effort to crush prospective contenders? Or might there even be the "cockroach response"—to stamp out an alien creature simply because it is different, as suggested in the closing scene of Franz Kafka's *Metamorphosis?*

▽ It may be that these gruesome possibilities are real. Or the fact that we can imagine them may be itself only a reflection of how much further we have to go before we will be ready for full membership in a Galactic community of societies. But in either case, there is no way back. It is of no use to maintain an interstellar radio silence; the signal has already been sent. Forty light years out from Earth, the news of a new technical civilization is winging its way among the stars. If there are beings out there, scanning their skies for the tidings of a new technical civilization, they will know of it, whether for good or for ill. If interstellar spaceflight by advanced technical civilizations is commonplace, we may expect an emissary, perhaps in the next several hundred years. Hopefully, there will then still be a thriving terrestrial civilization to greet the visitors from the far distant stars. △

34

Intelligent life as a factor on the cosmic scale

Alexander wept when he heard from Anaxarchus that there was an infinite number of worlds; and his friends asking him if any accident had befallen him, he returned this answer: "Do you not think it a matter worthy of lamentation that, when there is such a vast multitude of them, we have not yet conquered one?"

Plutarch, *On the Tranquillity of the Mind*

Had I been present at the Creation, I would have given some useful hints for the better ordering of the universe.

Alphonso the Wise (c. 1270)

Intelligent life in the universe tends to have an active influence on the character of the cosmos, as we have frequently mentioned in previous chapters. For example, the activities of man have greatly increased the intensity of radio radiation which the Earth emits into space [Chapter 18]. In the second half of the twentieth century, the inhabitants of the planet Earth are beginning to change the over-all organization of the solar system. For billions of years, our planet had only one moon. Now, many artificial satellites orbit the Earth. In the not-too-distant future, artificial satellites may be orbiting our natural moon and other planets of our solar system.

We must note in passing that advances in sciences have, unfortunately, not always been motivated by a desire for the betterment of mankind, but have sometimes been seen as a means for increasing the military power of nations. For purely military reasons, thermonuclear weapons have been exploded high above the atmosphere of the Earth, creating artificial aurorae and magnetic fields. It is hoped that the space sciences of the future will be dedicated solely to the benefit of mankind.

We are only entering the cosmic era. Only a few years have passed since the first artificial satellite was launched. What will the future hold?

Although it is difficult to speculate about the kind of changes which man may bring about in the solar system, several interesting and thought-provoking hypotheses have recently been advanced. For example, Carl Sagan has proposed a way of altering the atmosphere of Venus. ▽ The high surface temperature of Venus appears to be maintained by a greenhouse effect involving both the atmosphere and the clouds [Chapter 22]. Since the amounts of water in the atmospheres of the two planets seem to be roughly comparable, the great difference in temperature must be due at least in part to the fact that the terrestrial atmosphere has several thousand times less carbon dioxide than the Cytherean atmosphere. After the physical environment of Venus has been thoroughly investigated, and if indeed it proves to be lifeless, there will exist the prospect of microbiological planetary engineering.

▽ To prepare Venus for comfortable human habitation, it is necessary to lower the surface temperature and to increase the abundance of molecular oxygen. Both these ends could be accomplished, if a means were found to dissociate carbon dioxide into oxygen and elemental carbon. There is far too much carbon dioxide in the atmosphere for such a goal to be accomplished mechanically. Because of the very rapid growth rate of microorganisms in the absence of predators or competitors, the use of a living organism seems indicated. An organism is needed which can photosynthesize in the cooler parts of the atmosphere of Venus, according to the symbolic equation

$$CO_2 + H_2O + \text{light} \rightarrow [CH_2O] + O_2 \, .$$

The oxygen arises from the water; the symbol $[CH_2O]$ represents organic matter. Since the atmosphere is in convective equilibrium, the organisms would in time be carried to lower atmospheric levels where, because of the higher temperatures, they would be roasted and decomposed, ideally according to the symbolic equation

$$[CH_2O] + \text{heat} \rightarrow C + H_2O \, .$$

Although the oxygen is derived from water, the over-all effect would be to restore the water metabolized in photosynthesis to the atmosphere, and to dissociate carbon dioxide to carbon and oxygen. Since the clouds of Venus appear to be composed of water—probably even liquid water, in their lower parts—a suitable water supply for microorganisms seems to be available. The organisms would have to be nitrogen-fixers—that is, capable of removing molecular N_2 from the Cytherean atmosphere. It would also be useful if the organisms were highly temperature-resistant, and could survive temperatures as low as $-40°C$ ($-40°F$). The only photosynthetic, nitrogen-fixing, oxygen-evolving, and temperature-resistant microorganisms in wide abundance on the Earth are the blue-green algae, primarily of the Nostocaceae family.

▽ Before such a scheme can be seriously considered, we must know much more about the physical environment of Venus, and must be quite sure that the clouds are not previously inhabited by some indigenous Cytherean species. Before we can seed the clouds, we must know whether the algae could reproduce at the cloud level more rapidly than they would be destroyed by convection to the hotter, lower layers of the atmosphere; whether atmospheric convection can transport up from the surface the trace elements required for the reproduction of the organisms; and what the products of slow algal thermal decomposition might be. Ideally, we can envision the seeding of the upper Cytherean atmosphere with appropriately developed strains of Nostocaceae, after exhaustive studies of Venus have been performed. As the carbon dioxide content of the atmosphere falls, the greenhouse effect will be rendered less efficient, and the surface temperature will decline. After the atmospheric temperatures decline sufficiently, the decreasing rate of algal decomposition will reduce the water abundance, and hopefully permit the surface to cool below the boiling point of water. At this time, the original mechanism becomes inoperative, because the algae are no longer thermally decomposed; but surface photosynthesis then becomes possible. At somewhat lower temperatures, rain will reach the surface, and the inorganic production of carbonates will reduce the atmospheric carbon dioxide content still further. If we have properly understood the source of the high surface temperature, and if we can find microorganisms which will act in the desired fashion, it may be possible that in geologically short periods of time the temperature of Venus could be lowered; the CO_2 atmospheric content decreased; molecular oxygen introduced into the atmosphere; and liquid water formed on its surface for the first time. △ As an end result, the inhospitable planet Venus might become suitable for human habitation.

To discuss another possible modification of the cosmos by the activities of intelligent beings, consider the following question: Is it possible that in the future—perhaps the distant future—man could so change the solar system that his activities would be visible over interstellar distances? In Chapter 11, we discussed the difficulties in the detection of planets about even the nearest stars, with present techniques. But what of the future? Is it possible that someday we shall be able to conclude, from observed characteristics, that a star is accompanied by a planet populated by an advanced technical civilization? Let us consider some of the ideas of Constantin Edwardovich Tsiolkovskii, an illustrious Russian pioneer in problems of space exploration.

Three quarters of a century ago, this remarkable man suggested a plan for the rebuilding and reorganization of the solar system. In his book *Dreams of the Earth and Sky*, published in 1895, he pointed out that the Earth receives only 5×10^{-10} of the total flux of solar radiation. He speculated that eventually mankind would make use of all the heat and light of the Sun by colonizing the entire solar system. Tsiolkovskii suggested that first the asteroids be rebuilt. The intelligent beings of the future, he predicted, would control the motion of these small planets "in the same way that we drive horses." The energy necessary to maintain the inhabitants of the asteroids would come from "solar motors." Thus, we see that over 70 years ago, Tsiolkovskii predicted the invention of the solar battery, a device which is presently used to provide energy for space vehicles.

The transformed asteroids would form a chain of space cities. The construction materials would initially come from the asteroids themselves, "the mass of which would be dismantled in a day." ▽ Tsiolkovskii's ideas on the re-engineering and relocation of the asteroids have been echoed in recent years by the American engineer Dandridge Cole, of the General Electric Corporation. △ After the asteroidal material is exhausted, Tsiolkovskii envisions the rebuilding of the Moon. He allows several hundred years for this project. Then, the Earth and the larger planets would be reorganized. According to Tsiolkovskii, the entire transformation of the solar system would require hundreds of thousands—perhaps millions—of years. This plan would provide enough heat and light to support a population of 3×10^{23} manlike beings—approximately 10^{14} more people than presently inhabit the Earth.

Although to his contemporaries the daring ideas of Tsiolkovskii seemed to be merely the daydreams of a provincial school-teacher, his brilliant foresight is readily appreciated today. The eminent American theoretical physicist Freeman J. Dyson, of the Institute for Advanced Study, Princeton, basing his theories on the achievements of contemporary science, has recently independently repeated many of Tsiolkovskii's ideas, without knowing anything of the Russian's work.

Dyson, in a most interesting article published in 1960, attempted to perform a quantitative analysis of the problem of rebuilding the solar system. He first discussed the fact that scientific and technological development takes place very rapidly, after a society has entered its technological phase. The timescale of such development is insignificant, compared with astronomical and geological timescales. Dyson concluded that the one important factor which restricts the scientific and technical development of an intelligent society is the limited available supply of matter and energy resources. At present, the material resources which can be exploited by man are limited roughly to the biosphere of the Earth, which has a mass ▽ estimated variously between 5×10^{17} and 5×10^{19} gm △—that is, less than 10^{-8} the mass of the Earth. The energy required by contemporary mankind per year is approximately equal to that which is liberated in the combustion of 1 to 2 billion tons of hard anthracite coal per year. In terms of heat, we find that contemporary man is expending an average of 3×10^{19} erg sec^{-1}. The Earth's resources of coal, oil, and other fossil fuels will be exhausted in a few centuries.

The question of our reserves of matter and energy becomes more acute when we consider the prospective long-term technological development of our society. Even if we assume that the average annual growth rate in production is only one-third of a percent (a very small figure, when compared to the annual growth rate ▽ of a few percent in modern industrial societies △), our productivity will double in about a century. In 1000 years, the rate of manufacture will increase by 20,000 times; and in 2500 years, by 10 billion times. This means that the energy requirements in 2500 years will be 3×10^{29} erg sec^{-1}, or approximately 0.01 percent of the entire luminosity of the Sun. This figure is approaching cosmic proportions. Will all of our energy resources have been exhausted by the time we achieve this level of productivity?

To answer this question, let us now consider the material resources which are conceivably available to mankind in the future. We shall—perhaps optimistically—assume that we will be able to achieve controlled thermonuclear reactions. The total amount of hydrogen in the Earth's hydrosphere is approximately 3×10^{23} grams, while the amount of deuterium is approximately 5×10^{19} grams. Deuterium would be the basic fuel of a thermonuclear reactor. The amount of energy released by reaction of all the available deuterium would be about 5×10^{38} ergs. In 2500 years, this amount of energy—still assuming an increase in production of one-third of a percent per annum—would be sufficient for only a 50-year period. Even if we assume that controlled thermonuclear fusion can eventually be fueled by ordinary hydrogen, and that 10 percent of the world's oceans can be utilized as an energy source—to burn more would probably be inexpedient—in 2500 years we would be able to provide only enough energy for another few thousand years.

Another possible energy source would be the direct utilization of solar radiation. Each second, approximately 2×10^{24} ergs of solar radiation fall upon the surface of the Earth. This is almost 100,000 times more than the current production of all forms of energy. Yet it is 100,000 times less than the estimated energy requirements for the year 4500 A.D. Thus, direct solar radiation is inadequate to support a stable and sustained increase in production of only one-third of a percent per annum, over a long period of time. From this discussion, we can conclude that the energy resources of the Earth are insufficient to fulfil the long-term requirements of a developing technological society.

Before considering this question further, let us make a slight digression. A

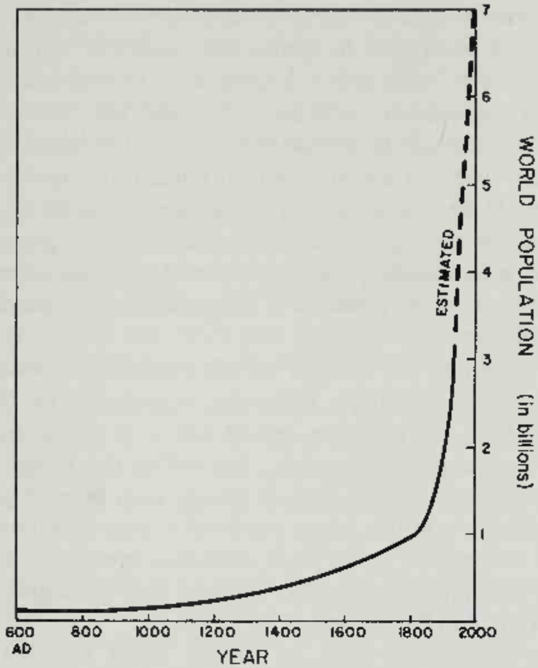

FIGURE 34–1. *Estimated past and extrapolated future rates of human population growth, planet Earth.*

hypercritical reader may claim that the above calculations are similar to the discussions of the English clergyman Thomas Malthus. This is, however, not the case. Malthus predicted that world population growth would outstrip the development of productive forces, and that this would lead to a progressive deterioration of living conditions. His proposed solution was that the poorer classes—that is, the working classes—lower their birthrate. Malthus' views are invalid, because in an intelligent, organized society, the increase of productive forces always outstrips the increase in population. The population of a nation is related, sometimes in a complex way, to its productivity, and in fact is ultimately determined by it. Our discussion of future energy budgets bears no relation to the Malthusian doctrine. We have been discussing only the possibilities of the increase in the productive capacities of a society, which is naturally limited to the material and energy resources available.

▽ The exponential increase in the population of the Earth during historical times is indicated schematically in Fig. 34–1. The required future productive capacity of our society is dramatically illustrated—assuming no major population self-limitation occurs—by extrapolation of the curve to the future. △

Let us ask another question: Will there in fact *be* any appreciable increase in the future productive capability of our society? What is the basis for assuming that mankind's progress will be directly related to an increase in his productive capacity?

Perhaps development will be in terms of qualitative, not quantitative, changes. These problems are philosophical in nature and cannot be discussed in detail here. However, I would like to state that I believe it to be impossible for a society to develop without a concurrent increase in production, both qualitatively and quantitatively. If an increase in productivity were eliminated, the society would eventually die. Note that if a society were to consciously interrupt its productive development, it would have to maintain a very precise level of production. Even the slightest progressive decrease would, after thousands of years reduce the technological potential to essentially nothing. Over these timescales, any civilization which consciously resolves to maintain a constant level of productivity would be balancing on a knife-edge.

Let us now return to the subject of the material resources available to a developing society. After reaching a high state of technical development, it would seem very natural that a civilization would strive to make use of energy and materials external to the planet of origin, but within the limits of the local solar system. Our star radiates 4×10^{33} ergs of energy each second, and the masses of the Jovian planets constitute the major potential source of material. Jupiter alone has a mass of 2×10^{30} grams. It has been estimated that about 10^{44} ergs of energy would be required to completely vaporize Jupiter. This is roughly equal to the total radiation output of the Sun over a period of 800 years.

According to Dyson, the mass of Jupiter could be used to construct an immense shell which would surround the Sun, and have a radius of about 1 A.U. (150 million kilometers). ▽ How thick would the shell of a Dyson sphere be? The volume of such a sphere would be $4\pi r^2 S$, where r is the radius of the sphere, 1 A.U., and S is its thickness. The mass of the sphere is just the volume times its density, ρ, and the mass available is approximately the mass of Jupiter. Thus, $4\pi r^2 \rho S = 2 \times 10^{30}$ grams. Thus, we find that $\rho S \simeq 200$ gm cm^{-2} △ of surface area would be sufficient to make the inner shell habitable. We recall that the mass of the atmosphere above each square centimeter of the Earth's surface is close to 1000 gm. ▽ If the over-all density of the shell were 1 gm cm^{-3} or slightly less, the thickness of the shell, S, would be a few meters. △ Man today, for all practical purposes, is a two-dimensional being, since he utilizes only the surface of the Earth. It would be entirely possible for mankind in the future—say, in 2500 to 3000 years—to create an artificial biosphere on the inner surface of a Dyson sphere. After man has accomplished this magnificent achievement, he would be able to use the total energy output of the Sun. ▽ Every photon emitted by the Sun would be absorbed by the Dyson sphere, and could be utilized productively. △ The inside surface area of the Dyson sphere would be approximately 1 billion times greater than the surface area of the Earth. The sphere could sustain a population great enough to fulfil the predictions made by Tsiolkovskii three quarters of a century ago.

We shall not at this time enter into a discussion of how such a sphere would be constructed, how it would rotate, or how we would guarantee that the inhabitants would not fall into the Sun. The fact is that the sphere would have different gravitational characteristics from those of a solid body. These problems, although complex, are not the principal problems. Dyson himself gave special attention to one interesting circumstance: A number of completely independent parameters—the mass of Jupiter, the thickness of an artificial biosphere, the total energy of the solar radiation, and the period of technological development—all, in Dyson's words,

> have consistent orders of magnitude. . . . It seems, then, a reasonable expectation that barring accidents, Malthusian pressures will ultimately drive an intelligent species to adopt some such efficient exploitation of its available resources. One should expect that within a few thousand years of its entering the stage of industrial development, any intelligent species should be found occupying an artificial biosphere which completely surrounds its parent star.

Up to this point, Dyson's speculations have been essentially the same as those of Tsiolkovskii, but based upon more recent scientific knowledge. At this point, Dyson introduces an idea novel ▽ even to Tsiolkovskii △: How will a civilization living on the inner surface of a sphere surrounding its star appear from outside? Dyson says:

> If the foregoing argument is accepted, then the search for extraterrestrial intelligent beings should not be confined to the neighborhood of visible stars. The most likely habitat for such beings would be a dark object having a size comparable to the Earth's orbit, and a surface temperature of 200 to 300°K. Such a dark object would be radiating as copiously as the star which is hidden inside it, but the radiation would be in the far infrared, at about 10μ wavelength.

If this were not the case, then the radiation produced by the star inside the shell would accumulate, and produce catastrophically high temperatures.

Since an extraplanetary civilization surrounded by a Dyson sphere would be a very powerful source of infrared radiation, and since the atmosphere of the Earth is transparent to radiation between 8 and 13μ, it would be possible to search for such infrared stars with existing telescopes on the Earth's surface. ▽ The sensitivity of contemporary infrared detectors is such that with the use of large telescopes, Dyson spheres could be detected over distances of hundreds of light-years even today. However, there is not necessarily any way of distinguishing a Dyson sphere detected at 8–13μ from a natural object such as a protostar, contracting towards the main sequence, and emitting infrared radiation with the same intensity. If the sky were mapped in the infrared for possible Dyson spheres, each radiation source could then be investigated by other techniques for characteristic radiation of an intelligent species—for example, at the 21 cm radio frequency. △

It is also possible that Dyson civilizations might be detected by existing optical techniques.

> Such radiation might be seen in the neighborhood of a visible star, under either of two conditions: A race of intelligent beings might be unable to exploit fully the energy radiated by their star because of an insufficiency of accessible matter, or they might live in an artificial biosphere surrounding one star of a multiple

system, in which one or more component stars are unsuitable for exploitation and would still be visible to us. It is impossible to guess the probability that either of these circumstances could arise for a particular race of extraterrestrial intelligent beings, but it is reasonable to begin the search for infrared radiation of artificial origin by looking in the direction of nearby visible stars, and especially in the direction of stars which are known to be binaries with invisible companions.

Dyson's idea is notable for the fact that it presents a specific example of how the activity of an intelligent society might change a planetary system to such an extent that the transformation would be detectable over interstellar distances. But a Dyson sphere is not the only way a civilization can utilize the available energy resources of its planetary system. There are other sources which may be even more effective than the complete utilization of local solar radiation.

First we shall consider using the mass of the large planets as a fuel for thermonuclear reactors. The Jovian planets consist primarily of hydrogen. The mass of Jupiter is 2×10^{30} gm, and the store of energy which would be released from the conversion of this quantity of hydrogen into helium would be approximately 10^{49} ergs, a vast amount of energy comparable to that released in a supernova explosion. If this energy were liberated gradually, over a long period of time—for example, at a rate of 4×10^{33} erg sec^{-1}, comparable to the present solar luminosity—it would last for nearly 300 million years, a time span most likely greater than the life of the technical civilization itself.

Perhaps a highly developed civilization could also use a fraction of its own star as an energy source. For example, it might be possible to "borrow" a few percent of the solar mass without any significant decrease in luminosity. Certainly, we do not yet know the methods for arranging such a loan, but it would probably be accomplished gradually. The conversion of, say, 5×10^{31} gm of solar hydrogen —25 times more than the mass of Jupiter—would provide some 3×10^{50} ergs, an energy supply adequate to satisfy the requirements of a technical civilization for several billion years.

It is also conceivable, but much less likely, that such utilization of the mass of a star would occur at a more rapid pace, perhaps regulated so that the lifetime of the star would correspond to the lifetime of the civilization. The spectral characteristics of such a star would slowly vary. At the time that the star finally was turned off, the civilization would cease to exist. ▽ But while we can imagine such a cosmic Götterdämmerung, it is not likely to be staged often. △

If intelligent use is made of the enormous stores of energy available in the solar system, it would not be necessary to construct a Dyson sphere about the Sun. Assume, for example, that half the mass of the Jovian planets were used to construct artificial satellites, the "space cities" of Tsiolkovskii. These cities would be established in orbits close to the Sun. We may imagine thermonuclear reactors installed in these satellites and fueled by the remaining material in the Jovian planets. This picture preserves the essential direction of the development of a technical civilization envisioned in *Dreams of the Earth and Sky,* but it adds controlled thermonuclear reactions as an energy source.

Now, given these enormous controlled energy sources, civilizations could expand their activities on a much larger scale. We shall presently consider several additional ways in which a civilization might announce its presence over interstellar distances. These methods seem fantastic. We wish to emphasize that we are not saying that such methods are actually in existence; but the probability of their existence is not zero. ▽ And what we have encompassed as "fantastic" has declined progressively with the centuries. △ The fundamental point is that the possibilities open to advanced technical civilizations are almost unlimited.

▽ First, let us reconsider the possibility broached in Chapter 28, that a technical civilization may make its presence known by changing the spectrum of its star. We found there that the dumping of 10^5 tons or less of atoms not normally found in the star might be detectable over interstellar distances as anomalous absorption lines. A short-lived radioisotope such as technetium−43 was discussed. △ We should point out that due to convection in the upper layers of a stellar atmosphere, any artificial technetium introduced would be rapidly conveyed to deeper layers, where it would no longer be detectable. Therefore, the technetium would have to be dumped periodically, ▽ or placed in orbit about the star. △

▽ The production and transportation of such quantities of rare isotopes is of course expensive, from our point of view. But we have just been considering the nuclear conversion and transportation of much larger masses. △ It is even possible that coded information could be incorporated by this process. Thus, the massive dumping of unstable atoms into a stellar atmosphere would be a powerful way of transmitting signals isotropically throughout interstellar space.

Let us now give an even freer rein to our imaginations. We shall assume that a certain highly developed civilization finds itself in need of materials, especially heavy elements. In principle, these materials could be obtained by exploiting a nearby star in a colossal experiment—the production of an artificial supernova. How could this be accomplished?

The British astrophysicist Geoffrey Burbidge, of the University of California at San Diego, has made an exciting, although unsubstantiated, speculation concerning the possibility of a supernova chain reaction. He postulated that if a supernova were accidentally exploded in the nucleus of a galaxy, where the density of stars was millions of times greater than in the solar neighborhood, the resulting gamma-ray flux to nearby stars would be so great that exceedingly high temperatures would be generated in the outer layers of these stars. Such high temperatures might trigger a supernova explosion which would then be transferred to other neighboring stars, and a supernova chain reaction would be initiated. In this way, over a period of several hundred years, perhaps hundreds of millions of stars making up the nucleus of a galaxy might become supernovae.

We must also consider the possibility that an artificial supernova might be induced in a single star. Let us assume that a technical society possessed a highly advanced and extremely powerful laser, operating at gamma ray frequencies—with wavelengths about 10^{-10} cm, 1 Ångstrom unit. With an aperture diameter of 10 meters, such a laser would have a beam width only 5×10^{-9} of a second of arc. If the star in this experiment were 10 light years from the gamma ray source, the laser beam on the surface of the star would have a diameter of only 10 km. According to Burbidge's hypothesis, the flow of gamma radiation at the surface of the star must be approximately 10^{10} erg cm^{-2} sec^{-1}, in order to initiate a supernova explosion. To produce this gamma ray flux with a source 10 light years away, the power output of the laser installation would have to be 10^{12} kilowatts. This is 1000 times greater than the total power consumption of contemporary civilization. But for the Type II civilizations we have been discussing, this does not seem an excessively large figure.

We must bear in mind that life forms greatly in advance of ourselves may possess capabilities which are unknown to us. Perhaps they can channel other types of penetrating radiation, both electromagnetic and corpuscular, into extremely narrow beams. Since each star is a vast potential source of nuclear energy, such beams might serve as the match which ignites the powder keg.

Let us speculate further. Would it be possible, through the controlled use of radiation, to modulate the course of stellar nuclear reactions, increasing or decreasing the pulse of the stars? A star regulated by remote control could become an effective source of energy for a Type II civilization. The supernova could be a quarry, where heavy elements are made and mined for the use of the civilization. Might there in fact actually be any connection between supernovae and the activities of highly developed technical civilizations? No—it is very likely that supernovae, even supernovae of Type I, result from natural phenomena which are still unknown to us. This example merely serves to illustrate the boundless ways in which intelligent life might manifest itself in the universe.

Could a highly developed civilization ▽ —one which we have called a Type III civilization— △ change the characteristics of entire galaxies? For example, could the emission of the radio galaxies ▽ and quasars [see Chapters 3 and 9] △ be ultimately of biological origin? This brings us to a critical question: Are any of the phenomena which we observe in the universe inexplicable in terms of the physics of non-living matter? Can some phenomena be understood only if we invoke the intervention of living organisms in technical civilizations? We cannot yet answer this question. If none of the many unexplained phenomena known today can be traced to some form of intelligent life, it might follow that life has not yet reached an extremely high level of development ▽ —say, between Type II and Type III civilizations— △ anywhere in the universe. ▽ But if other civilizations are common, many of them must be much older than our own; △ the absence of unexplained phenomena could then be a serious argument in favor of the melancholy theory that we are alone in the universe. ▽ Any such anomalous phenomena will be carefully investigated, because they are promising leads to new physical phenomena; the quasars, for example, may be due to an aggregation of matter so dense that only the theory of general relativity can be used to describe it. But the failures at purely physical understanding will perhaps be of even greater interest. △

Now let us consider the interesting ideas of the Soviet astrophysicist N. S.

Kardashev, of the Sternberg Astronomical Institute ▽ —ideas which we have already touched upon in Chapter 27. △ Assume that a highly developed civilization which has achieved mastery over all its interplanetary space—either by the construction of a Dyson sphere, or by thermonuclear-powered space cities—decides to broadcast isotropic signals into interstellar space. Dyson proposed that ▽ infrared radiation would necessarily be emitted by △ the sphere surrounding the central star. This, however, would be a most uneconomical means of signaling. For a given amount of power, the most efficient medium would be radio waves, since they would be detectable over greater distances. As we mentioned in Chapter 27, a radio signal can be very narrow-banded, and also easily modulated, so that an almost unlimited potential is available in terms of information transmittance.

Let us assume that such a civilization decides to use a portion of its energy resources for the purpose of contacting extraplanetary civilizations; and further, that this radiation is transmitted isotropically. It would be extremely difficult to construct a large transmitter for conveying radio waves to all directions. It would be much more reasonable to construct a number of smaller transmitters and place them throughout the planetary system.

Such an isotropic signal could be detected over a range $d = (WA/4\pi kT)^{1/2} \times (\tau/\Delta f)^{1/4}$, where W is the power output of the transmitters; A is the surface area of the receiver antenna; T is the noise temperature of the receiver; τ is the integration time of the recording device; $k = 1.38 \times 10^{-16}$ erg $(\mathrm{K}°)^{-1}$ is Boltzmann's constant; and Δf is the bandwidth of the receiver, which depends in turn on the bandwidth of the transmitter. This formula is very similar to the expression for d mentioned in Chapter 27, where the transmitter antenna had a high directivity. The wavelength does not enter into the formula, but is assumed to be close to 21 cm. We shall further assume that a highly organized civilization will use about 0.1 percent of its power resources for interstellar communication. For example, let us suppose that a Type II civilization is distributed on a Dyson sphere surrounding a star similar to our Sun. Then $W = 4 \times 10^{30}$ erg sec^{-1}. Setting $A = 400$ meters^2, $\Delta f = 10^6$ c.p.s., $\tau = 1$ sec, and $T = 100°$K, we find that $d = 4 \times 10^{22}$ cm, or about 13,000 parsecs. This is considerably in excess of the distance from the solar system to the Galactic center.

Thus, an isotropic radio signal of the power we have assumed could reach out to the limits of the Galaxy. Furthermore, by making the bandwidth Δf sufficiently narrow, it would be possible in principle to establish intergalactic radio communications.

For this purpose, it would be expedient to use a highly directional beam width. For example, assume that such a civilization in our Galaxy wished to send a signal to M 31, the great galaxy in Andromeda, using the same over-all power, $W = 4 \times 10^{30}$ erg sec^{-1}. The angular dimension of M 31, seen from our Galaxy, is about 2°. Therefore, it would be useful to use a system of antennas with an angular dimension of 2° in the main lobe [see Figure 27–2]. With this antenna, the power gain, G, would be 10,000 times that of an isotropic radiator. Therefore, the effective contact distance would be increased by a factor of 100. Using the same values for A, T, τ, and Δf as given above, we find that $d = 1.3 \times 10^6$ parsecs, or twice the distance to the great galaxy in Andromeda.

For contacting remote galaxies, even more highly directional antennas could be used. It is possible to diminish Δf still further. Thus, there is the possibility of sending narrow-beam, narrow bandwidth signals of detectable power to the very limits of the metagalaxy. ▽ For isotropic broadcast of radio signals over such distances, the power level would have to be very much greater, and a Type III civilization in the sense of Kardashev [Chapter 27] would be required. △

Will the receiving civilizations respond by showering us with replies? We recall that a two-way radio contact with M 31 would take 3 million years. Only a very long-lived civilization would be in a position to send a query and intercept a reply. However, intergalactic radio contact does have a singular advantage over interstellar contact: the signal would be directed simultaneously at several hundred billion stars, rather than at one particular star. The probability of contacting a civilization out of this vast number of stars would be much greater than if we were to send signals toward but one star.

In a short time, Kardashev and Paschenko, of the Sternberg Astronomical Institute, Moscow, will be attempting to detect signals of artificial origin, using a highly sensitive receiver which operates in the 21 cm waveband and which is capable of a smooth frequency variation. The anticipated power of the signals should be relatively great. Consequently, large, highly directional antennae are not required. A negative result from this search could possibly mean that our Galaxy does not contain highly developed civilizations with power resources $\sim 10^{33}$ erg sec^{-1}. Particular interest will be centered on attempts to detect signals from M 31. ▽ No similar plans for the extension or elaboration of Project Ozma have been announced in the United States. △

35

Artificial intelligence and galactic civilizations

Gilgamesh, whither rovest thou?
The life thou pursuest thou shalt not find.
When the gods created mankind,
Death for mankind they set aside,
Life in their own hands retaining . . .
Do we build a house for ever?

Epic of Gilgamesh (third millennium B.C.)

In our final chapter, we shall consider several questions, some of a philosophical nature. The discussion will continue to be speculative in intent.

▽ We have mentioned several times the possibility that the lifetime of a technical civilization, is not indefinitely long. △ It has been suggested that the thesis of a finite lifetime of technical civilizations is a sermon on pessimistic materialism. However, I believe that the combination of the words "pessimistic" and "materialism" is a contradiction in terms. Materialism is an objective analysis of the material world outside of and independent of our own consciousnesses. It is an attempt at an objective coping with the complexities of the universe. It is meaningless to label any particular law of nature as either pessimistic or optimistic. Even an attempt to comprehend the language of nature is a reason for genuine optimism; but ignorance and apathy go hand in hand with pessimism and obscurantism.

The acceptance of our individual mortality is no cause for pessimism. Why should it be any more pessimistic to assume that even societies of intelligent beings do not live forever? Just as the death of one individual does not obstruct the progress of society, the death of civilization on one small planet does not imply the end of intelligent life in the universe. Just as the activity of each individual can introduce a definite, although small, contribution to society, a given planetary civilization may make a contribution to the general development of intelligent life in the universe. And finally, just as the participation of the individual in society would be impossible without some sort of communication, the contribution of one planet to the development of intelligent life in the universe as a whole cannot take place without interstellar communications.

▽ Perhaps many young technical societies, like young men, are unmindful of the end of life because it seems so distant in time, and because there is so much yet to do. But when men are older, the thought of death is not so fearsome, and the unfinished tasks are somehow fewer. We live in a time when the thought of violent and accidental death of our civilization is a legitimate cause for anxiety. But perhaps an elder civilization, long past the problems of infantile societies, will willingly embrace the Elysian dreams of the lotus-eaters, and sink into an eternal sleep. △

In the *Dialectics of Nature,* Frederick Engels concluded, in the last century, that the lifetime for intelligent life on any particular planet is finite, and that this is an inevitable consequence of the development of the universe. He wrote:

> It is an eternal cycle in which matter moves, a cycle that certainly only completes its orbit in periods of time for which our terrestrial year is no adequate measure, a cycle in which the time of highest development, the time of organic life and still more, that of the life of beings conscious of nature and of themselves, is

just as narrowly restricted as the space in which life and self-consciousness came into operation; a cycle in which every finite mode of existence of matter, whether it be sun or nebular vapour, single animal or genus of animals, chemical combination or dissociation, is equally transient, and where nothing is eternal but eternally changing, eternally moving matter and the laws, according to which it moves and changes. But however often and however relentlessly this cycle is completed in time and space, however many millions of suns and earths may arise and pass away, however long it may take before the conditions of organic life arise, however innumerable the organic beings that have to arise and to pass away before animals with a brain capable of thought are developed from their midst, and for a short span of time find conditions suitable for life only to be exterminated later without mercy, we have the certainty that matter remains eternally the same in all its transformations, that none of its attributes can ever be lost, and therefore also that with the same iron necessity that it will exterminate on the earth its higher creation the thinking mind, it must somewhere else and at another time again produce it.

If the lifetime of a technical civilization is limited only by astronomical factors, then civilizations might continue for several billions of years—a period which we might be tempted to describe as "eternal"—and the probability would be high that intelligent life is almost ubiquitous. But as we have seen in previous chapters, the lifetimes of technical civilizations may well be limited. The majority of investigators believe that this timescale may be very short ▽ compared with the age of the Galaxy. △ However, we believe that this question must be reevaluated in the light of recent advances in cybernetics and in molecular biology.

In Part III of this book, we have repeatedly used the words "intelligent life," taking it for granted that a definition of this term was self-evident. But what in fact do we mean by "intelligent life"? Is a being intelligent if it possesses the ability to think? If so, what do we mean by "thinking"?

Human thought has been considered, ▽ until very recently, △ the only form of creative thinking known to mankind. Thus, any definition of "thinking" and "intelligence" inevitably leads to a description of the activities of men, or of the specific functions of the human brain.

But the Soviet physicist A. N. Kolmogorov has emphasized that such a definition is unsatisfactory in the light of current knowledge for two reasons: As astronomical and space exploratory investigations progress, there is the distinct possibility that we shall encounter on other planets entities which have all the essential attributes of life and thought but which are nonetheless essentially different from terrestrial forms of life. Second, there is now the possibility of the duplication of any complex material system, ▽ and in particular, the artificial construction of a thinking machine. △ There is, accordingly, a great need for a functional definition of the term "thought" which is not confined to our preconceived notions about the physical nature of this process.

A systematic approach to such a functional view of life and thought leads us to a startling conclusion which, in our opinion, is of substantial significance to the problem of intelligent life in the universe. Kolmogorov writes:

> . . . A model of the operational processes and organization of a material system must be constructed of other material elements in a new system which possesses the same essential characteristics of organization as the system which is being modeled. Therefore, a sufficiently complete model of a living being, in all fairness, must be called a living being, and a model of a thinking being must be called a thinking being. . . . The following questions are of general interest:
>
> Could machines reproduce themselves? And in the course of such reproduction, could progressive evolutionary changes occur which would lead to the production of new machines which are progressively more perfect ▽ [that is, better adapted to their environment] △ than their predecessors?
>
> Could these machines experience emotions? Would they feel desires; would they be capable of solving original problems which their creators did not build into them?
>
> Negative answers to questions of this nature are frequently the result of the following misconceptions: (a) a too-limited definition of the concept of "machine"; (b) an idealistic interpretation of the concept "thought," by which it is easy to prove that not only machines, but also human beings could not think.
>
> . . . However, it is important to understand that within the framework of materialist ideology there are no well-founded arguments against a positive answer to our questions. Such a positive answer is in accord with contemporary views on the origin of life, and on the physical basis of consciousness. . . .
>
> The possibility that complete living beings can be constructed out of discrete units capable of information processing and control does not contradict the principles of dialectic materialism.

Kolmogorov cautions against oversimplified specifications of the basic requirements for the synthesis of artificial intelligent beings. At present, we understand but a small portion of man's conscious activity. Only the mechanisms of conditioned reflex and of formal logic are understood to any degree. Much further work remains to be done on an objective definition in terms of information theory of the intricacies of the creative activity of man and other aspects of his highly developed nervous system.

Kolmogorov continues:

> . . . A serious objective study of the higher neural activity of man is a necessary link in the development of such mathematical humanism. As science has developed, the illusions of mankind have been progressively eroded. At the stage of half-truths and half-knowledge, these so-called "destructive conclusions" often become arguments against science itself, in favor of irrationalism and idealism. Thus, Darwin's insights into the origins of species, and Pavlov's studies of the higher nervous system have been described as degrading the higher capacities of man, debasing his ability to create moral and aesthetic ideals. Analogously in our time, fear that man is no better than a "cold-hearted" machine has produced a psychological argument for vitalism and irrationalism.

Artificial mechanical beings—robots—are a favorite subject of science fiction writers. They are usually pictured as an assemblage of nuts and bolts with the external shape of a man, but powered by electron tubes. In his play *R.U.R.*, the remarkable Czechoslovakian writer Karel Čapek coined the word "robot" to describe an artificial, manlike being, made of organic molecules. ▽ In Western science fiction, the word "robot" has evolved into an inorganic, usually metallic artificial being, while the word "android" has been used for an organic simulacrum of a human being. Actually, Čapek's original conception of the robot and the contemporary idea of an android have both been anticipated by the golem, an artificial human being which, according to Jewish folk legend, was created by the Rabbi of Prague to perform labors on the Sabbath from which Jews were forbidden by Biblical law. △ It is probable that after mankind has knowledge and control of the synthetic pathways for the production of proteins, under the guidance of the nucleic acids, artificial living organisms will have a natural external appearance. But it is premature to predict just how such artificial beings will look. We reemphasize that contemporary terrestrial science and technology cannot yet synthesize even the simplest living beings.

▽ In Chapter 14, we estimated that the number of possible combinations of the approximately 4×10^9 nucleotide pairs in human chromosomes was $4^{4\times10^9}$. This corresponds to approximately 10^{10} bits of information contained in the genetic code, and required for the construction of a human being. We can show that the information content of the human brain is probably even greater than the information content of the genetic material. There are something like 10^{10} neurons in the brain, each of which has probably more than 100 connections (dendrites) with other neurons. It is believed that the information content of the brain is at least in part stored through the intermediation of such neurons, although additional non-electrical information repositories—for example, proteins, or RNA, or even the configuration of membranes of cells in the brain—may be more significant. The number of possible arrangements of 10^{10} neurons, each with 100 dendrites, is $10^{2\times10^{10}}$, corresponding to an information content of some 10^{13} bits. Even if the great majority of the neurons in the brain are redundant or inactive, the information content of the human brain is far in excess of the information content of the genetic material. This is another way of saying that we are not born with all we know, and that the great bulk of our knowledge is acquired during our lifetimes.

▽ The characteristic mass of a human brain is ~ 1300 grams. We may consider a typical neuron to be cylindrical in shape, with a radius of a few microns, and a length of perhaps 1 mm. The volume of a typical neuron is therefore about $\pi(3 \times 10^{-4}\ \text{cm})^2(10^{-1}\ \text{cm}) \simeq 3 \times 10^{-8}\ \text{cm}^3$. Since neurons, like other biological material, have a density of about 1 gm cm^{-3}, each neuron has a mass of about 3×10^{-8} gm. 10^{10} neurons have, therefore, a mass of about 300 gm, and we see that a major fraction of the total mass of the brain is composed of neurons.

▽ The transistors which, in modern computing machines, are the analogues of the neurons in our brains, have masses considerably larger than 3×10^{-8} gm. Therefore, a computing machine with the same number of connecting units as the human brain would have to be much more massive. For example, if each transistor had a mass of $\frac{1}{100}$ of a gram, the total mass of an equivalent computing machine would be 10^8 grams, or 100 tons. We see that the human brain is marvelously microminiaturized.

▽ Many scientists believe that the complexities of human thinking are simply the consequence of the complexities of the interactions among 10^{10} units. Among organisms on Earth, there is a general, although by no means complete, correspondence between brain mass and intelligence; an even more striking correlation exists between intelligence and the ratio of brain mass to total body mass. It is in this context that the large mass of the dolphin brain—comparable to the mass of the human brain—is notable (see Chapter 29). If the information content of intelligent beings on other planets is stored in units of mass comparable to our neurons, then it is clear that they must be approximately as massive as we, or even larger. There is no general tendency for neurons to be of smaller mass in what we like to think of as the more advanced species on the planet Earth.

▽ But we can imagine other possibilities. Suppose, for example, that information is coded not on the level of neurons, but on the molecular level, and that provisions are made for the long-term stability of these information-carrying molecules. In the genetic material, such molecular information stores are of course used, and we have already mentioned that there is some evidence that molecules such as RNA are involved as a molecular basis of memory in animals and perhaps in human beings. We can imagine a crystal lattice, in which the information is stored by atoms, in terms of the position they occupy within the lattice. If there are 10 possible atoms for each position, we require about 2×10^{10} total atoms to reproduce the information content of the human brain. A cube containing 2×10^{10} atoms has about $(2 \times 10^{10})^{1/3} = 5000$ atoms on a side. The atoms in a crystal are usually a few Å apart. Therefore, such a cubical crystal could be 10^{-4} cm, or about 1 micron on a side. Some examples of coding miniaturization in contemporary technology—not yet up to the efficiency of our cube—are displayed in Figures 35–1 and 35–2.

▽ This example of the cube, due to Philip M. Morrison, is probably the extreme in the compression of information. It would be very difficult to extract information contained within the crystal without disrupting the information contained in the exterior atoms of the crystal. But such examples do illustrate that organisms can conceivably be considerably smaller than we and yet contain a vastly greater quantity of information. If our intelligence is characterized by an information storage capability of, say, 10^{13} bits, what will we have to say to a member of an advanced civilization with a storage capability of 10^{20} bits?

▽ These considerations suggest not only that beings may exist elsewhere in the universe with intelligence substantially beyond our own, but also that we may be able to construct such a being ourselves. △ Of course, many difficulties would have to be overcome before an artificial intelligent being could be constructed. The greatest difficulty is not the storage of information, but the development of the very complex program that represents the actual operation of the brain and associated nervous system, which in turn represents thought. It is possible in principle to build a complex machine which would solve problems through the use of smaller, ancillary machines, into which simpler problems could be introduced. However, such cascaded machines appear to be cumbersome and slow. At present, it is not clear just how these difficulties will be overcome.

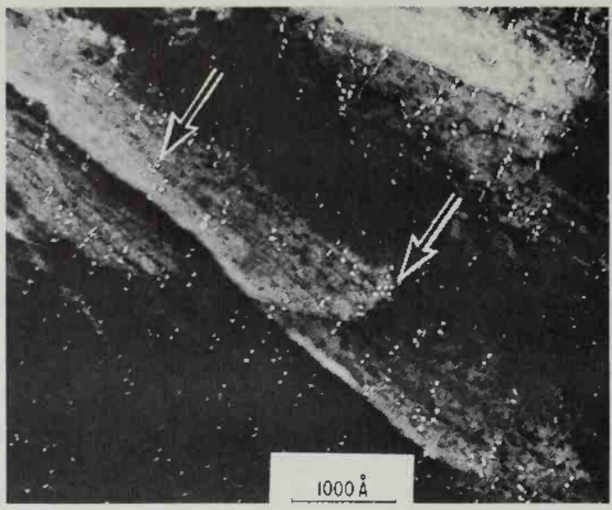

FIGURE 35–1. *A photograph taken with an electron microscope of special films of mica, a single crystal thick. The magnification is 800,000 times. The holes to which the arrows point are produced in the mica by radioactive decay. Each hole is 50–100 Å in diameter. Similar techniques may be extremely useful in microminiaturizing information coding. (Courtesy: Dr. H. Fernandez-Moran, University of Chicago.)*

▽ Great progress has already been made in the construction of machines sufficiently complex to learn by experience and to show signs of creative thinking. Computing machines today can perform in a few seconds mathematical problems which previously would have taken a team of mathematicians decades. There is every reason to believe that artificial intelligence will be increasingly pervasive in the future development of our civilization. △ Cybernetics, molecular biology, and neurophysiology together will some day very likely be able to create artificial intelligent beings which hardly differ from men, except for being significantly more advanced. Such beings would be capable of self-improvement, and probably would be much longer-lived than conventional human beings.

One proposed cause for the aging process of organisms is the gradual accumulation of imperfections in the genetic code over the lifetime of the individual. ▽ As time progresses, more and more nonsense information is transmitted to the cytoplasm (see Chapter 14), and the proper functioning of the cell is impaired. But the information repositories and coding procedures of artificial organisms could be much more durable and stable than those of contemporary organisms. △

The division of intelligent life into two categories—natural and artificial—may eventually prove to be meaningless. We may anticipate the synthesis of body parts. For example, we all know that some artificial body parts, such as teeth, are widely used today. ▽ Partial substitutes for the lenses of our eyes have been common for some centuries, and today we are witnessing the very rapid development of artificial hearts, lungs, kidneys, and other organs. △ The intelligent beings of the future may be made largely of artificial organs. ▽ Is it therefore out of the

FIGURE 35–2. *Upper: Photograph taken with an electron microscope of an ultra-miniaturized electronic circuit pattern. Is is produced by photo-engraving with an electron microbeam on special ultra-fine photographic film. The widths of the lines are 500–1,000 Å in diameter, and the magnification is 10,000 times. Lower: Miniaturized letters less than 1 micron high engraved on thin collodion film, using electron microbeam probes. The writing is produced with an electron microscope (after G. Möllenstedt and R. Speidel, Physik. Bl. 16, 192, 1960). (Courtesy: Dr. H. Fernandez-Moran, University of Chicago.)*

question that the brains of our descendants may also be artificial, so that vast quantities of information may be made accessible without a tortuous learning process? Perhaps in the future we shall be able to plug in modular units containing the entire body of knowledge of specialized areas, which we may then unplug and return to our library when no longer of immediate use. △ In principle, we can anticipate the construction of highly organized, intelligent, self-improving, and non-anthropomorphic forms of life.

We have mentioned the possibility that the artificial intelligent beings of the future may be very long-lived. ▽ Their civilizations might be vastly longer-lived than civilizations like our own. △ Such long lifetimes could be very advantageous for interstellar contact among advanced communities. The sluggishness of two-way radio communication over interstellar distances tends to make such contact unsatisfactory for beings with lifetimes measured in decades. But for very long-lived beings, such communication would be much more interesting. Further, such beings would be able to undertake interstellar flights over vast distances at sub-relativistic velocities ▽ without the use of metabolic inhibitors. △ Perhaps highly specialized beings could be constructed specifically for such flights of long duration. These beings would be capable of enduring the hardships of the flight, and of implementing the tasks awaiting them at the end of the journey. It would be impossible to draw a clear distinction between such specialized automatic machines, artificial intelligent living beings ▽ and natural advanced organisms of an exotic type. △

It is possible for intelligent life in the universe to make fundamental qualitative transformations of itself. ▽ Major improvements in the lifetimes of advanced technical civilizations and of the organisms which compose them, and qualitatively different advances in their intelligence, make the prospect of successful interstellar contact much larger. △

▽ Let us now consider the possibilities more in consonance with the discussion of the beginning of this chapter. Perhaps technical civilizations are nowhere able to construct long-lived artificial beings of vast intelligence; or perhaps, while they are capable, the lifetimes of the initial technical civilizations are so short that a society of intelligent artificial beings is never able to develop. △ Under these circumstances, could an advanced civilization create a large artificial satellite containing electronic equipment capable of transacting interstellar radio communications for periods of millions of years or longer? Such a satellite, launched into circular orbit high above the planet of origin, could have a life span of hundreds of millions of years. It is possible that we have an example of such a moon in our own solar system (see Chapter 26); and in fact, when I first developed the hypothesis that the moons of Mars may be of artificial origin, I had such a function in mind. The energy source for the equipment aboard the satellite could be either the radiation flux of the local sun or controlled thermonuclear fusion. The radio transmitters aboard the satellite would transmit modulated signals according to a pre-programmed plan; answers to these signals could be recorded, ▽ and appropriate responses automatically devised, according to program. △ In this way, two-way automatic radio contact among Galactic civilizations could be established.

There are, of course, formidable technical problems which must be solved before such a satellite would be feasible. The automatic equipment must function stably and be protected against meteors over immense periods of time.

There are three primary advantages for interstellar contact that an artificial satellite has over a station on a planetary surface. ▽ First, the satellite is capable of transmission at frequencies which are absorbed by the planetary atmosphere or ionosphere. △ Second, the lifetime of the satellite could be much longer than the lifetime of the civilization which constructed it. Such a satellite might orbit its planet for millions of years after the local civilization had perished. Finally, in the epoch of decay and destruction of the parent civilization, very likely the safest place for such a station would be aboard a satellite. Here, the instruments would be protected not only from wars, but also from the destructive action of wind and water, and from geological changes on the surface of the planet. A large instrumented artificial satellite might be able to transmit the treasures of science and the heritage of culture of a dead civilization into the cosmos for hundreds of millions of years. We draw upon the knowledge and insights of men long dead through the books which they once wrote. Is it not possible that civilizations throughout the universe also draw upon the knowledge and insights of civilizations long vanished? If some technical societies have devised methods for transmitting information to space for extremely long periods of time, longer than their own life spans, the probability of contact among Galactic civilizations is immeasurably enhanced.

Bibliography

The following references are given in an order which approximates the introduction of the topics in this book. Only a few of these are written primarily for specialists in the field, and the more difficult ones are starred.

1. A masterly discussion of a wide range of topics in introductory chemistry, physics, biology and astronomy—highly recommended to the reader with little previous science background—is *Knowledge and Wonder* by Victor Weisskopf (Anchor Books, 1962).

2.* Many of the most exciting contemporary scientific research endeavors are described in a collection of papers presented at a meeting commemorating the 100th anniversary of the founding of the United States National Academy of Sciences: *The Scientific Endeavor* (Rockefeller Institute Press, 1965).

3. An intriguing essay on pseudoscience, including a short description of the flying saucer cult is *Fads and Fallacies in the Name of Science* by Martin Gardner (Dover Publications, New York, 1957).

4. Flying saucers are comprehensively discussed and concluded to be exclusively misapprehended natural objects in *The World of Flying Saucers: A Scientific Examination of a Major Myth of the Space Age*, by Donald H. Menzel and Lyle B. Boyd (Doubleday, 1963).

5. Some of Chapter 2 of the present work is based upon the article "Unidentified Flying Objects," by Carl Sagan, written for the 1967 edition of the *Encyclopedia Americana*.

6. Perhaps the most restrained book, despite occasional errors of fact and interpretation, which concludes that some flying saucers may be extraterrestrial space vehicles is *Anatomy of a Phenomenon: Unidentified Objects in Space—A Scientific Appraisal*, by Jacques Vallee (Henry Regnery Co., Chicago, 1965).

7. An excellent introduction to astronomy, particular to stellar and galactic studies, is the introductory college textbook, *Exploration of the Universe* by George Abell (Holt, Rinehart and Winston, 1964).

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9. Somewhat more detailed and semi-quantitative is *The Universe* by Otto Struve (M. I. T. Press, Cambridge, Massachusetts, 1962).

10. Another excellent introductory astronomy textbook is *Elementary Astronomy* by Otto Struve, Beverly Lynds, and Helan Pillans (Oxford University Press, 1959).

11. A clear exposition of a variety of astronomical topics, only slightly out of date, is contained in *Frontiers of Astronomy* by Fred Hoyle (Harper, 1955).

12. The historical aspects of astronomy are treated in *The History of Astronomy* by A. Pannekoek (John Wiley & Sons, 1961).

13. The interstellar medium is treated in comprehensive, popular fashion in *Physics of Interstellar Space* by S. B. Pikelner [Foreign Languages Publishing House, Moscow, 1961]. This book is published in English.

14. An up-to-date discussion of the origin of the elements is contained in the article by W. H. Fowler, in reference 2.

15. Many of Shklovskii's contributions to radio astronomy are summarized in *Cosmic Radio Waves* by I. S. Shklovskii (Harvard University Press, 1960).

16.* The best contemporary book on stellar evolution is *Structure and Evolution of the Stars,* by Martin Schwarzschild (Princeton University Press, 1958).

17.* A good introductory text on stellar atmospheres is *Introduction to Astrophysics: The Stars* by Jean Dufay, translated by Owen Gingerich (Dover, 1964).

18. A superb picture folio of galaxies photographed at Mt. Wilson and Palomar Observatories with an accompanying discussion of their evolution is contained in *The Hubble Atlas of Galaxies* by Alan Sandage, Publication 618 of the Carnegie Institution of Washington, D.C., 1961.

19.* Stimulating and recent discourse on many of the later topics of Part I can be found in *Galaxies, Nuclei and Quasars* by Fred Hoyle (Harper, 1965).

20. Perhaps the best popular discussion of cosmology, which very successfully explains sophisticated concepts to the layman, is *The Mystery of the Expanding Universe* by William Bonner (Macmillan, 1964).

21. A novel discussion of both special and general relativity which begins with elementary algebra and works up to quantitative discussions of the curvature of space, etc., is *The Einstein Theory of Relativity: A Trip to the Fourth Dimension* by Lillian R. Lieber and Hugh Gray Lieber (Holt, Rinehart and Winston, New York, 1945).

22. A charming popular excursion into cosmology, relativity and quantum theory is *Mr. Tompkins in Paperback* by George Gamow (Cambridge University Press, 1965).

23. Googols, googolplexes and other mathematical delights can be discovered in *Mathematics and the Imagination* by Edward Kasner and James R. Newman (Simon and Schuster, 1953).

24.* A convenient source of both historical and modern views on the origin of the solar system is the symposium proceedings: *Origin of the Solar System* by Robert Jastrow and A. G. W. Cameron (Academic Press, New York, 1963).

25. A Soviet view in English on the origin of the solar system can be found in *Origin of the Earth and Planets* by B. J. Levin (Foreign Languages Publishing House, Moscow, 1956).

26. A fascinating pictorial discussion of the scale of the universe is *Cosmic View: The Universe in Forty Jumps* by Kees Boeke (John Day, 1957).

Part II—Life in the Universe

27. An up-to-date discussion of extraterrestrial life, written over a period of two years by 66 scientists in various disciplines is *Biology and the Exploration of Mars* (U.S. National Academy of Sciences, Washington, D.C. 1966). The discussion includes questions of the origin and nature of life, environments in the solar system, evidence for life on Mars and the strategy of Martian exploration.

28. Many important articles on the origin of life and related topics are collected in *Extraterrestrial Life: An Anthology and Bibliography* (U.S. National Academy of Sciences, Washington, D.C., 1966). It includes a classic paper by J. B. S. Haldane, and the most complete bibliography in print on the subjects of Parts II and III of the present book.

29. Questions of organic chemistry used in contemporary molecular biology are well introduced in *A Direct Entry to Organic Chemistry*, by John Read (Harper Torchbooks, 1960).

30.* A modern classic on molecular biology by one of the leaders in the field is *Molecular Biology of the Gene*, by James D. Watson (W. A. Benjamin, Inc., 1965).

31. A more elementary treatment of the same subject is *The Genetic Code*, by Isaac Asimov (Signet Science Library, 1962).

32. One of the best introductions to cell biology is *Cell Structure and Function* by A. G. Loewy and Philip Siekevitz (Holt, Rinehart, and Winston, 1963).

33. Highly recommended is *The Molecular Basis of Evolution* by C. R. Anfinsen (John Wiley, 1963).

34. Physical and biological aspects of living systems, including the question of fitness of the environment, are treated in *Time's Arrow and Evolution* by Harold Blum (Princeton University Press, 2nd edition, 1961).

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36. Another popular discussion of the origin of life is *The Dawn of Life,* by J. H. Rush (New American Library, 1962).

37.* The proceedings of a lively symposium on the origin of life, at which the pioneers, A. I. Oparin and J. B. S. Haldane, both participated, is *The Origins of Prebiological Systems,* edited by S. W. Fox (Academic Press, 1965).

38. A basic popular discussion of evolution which provides an excellent modern companion to Darwin's "Origin of Species" is *The Meaning of Evolution* by George Gaylord Simpson (Yale University Press, 1949).

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45.* On a more technical level, see *Study of the Earth: Readings in Geological Science,* edited by J. F. White (Prentice Hall, 1962).

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47.* A comprehensive discussion of lunar problems, including questions of its origin, is *Measure of the Moon* by Ralph Baldwin (University of Chicago Press, 1963).

48.* An earlier discussion of the moon and planets, with particular attention to questions of origin is *The Planets* by Harold C. Urey (Yale University Press, 1952).

49. An exceptionally well-illustrated layman's introduction to planetary astronomy is *Planets* by Carl Sagan and Jonathan Leonard (Life Science Library, 1966).

50. See also, *Pictorial Guide to the Planets,* Joseph H. Jackson (Thomas Y. Crowell, 1965).

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53. An introductory discussion on the debris of the solar system is *Meteors, Comets and Meteorites* by Gerald S. Hawkins (McGraw-Hill, 1964).

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56. A recent discussion of methods for the detection of extraterrestrial life is *Concepts for Detection of Extraterrestrial Life,* edited by Freeman H. Quimby (NASA Document SP56, U.S. Government Printing Office, 1964).

Part III—Intelligent Life in the Universe

57.* A useful collection of papers referred to in the present work, and which were previously published in the scientific literature is *Interstellar Communication,* edited by A. G. W. Cameron (W. A. Benjamin, Inc. 1963). This includes papers by Shklovskii, Huang, Dyson, von Hoerner, Cocconi and Morrison, Bracewell, Schwartz and Townes, and a short summary by J. P. T. Pearman of the Space Science Board meeting on intelligent extraterrestrial life.

58. A stimulating popular discussion of some of these topics is *We Are Not Alone* by Walter Sullivan (McGraw-Hill, 1964).

59.* Some of the discussion of Chapters 29, 32 and 33 follows "Direct Contact Among Galactic Civilizations by Relativistic Interstellar Space Flight" by Carl Sagan, published in the journal, *Planetary and Space Science,* Vol. 11, p. 485 (1963).

60.* N. S. Kardashev's views on Type I, Type II, and Type III civilizations are contained in "Transmission of information by extraterrestrial civilizations," in *Soviet Astronomy—A. J.,* Vol. 8, p. 217 (1964). [This is an English translation of the Soviet journal *Astronomicheskhi Zhurnal.*]

61.* A further discussion of Dyson civilizations is "The infrared detectability of Dyson civilizations," by Carl Sagan and Russell G. Walker, *Astrophysical Journal* (June, 1966).

62. Intelligent extraterrestrial life and a wide variety of other topics are touched on in *Of Stars and Men,* by Harlow Shapley (Beacon Press, Boston, 1958).

63. A similar range of subjects discussed with a similar philosophical outlook is the similarly titled *Of Men and Galaxies* by Fred Hoyle (University of Washington Press, 1964).

64.* An interesting discussion of the frequency of extra-solar planetary systems is *Habitable Planets for Man* by Stephen Dole (Blaisdell, 1964).

65. An exciting, but not always reliable, discussion of the origin and nature of man is *The Human Animal,* by Weston LaBarre (University of Chicago Press, 1954).

66. See also: *The Primates,* by Sarel Eimerl and Irven Devore (Life Nature Library, 1965),

67. *Early Man* by F. Clark Howell (Life Nature Library, 1965), and

68. "The biological nature of man," by George Gaylord Simpson, in the journal *Science,* Vol. 152, p. 472 (1966).

69. A discussion of a variety of evolutionary topics which concludes in the last chapter that animals similar to human beings are unlikely to be found anywhere but on earth is *This View of Life* by George Gaylord Simpson (Harcourt, Brace and World, 1965).

70. Many of the topics of Part III used to be the exclusive province of science fiction. An able science fiction excursion into the question of interstellar radio contact co-authored by a well-known astronomer is *A For Andromeda* by Fred Hoyle and John Elliott (Harper, 1962).

71. An excellent discussion of the origins and nature of Mesopotamian civilization is the book *The Intellectual Adventure of Ancient Man* by H. Frankfort, H. A. Frankfort, J. A. Wilson and T. Jacobsen (University of Chicago Press, 1946). The book has been reprinted by Penguin Books as *Before Philosophy.* The quote from Jacobsen in Chapter 33 is contained in Chapter 5, "The Cosmos as a State," of this work.

72. A profound essay on the philosophy of science which covers in great detail many questions touched on in this work is *The Language of Nature* by David Hawkins (W. H. Freeman and Co., 1964).

73. The magazine *Scientific American* contains excellent popular discussions of the entire subject matter of science. Offprints of these articles can be obtained from W. H. Freeman Co., San Francisco. A very short sample of such articles relevant to the present volume follows:

"The Smallest Living Cells" by Harold Morowitz and Mark E. Tourtellot (March 1962).

"Antimatter," by Geoffrey Burbidge and Fred Hoyle (April 1958).

"The Fine Structure of the Gene," by Seymour Benzer (January 1962).
"Messenger RNA" by J. Hurwitz and J. J. Furth (February, 1962).
"Paleobiochemistry" by P. H. Abelson (July 1956).
"The Genetic Basis of Evolution" by Theodosius Dobzhansky (January 1950).
"The Ages of the Elements in the Solar System," by John H. Reynolds (November 1960).
"The Evolution of Intelligence" by M. E. Bitterman (January 1965).

Subject Index

Name Index