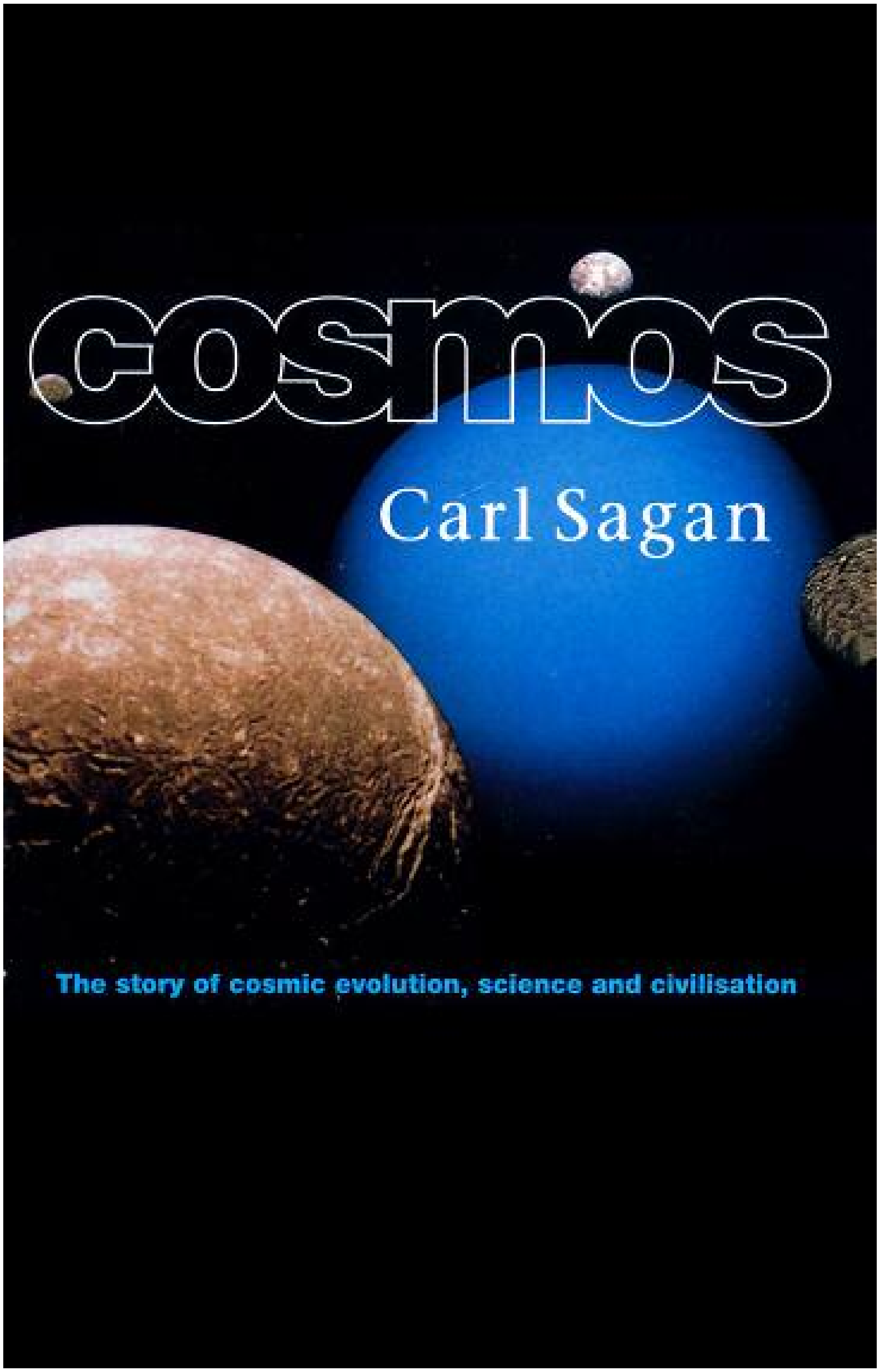

For Ann Druyan

In the vastness of space and the immensity of time,
it is my joy to share
a planet and an epoch with Annie

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- Group 4: The Classified

Carl Sagan was the Director of the Laboratory for Planetary studies and David Duncan Professor of Astronomy and Space Sciences at Cornell University. He played a leading role in the Mariner, Viking and Voyager expeditions to the planets, for which he received the NASA medals for Exceptional Scientific Achievement and for Distinguished Public Service, and the international astronautics prize, the Prix Galabert.

He served as Chairman of the Division for Planetary Sciences of the American Astronomical Society, as Chairman of the Astronomy Section of the American Association for the Advancement of Science, and as President of the Planetology Section of the American Geophysical Union. For twelve years, he was Editor-in-Chief of *Icarus*, the leading professional journal devoted to planetary research. In addition to four hundred published scientific and popular articles, Dr Sagan was the author, co-author or editor of more than a dozen books, including *Intelligent Life in the Universe*, *The Cosmic Connection*, *The Dragons of Eden*, *Murmurs of Earth*, *Broca's Brain* and the bestselling science fiction novel, *Contact*.

He was a recipient of the Joseph Priestly Award 'for distinguished contributions to the welfare of mankind', and the Pulitzer Prize for literature.

Carl Sagan died in December 1996.

Eratosthenes asked himself how, at the same moment, a stick in Syene could cast no shadow and a stick in Alexandria, far to the north, could cast a pronounced shadow. Consider a map of ancient Egypt with two vertical sticks of equal length, one stuck in Alexandria, the other in Syene. Suppose that, at a certain moment, each stick casts no shadow at all. This is perfectly easy to understand - provided the Earth is flat. The Sun would then be directly overhead. If the two sticks cast shadows of equal length, that also would make sense on a flat Earth: the Sun's rays would then be inclined at the same angle to the two sticks. But how could it be that at the same instant there was no shadow at Syene and a substantial shadow at Alexandria?

The only possible answer, he saw, was that the surface of the Earth is curved. Not only that: the greater the curvature, the greater the difference in the shadow lengths. The Sun is so far away that its rays are parallel when they reach the Earth. Sticks placed at different angles to the Sun's rays cast shadows of different lengths. For the observed difference in the shadow lengths, the distance between Alexandria and Syene had to be about seven degrees along the surface of the Earth; that is, if you imagine the sticks extending down to the center of the Earth, they would there intersect at an angle of seven degrees. Seven degrees is something like one-fiftieth of three hundred and sixty degrees, the full circumference of the Earth. Eratosthenes knew that the distance between Alexandria and Syene was approximately 800 kilometers, because he hired a man to pace it out. Eight hundred kilometers times 50 is 40,000 kilometers: so that must be the circumference of the Earth.*

* Or if you like to measure things in miles, the distance between Alexandria and Syene is about 500 miles, and 500 miles x 50 = 25,000 miles.

This is the right answer. Eratosthenes' only tools were sticks, eyes, feet and brains, plus a taste for experiment. With them he deduced the circumference of the Earth with an error of only a few percent, a remarkable achievement for 2,200 years ago. He was the first person accurately to measure the size of a planet.

The Mediterranean world at that time was famous for seafaring. Alexandria was the greatest seaport on the planet. Once you knew the Earth to be a sphere of modest diameter, would you not be tempted to make voyages of exploration, to seek out undiscovered lands, perhaps even to attempt to sail around the planet? Four hundred years before Eratosthenes, Africa had been circumnavigated by a Phoenician fleet in the employ of the Egyptian Pharaoh Necho. They set sail, probably in frail open boats, from the Red Sea, turned down the east coast of Africa up into the Atlantic, returning through the Mediterranean. This epic journey took three years, about as long as a modern Voyager spacecraft takes to fly from Earth to Saturn.

After Eratosthenes' discovery, many great voyages were attempted by brave and venturesome sailors. Their ships were tiny. They had only rudimentary navigational instruments. They used dead reckoning and followed coastlines as far as they could. In an unknown ocean they could determine their latitude, but not their longitude, by observing, night after night, the position of the constellations with respect to the horizon. The familiar constellations must have been reassuring in the midst of an unexplored ocean. The stars are the friends of explorers, then with seagoing ships on Earth and now with spacefaring ships in the sky. After Eratosthenes, some may have tried, but not until the time of Magellan did anyone succeed in circumnavigating the Earth. What tales of daring and adventure must change in the environment of the Earth. Green plants generate molecular oxygen. Since the oceans were by now filled with simple green plants, oxygen was becoming a major constituent of the Earth's atmosphere, altering it irreversibly from its original hydrogen-rich character and ending the epoch of Earth history when the stuff of life was made by nonbiological processes. But oxygen tends to make organic molecules fall to pieces. Despite our fondness for it, it is fundamentally a poison for unprotected organic matter. The transition to an oxidizing atmosphere posed a supreme crisis in the history of life, and a great many organisms, unable to cope with oxygen, perished. A few primitive forms, such as the botulism and tetanus bacilli, manage to survive even today only in oxygen-free environments. The nitrogen in the Earth's atmosphere is much more chemically inert and therefore much more benign than oxygen. But it, too, is biologically sustained. Thus, 99 percent of the Earth's atmosphere is of biological origin. The sky is made by life.

For most of the four billion years since the origin of life, the dominant organisms were microscopic blue-green algae, which covered and filled the oceans. Then some 600 million years ago, the monopolizing grip of the algae was broken and an enormous proliferation of new lifeforms emerged, an event called the Cambrian explosion. Life had arisen almost immediately after the origin of the Earth, which suggests that life may be an inevitable chemical process on an Earth-like planet. But life did not evolve much beyond blue-green algae for three billion years, which suggests that large lifeforms with specialized organs are hard to evolve, harder even than the origin of life. Perhaps there are many other planets that today have abundant microbes but no big beasts and vegetables.

Soon after the Cambrian explosion, the oceans teemed with many different forms of life. By 500 million years ago there were vast herds of trilobites, beautifully constructed animals, a little like large insects; some hunted in packs on the ocean floor. They stored crystals in their eyes to detect polarized light. But there are no trilobites alive today; there have been none for 200 million years. The Earth used to be inhabited by plants and animals of which there is today no living trace. And of course every species now on the planet once did not exist. There is no hint in the old rocks of animals like us. Species appear, abide more or less briefly and then flicker out.

Before the Cambrian explosion species seem to have succeeded one another rather slowly. In part this may be because the richness of our information declines rapidly the farther into the past we peer; in the early history of our planet, few organisms had hard parts and soft beings leave few fossil remains. But in part the sluggish rate of appearance of dramatically new forms before the Cambrian explosion is real; the painstaking evolution of cell structure and biochemistry is not immediately reflected in the external forms revealed by the fossil record. After the Cambrian explosion, exquisite new adaptations followed one another with comparatively breathtaking speed. In rapid succession, the first fish and the first vertebrates appeared; plants, previously restricted to the oceans, began the colonization of the land; the first insect evolved, and its descendants became the pioneers in the colonization of the land by animals; winged insects arose together with the amphibians, creatures something like the lungfish, able to survive both on land and in the water; the first trees and the first reptiles appeared; the dinosaurs evolved; the mammals emerged, and then the first birds; the first flowers appeared; the dinosaurs became extinct; the earliest cetaceans, ancestors to the dolphins and whales, arose and in the same period the primates - the ancestors of the monkeys, the apes and the humans. Less than ten million years ago, the first creatures who closely resembled human beings evolved, accompanied by a spectacular increase in brain size. And then, only a few million years ago, the first true humans circular course, my feet no longer touch the Earth. . .'

Ptolemy believed that the Earth was at the center of the universe; that the Sun, Moon, planets and stars went around the Earth. This is the most natural idea in the world. The Earth seems steady, solid, immobile, while we can see the heavenly bodies rising and setting each day. Every culture has leaped to the geocentric hypothesis. As Johannes Kepler wrote, 'It is therefore impossible that reason not previously instructed should imagine anything other than that the Earth is a kind of vast house with the vault of the sky placed on top of it; it is motionless and within it the Sun being so small passes from one region to another, like a bird wandering through the air.' But how do we explain the apparent motion of the planets - Mars, for example, which had been known for thousands of years before Ptolemy's time? (One of the epithets given Mars by the ancient Egyptians was *sekded-ef em khetkhet*, which means 'who travels backwards,' a clear reference to its retrograde or loop-the-loop apparent motion.)

Ptolemy's model of planetary motion can be represented by a little machine, like those that, serving a similar purpose, existed in Ptolemy's time.* The problem was to figure out a 'real' motion of the planets, as seen from up there, on the 'outside,' which would reproduce with great accuracy the apparent motion of the planets, as seen from down here, on the 'inside.'

* Four centuries earlier, such a device was constructed by Archimedes and examined and described by Cicero in Rome, where it had been carried by the Roman general Marcellus, one of whose soldiers had, gratuitously and against orders, killed the septuagenarian scientist during the conquest of Syracuse.

The planets were imagined to go around the Earth affixed to perfect transparent spheres. But they were not attached directly to the spheres, but indirectly, through a kind of off-center wheel. The sphere turns, the little wheel rotates, and, as seen from the Earth, Mars does its loop-the-loop. This model permitted reasonably accurate predictions of planetary motion, certainly good enough for the precision of measurement available in Ptolemy's day, and even many centuries later.

Ptolemy's aetherial spheres, imagined in medieval times to be made of crystal, are why we still talk about the music of the spheres and a seventh heaven (there was a 'heaven,' or sphere for the Moon, Mercury, Venus, the Sun, Mars, Jupiter and Saturn, and one more for the stars). With the Earth the center of the Universe, with creation pivoted about terrestrial events, with the heavens imagined constructed on utterly unearthly principles, there was little motivation for astronomical observations. Supported by the Church through the Dark Ages, Ptolemy's model helped prevent the advance of astronomy for a millennium. Finally, in 1543, a quite different hypothesis to explain the apparent motion of the planets was published by a Polish Catholic cleric named Nicholas Copernicus. Its most daring feature was the proposition that the Sun, not the Earth, was at the center of the universe. The Earth was demoted to just one of the planets, third from the Sun, moving in a perfect circular orbit. (Ptolemy had considered such a heliocentric model but rejected it immediately; from the physics of Aristotle, the implied violent rotation of the Earth seemed contrary to observation.)

It worked at least as well as Ptolemy's spheres in explaining the apparent motion of the planets. But it annoyed many people. In 1616 the Catholic Church placed Copernicus' work on its list of forbidden books 'until corrected' by local ecclesiastical censors, where it remained until 1835.* Martin Luther described him as 'an upstart astrologer . . . This fool of physics was Einstein's 'Miracle Year' of 1905. When asked how he accomplished his astonishing discoveries, Newton replied unhelpfully, 'By thinking upon them.' His work was so significant that his teacher at Cambridge, Isaac Barrow, resigned his chair of mathematics in favor of Newton five years after the young student returned to college.

Newton, in his mid-forties, was described by his servant as follows:

> I never knew him to take any recreation or pastime either in riding out to take the air, walking, bowling, or any other exercise whatever, thinking all hours lost that were not spent in his studies, to which he kept so close that he seldom left his chamber unless [to lecture] at term time . . . where so few went to hear him, and fewer understood him, that ofttimes he did in a manner, for want of hearers, read to the walls.

Students both of Kepler and of Newton never knew what they were missing.

Newton discovered the law of inertia, the tendency of a moving object to continue moving in a straight line unless something influences it and moves it out of its path. The Moon, it seemed to Newton, would fly off in a straight line, tangential to its orbit, unless there were some other force constantly diverting the path into a near circle, pulling it in the direction of the Earth. This force Newton called gravity, and believed that it acted at a distance. There is nothing physically connecting the Earth and the Moon. And yet the Earth is constantly pulling the Moon toward us. Using Kepler's third law, Newton mathematically deduced the nature of the gravitational force.* He showed that the same force that pulls an apple down to Earth keeps the Moon in its orbit and accounts for the revolutions of the then recently discovered moons of Jupiter in their orbits about that distant planet.

* Sadly, Newton does not acknowledge his debt to Kepler in his masterpiece the *Principia*. But in a 1686 letter to Edmund Halley, he says of his law of gravitation: 'I can affirm that I gathered it from Kepler's theorem about twenty years ago.'

Things had been falling down since the beginning of time. That the Moon went around the Earth had been believed for all of human history. Newton was the first person ever to figure out that these two phenomena were due to the same force. This is the meaning of the word 'universal' as applied to Newtonian gravitation. The same law of gravity applies everywhere in the universe.

It is a law of the inverse square. The force declines inversely as the square of distance. If two objects are moved twice as far away, the gravity now pulling them together is only one-quarter as strong. If they are moved ten times farther away, the gravity is ten squared, $10^2 = 100$ times smaller. Clearly, the force must in some sense be inverse - that is, declining with distance. If the force were direct, increasing with distance, then the strongest force would work on the most distant objects, and I suppose all the matter in the universe would find itself careering together into a single cosmic lump. No, gravity must decrease with distance, which is why a comet or a planet moves slowly when far from the Sun and faster when close to the Sun - the gravity it feels is weaker the farther from the Sun it is.

All three of Kepler's laws of planetary motion can be derived from Newtonian principles. Kepler's laws were empirical, based upon the painstaking observations of Tycho Brahe. Newton's laws were theoretical, rather simple mathematical abstractions from which slightly wobbling. Eventually the vibrations die down but not in so short a period as eight hundred years. Such a quivering can be studied by laser reflection techniques. The Apollo astronauts emplaced in several locales on the Moon special mirrors called laser retro-reflectors. When a laser beam from Earth strikes the mirror and bounces back, the round-trip travel time can be measured with remarkable precision. This time multiplied by the speed of light gives us the distance to the Moon at that moment to equally remarkable precision. Such measurements, performed over a period of years, reveal the Moon to be librating, or quivering with a period (about three years) and amplitude (about three meters), consistent with the idea that the crater Giordano Bruno was gouged out less than a thousand years ago.

All this evidence is inferential and indirect. The odds, as I have said, are against such an event happening in historical times. But the evidence is at least suggestive. As the Tunguska Event and Meteor Crater, Arizona, also remind us, not all impact catastrophes occurred in the early history of the solar system. But the fact that only a few of the lunar craters have extensive ray systems also reminds us that, even on the Moon, some erosion occurs.* By noting which craters overlap which and other signs of lunar stratigraphy, we can reconstruct the sequence of impact and flooding events of which the production of crater Bruno is perhaps the most recent example.

* On Mars, where erosion is much more efficient, although there are many craters there are virtually no ray craters, as we would expect.

The Earth is very near the Moon. If the Moon is so severely cratered by impacts, how has the Earth avoided them? Why is Meteor Crater so rare? Do the comets and asteroids think it inadvisable to impact an inhabited planet? This is an unlikely forbearance. The only possible explanation is that impact craters are formed at very similar rates on both the Earth and the Moon, but that on the airless, waterless Moon they are preserved for immense periods of time, while on the Earth slow erosion wipes them out or fills them in. Running water, windblown sand and mountain-building are very slow processes. But over millions or billions of years, they are capable of utterly erasing even very large impact scars.

On the surface of any moon or planet, there will be external processes, such as impacts from space, and internal processes, such as earthquakes; there will be fast, catastrophic events, such as volcanic explosions, and processes of excruciating slowness, such as the pitting of a surface by tiny airborne sand grains. There is no general answer to the question of which processes dominate, the outside ones or the inside ones; the rare but violent events, or the common and inconspicuous occurrences. On the Moon, the outside, catastrophic events hold sway; on Earth, the inside, slow processes dominate. Mars is an intermediate case.

Between the orbits of Mars and Jupiter are countless asteroids, tiny terrestrial planets. The largest are a few hundred kilometers across. Many have oblong shapes and are tumbling through space. In some cases there seem to be two or more asteroids in tight mutual orbits. Collisions among the asteroids happen frequently, and occasionally a piece is chipped off and accidentally intercepts the Earth, falling to the ground as a meteorite. In the exhibits, on the shelves of our museums are the fragments of distant worlds. The asteroid belt is a great grinding mill, producing smaller and smaller pieces down to motes of dust. The bigger asteroidal pieces, along with the comets, are mainly responsible for the recent

But our psychological predispositions pro or con must not mislead us. All that matters is the evidence, and the evidence is not yet in. The real Mars is a world of wonders. Its future prospects are far more intriguing than our past apprehensions about it. In our time we have sifted the sands of Mars, we have established a presence there, we have fulfilled a century of dreams!

> No one would have believed in the last years of the nineteenth century that this world was being watched keenly and closely by intelligences greater than man's and yet as mortal as his own; that as men busied themselves about their various concerns, they were scrutinized and studied, perhaps almost as narrowly as a man with a microscope might scrutinize the transient creatures that swarm and multiply in a drop of water. With infinite complacency, men went to and fro over this globe about their little affairs, serene in their assurances of their empire over matter. It is possible that the infusoria under the microscope do the same. No one gave a thought to the older worlds of space as sources of human danger, or thought of them only to dismiss the idea of life upon them as impossible or improbable. It is curious to recall some of the mental habits of those departed days. At most, terrestrial men fancied there might be other men upon Mars, perhaps inferior to themselves and ready to welcome a missionary enterprise. Yet across the gulf of space, minds that are to our minds as ours are to those of the beasts that perish, intellects vast and cool and unsympathetic, regarded this Earth with envious eyes, and slowly and surely drew their plans against us.

These opening lines of H. G. Wells' 1897 science fiction classic *The War of the Worlds* maintain their haunting power to this day.* For all of our history, there has been the fear, or hope, that there might be life beyond the Earth. In the last hundred years, that premonition has focused on a bright red point of light in the night sky. Three years before *The War of the Worlds* was published, a Bostonian named Percival Lowell founded a major observatory where the most elaborate claims in support of life on Mars were developed. Lowell dabbled in astronomy as a young man, went to Harvard, secured a semi-official diplomatic appointment to Korea, and otherwise engaged in the usual pursuits of the wealthy. Before he died in 1916, he had made major contributions to our knowledge of the nature and evolution of the planets, to the deduction of the expanding universe and, in a decisive way, to the discovery of the planet Pluto, which is named after him. The first two letters of the name Pluto are the initials of Percival Lowell. Its symbol is ■, a planetary monogram.

* In 1938, a radio version, produced by Orson Welles, transposed the Martian invasion from England to the eastern United States, and frightened millions in war-jittery America into believing that the Martians were in fact attacking.

But Lowell's lifelong love was the planet Mars. He was electrified by the announcement in 1877 by an Italian astronomer, Giovanni Schiaparelli, of *canali* on Mars. Schiaparelli had reported during a close approach of Mars to Earth an intricate network of single and double straight lines crisscrossing the bright areas of the planet. *Canali* in Italian means channels or grooves, but was promptly translated into English as *canals*, a word that implies intelligent design. A Mars mania coursed through Europe and America, and Lowell widow, Helen Simpson Vishniac. Large rocks returned from Antarctica in that expedition, examined by Imre Friedmann, turn out to have a fascinating microbiology - one or two millimeters inside the rock, algae have colonized a tiny world in which small quantities of water are trapped and made liquid. On Mars such a place would be even more interesting, because while the visible light necessary for photosynthesis would penetrate to that depth, the germicidal ultraviolet light would be at least partially attenuated.

Because the design of space missions is finalized many years before launch, and because of Vishniac's death, the results of his Antarctic experiments did not influence the Viking design for seeking Martian life. In general, the microbiology experiments were not carried out at the low ambient Martian temperatures, and most did not provide long incubation times. They all made fairly strong assumptions about what Martian metabolism had to be like. There was no way to look for life inside the rocks.

Each Viking lander was equipped with a sample arm to acquire material from the surface and then slowly withdraw it into the innards of the spacecraft, transporting the particles on little hoppers like an electric train to five different experiments: one on the inorganic chemistry of the soil, another to look for organic molecules in the sand and dust, and three to look for microbial life. When we look for life on a planet, we are making certain assumptions. We try, as well as we can, not to assume that life elsewhere will be just like life here. But there are limits to what we can do. We know in detail only about life here. While the Viking biology experiments are a pioneering first effort, they hardly represent a definitive search for life on Mars. The results have been tantalizing, annoying, provocative, stimulating, and, at least until recently, substantially inconclusive.

Each of the three microbiology experiments asked a different kind of question, but in all cases a question about Martian metabolism. If there are microorganisms in the Martian soil, they must take in food and give off waste gases; or they must take in gases from the atmosphere and, perhaps with the aid of sunlight, convert them into useful materials. So we bring food to Mars and hope that the Martians, if there are any, will find it tasty. Then we see if any interesting new gases come out of the soil. Or we provide our own radioactively labeled gases and see if they are converted into organic matter, in which case small Martians are inferred.

By criteria established before launch, two of the three Viking microbiology experiments seem to have yielded positive results. First, when Martian soil was mixed with a sterile organic soup from Earth, something in the soil chemically broke down the soup - almost as if there were respiring microbes metabolizing a food package from Earth. Second, when gases from Earth were introduced into the Martian soil sample, the gases became chemically combined with the soil - almost as if there were photosynthesizing microbes, generating organic matter from atmospheric gases. Positive results in Martian microbiology were achieved in seven different samplings- in two locales on Mars separated by 5,000 kilometers.

But the situation is complex, and the criteria of experimental success may have been inadequate. Enormous efforts were made to build the Viking microbiology experiments and test them with a variety of microbes. Very little effort was made to calibrate the experiments with plausible inorganic Martian surface materials. Mars is not the Earth. As the legacy of Percival Lowell reminds us, we can be fooled. Perhaps there is an exotic inorganic chemistry in the Martian soil that is able by itself, in the absence of Martian microbes, to oxidize foodstuffs. Perhaps there is some special inorganic, nonliving catalyst in the soil that is able to fix atmospheric gases and convert them into organic molecules.

as a beam of particles and in others as a wave. This wave-particle dualism may not correspond readily to our common-sense notions, but it is in excellent accord with what experiments have shown light really does. There is something mysterious and stirring in this marriage of opposites, and it is fitting that Newton and Huygens, bachelors both, were the parents of our modern understanding of the nature of light.

Leeuwenhoek's microscope evolved from the magnifying glasses employed by drapers to examine the quality of cloth. With it he discovered a universe in a drop of water: the microbes, which he described as 'animalcules' and thought 'cute'. Huygens had contributed to the design of the first microscopes and himself made many discoveries with them. Leeuwenhoek and Huygens were among the first people ever to see human sperm cells, a prerequisite for understanding human reproduction. To explain how microorganisms slowly develop in water previously sterilized by boiling, Huygens proposed that they were small enough to float through the air and reproduced on alighting in water. Thus he established an alternative to spontaneous generation - the notion that life could arise, in fermenting grape juice or rotting meat, entirely independent of preexisting life. It was not until the time of Louis Pasteur, two centuries later, that Huygens' speculation was proved correct. The Viking search for life on Mars can be traced in more ways than one back to Leeuwenhoek and Huygens. They are also the grandfathers of the germ theory of disease, and therefore of much of modern medicine. But they had no practical motives in mind. They were merely tinkering in a technological society.

The microscope and telescope, both developed in early seventeenth-century Holland, represent an extension of human vision to the realms of the very small and the very large. Our observations of atoms and galaxies were launched in this time and place. Christiaan Huygens loved to grind and polish lenses for astronomical telescopes and constructed one five meters long. His discoveries with the telescope would by themselves have ensured his place in the history of human accomplishment. In the footsteps of Eratosthenes, he was the first person to measure the size of another planet. He was also the first to speculate that Venus is completely covered with clouds; the first to draw a surface feature on the planet Mars (a vast dark windswept slope called Syrtis Major); and by observing the appearance and disappearance of such features as the planet rotated, the first to determine that the Martian day was, like ours, roughly twenty-four hours long. He was the first to recognize that Saturn was surrounded by a system of rings which nowhere touches the planet.* And he was the discoverer of Titan, the largest moon of Saturn and, as we now know, the largest moon in the solar system - a world of extraordinary interest and promise. Most of these discoveries he made in his twenties. He also thought astrology was nonsense.

* Galileo discovered the rings, but had no idea what to make of them. Through his early astronomical telescope, they seemed to be two projections symmetrically attached to Saturn, resembling, he said in some bafflement, ears.

Huygens did much more. A key problem for marine navigation in this age was the determination of longitude. Latitude could easily be determined by the stars - the farther south you were, the more southern constellations you could see. But longitude required precise timekeeping. An accurate shipboard clock would tell the time in your home port; the rising and setting of the Sun and stars would specify the local shipboard time; and the difference between the two would yield your longitude. Huygens invented the pendulum clock (its principle had been discovered earlier by Galileo), which was then employed,

CHAPTER VII

The Backbone of Night

> They came to a round hole in the sky . . . glowing like fire. This, the Raven said, was a star.
>
> - Eskimo creation myth

> I would rather understand one cause than be King of Persia.
>
> - Democritus of Abdera

> Bur Aristarchus of Samos brought out a book consisting of some hypotheses, in which the premises lead to the result that the universe is many times greater than that now so called. His hypotheses are that the fixed stars and the Sun remain unmoved, that the Earth revolves about the Sun in the circumference of a circle, the Sun lying in the middle of the orbit, and that the sphere of the fixed stars, situated about the same center as the Sun, is so great that the circle in which he supposes the Earth to revolve bears such a proportion to the distance of the fixed stars as the center of the sphere bears to its surface.
>
> - Archimedes, *The Sand Reckoner*

> If a faithful account was rendered of Man's ideas upon Divinity, he would be obliged to acknowledge, that for the most part the word 'gods' has been used to express the concealed, remote, unknown causes of the effects he witnessed; that he applies this term when the spring of the natural, the source of known causes, ceases to be visible: as soon as he loses the thread of these causes, or as soon as his mind can no longer follow the chain, he solves the difficulty, terminates his research, by ascribing it to his gods . . . When, therefore, he ascribes to his gods the production of some phenomenon . . . does he, in fact, do any thing more than substitute for the darkness of his own mind, a sound to which he has been accustomed to listen with reverential awe?
>
> - Paul Heinrich Dietrich, Baron von Holbach, *Système de la Nature*, London, 1770

When I was little, I lived in the Bensonhurst section of Brooklyn in the City of New York. I knew my immediate neighborhood intimately, every apartment building, pigeon coop, backyard, front stoop, empty lot, elm tree, ornamental railing, coal chute and wall for playing Chinese handball, among which the brick exterior of a theater called the Loew's Stillwell was of superior quality. I knew where many people lived: Bruno and Dino, Ronald and Harvey, Sandy, Bernie, Danny, Jackie and Myra. But more than a few blocks away, north of the raucous automobile traffic and elevated railway on 86th Street, was a strange unknown territory, off-limits to my wanderings. It could have been Mars for all I knew.

Even with an early bedtime, in winter you could sometimes see the stars. I would look at them, twinkling and remote, and wonder what they were. I would ask older children and adults, who would only reply, 'They're lights in the sky, kid.' I could see they were lights in the sky. But what *were* they? Just small hovering lamps? Whatever for? I felt a kind of sorrow for them: a commonplace whose strangeness remained somehow hidden the heavens,' the reply of a true astronomer. He performed a clever experiment in which a single drop of white liquid, like cream, was shown not to lighten perceptibly the contents of a great pitcher of dark liquid, like wine. There must, he concluded, be changes deducible by experiment that are too subtle to be perceived directly by the senses.

Anaxagoras was not nearly so radical as Democritus. Both were thoroughgoing materialists, not in prizing possessions but in holding that matter alone provided the underpinnings of the world. Anaxagoras believed in a special mind substance and disbelieved in the existence of atoms. He thought humans were more intelligent than other animals because of our hands, a very Ionian idea.

He was the first person to state clearly that the Moon shines by reflected light, and he accordingly devised a theory of the phases of the Moon. This doctrine was so dangerous that the manuscript describing it had to be circulated in secret, an Athenian *samizdat*. It was not in keeping with the prejudices of the time to explain the phases or eclipses of the Moon by the relative geometry of the Earth, the Moon and the self-luminous Sun. Aristotle, two generations later, was content to argue that those things happened because it was the nature of the Moon to have phases and eclipses - mere verbal juggling, an explanation that explains nothing.

The prevailing belief was that the Sun and Moon were gods. Anaxagoras held that the Sun and stars are fiery stones. We do not feel the heat of the stars because they are too far away. He also thought that the Moon has mountains (right) and inhabitants (wrong). He held that the Sun was so huge that it was probably larger than the Peloponnesus, roughly the southern third of Greece. His critics thought this estimate excessive and absurd.

Anaxagoras was brought to Athens by Pericles, its leader in its time of greatest glory, but also the man whose actions led to the Peloponnesian War, which destroyed Athenian democracy. Pericles delighted in philosophy and science, and Anaxagoras was one of his principal confidants. There are those who think that in this role Anaxagoras contributed significantly to the greatness of Athens. But Pericles had political problems. He was too powerful to be attacked directly, so his enemies attacked those close to him. Anaxagoras was convicted and imprisoned for the religious crime of impiety - because he had taught that the Moon was made of ordinary matter, that it was a place, and that the Sun was a red-hot stone in the sky. Bishop John Wilkins commented in 1638 on these Athenians: 'Those zealous idolators [counted] it a great blasphemy to make their God a stone, whereas notwithstanding they were so senseless in their adoration of idols as to make a stone their God.' Pericles seems to have engineered Anaxagoras' release from prison, but it was too late. In Greece the tide was turning, although the Ionian tradition continued in Alexandrian Egypt two hundred years later.

The great scientists from Thales to Democritus and Anaxagoras have usually been described in history or philosophy books as 'Presocratics', as if their main function was to hold the philosophical fort until the advent of Socrates, Plato, and Aristotle and perhaps influence them a little. Instead, the old Ionians represent a different and largely contradictory tradition, one in much better accord with modern science. That their influence was felt powerfully for only two or three centuries is an irreparable loss for all those human beings who lived between the Ionian Awakening and the Italian Renaissance.

Perhaps the most influential person ever associated with Samos was Pythagoras,* a contemporary of Polycrates in the sixth century B.C. According to local tradition, he lived for a time in a cave on the Samian Mount Kerkis, and was the first person in the history of the world to deduce that the Earth is a sphere. Perhaps he argued by analogy with the Moon something of an anomaly.

The second brightest star in the constellation Andromeda, called Beta Andromedae, is seventy-five light-years away. The light by which we see it now has spent seventy-five years traversing the dark of interstellar space on its long journey to Earth. In the unlikely event that Beta Andromedae blew itself up last Tuesday, we would not know it for another seventy-five years, as this interesting information, traveling at the speed of light, would require seventy-five years to cross the enormous interstellar distances. When the light by which we now see this star set out on its long voyage, the young Albert Einstein, working as a Swiss patent clerk, had just published his epochal special theory of relativity here on Earth.

Space and time are interwoven. We cannot look out into space without looking back into time. Light travels very fast. But space is very empty, and the stars are far apart. Distances of seventy-five light-years or less are very small compared to other distances in astronomy. From the Sun to the center of the Milky Way Galaxy is 30,000 light-years. From our galaxy to the nearest spiral galaxy, M31, also in the constellation Andromeda, is 2,000,000 light-years. When the light we see today from M31 left for Earth, there were no humans on our planet, although our ancestors were evolving rapidly to our present form. The distance from the Earth to the most remote quasars is eight or ten billion light-years. We see them today as they were before the Earth accumulated, before the Milky Way was formed.

This is not a situation restricted to astronomical objects, but only astronomical objects are so far away that the finite speed of light becomes important. If you are looking at a friend three meters (ten feet) away, at the other end of the room, you are not seeing her as she is 'now'; but rather as she 'was' a hundred millionth of a second ago. [(3 m) / (3 x 10^8 m/sec) = 1/(10^8/sec) =10^{-8} sec, or a hundredth of a microsecond. In this calculation we have merely divided the distance by the speed to get the travel time.] But the difference between your friend 'now' and now minus a hundred-millionth of a second is too small to notice. On the other hand, when we look at a quasar eight billion light-years away, the fact that we are seeing it as it was eight billion years ago may be very important. (For example, there are those who think that quasars are explosive events likely to happen only in the early history of galaxies. In that case, the more distant the galaxy, the earlier in its history we are observing it, and the more likely it is that we should see it as a quasar. Indeed, the number of quasars increases as we look to distances of more than about five billion light-years).

The two Voyager interstellar spacecraft, the fastest machines ever launched from Earth, are now traveling at one ten-thousandth the speed of light. They would need 40,000 years to go the distance to the nearest star. Do we have any hope of leaving Earth and traversing the immense distances even to Proxima Centauri in convenient periods of time? Can we do something to approach the speed of light? What is magic about the speed of light? Might we someday be able to go faster than that?

If you had walked through the pleasant Tuscan countryside in the 1890's, you might have come upon a somewhat long-haired teenage high school dropout on the road to Pavia. His teachers in Germany had told him that he would never amount to anything, that his questions destroyed classroom discipline, that he would be better off out of school. So he left and wandered, delighting in the freedom of Northern Italy, where he could ruminate on matters remote from the subjects he had been force-fed in his highly disciplined Prussian schoolroom. His name was Albert Einstein, and his ruminations changed the world.

nowhere near, the idea of infinity. A googolplex is *precisely* as far from infinity as is the number one. We could try to write out a googolplex, but it is a forlorn ambition. A piece of paper large enough to have all the zeroes in a googolplex written out explicitly could not be stuffed into the known universe. Happily, there is a simpler and very concise way of writing a googolplex: $10^{10^{10}}$; and even infinity: $\propto$ (pronounced 'infinity').

* The spirit of this calculation is very old. The opening sentences of Archimedes' *The Sand Reckoner* are: 'There are some, King Gelon, who think that the number of the sand is infinite in multitude: and I mean by the sand not only that which exists about Syracuse and the rest of Sicily, but also that which is found in every region, whether inhabited or uninhabited. And again, there are some who, without regarding it as infinite, yet think that no number has been named which is great enough to exceed its multitude.' Archimedes then went on not only to name the number but to calculate it. Later he asked how many grains of sand would fit, side by side, into the universe that he knew. His estimate; 10^{63}, which corresponds, by a curious coincidence, to 10^{83} or so atoms.

In a burnt apple pie, the char is mostly carbon. Ninety cuts and you come to a carbon atom, with six protons and six neutrons in its nucleus and six electrons in the exterior cloud. If we were to pull a chunk out of the nucleus - say, one with two protons and two neutrons - it would be not the nucleus of a carbon atom, but the nucleus of a helium atom. Such a cutting or fission of atomic nuclei occurs in nuclear weapons and conventional nuclear power plants, although it is not carbon that is split. If you make the ninety-first cut of the apple pie, if you slice a carbon nucleus, you make not a smaller piece of carbon, but something else - an atom with completely different chemical properties. If you cut an atom, you transmute the elements.

But suppose we go farther. Atoms are made of protons, neutrons and electrons. Can we cut a proton? If we bombard protons at high energies with other elementary particles - other protons, say - we begin to glimpse more fundamental units hiding inside the proton. Physicists now propose that so-called elementary particles such as protons and neutrons are in fact made of still more elementary particles called quarks, which come in a variety of 'colors' and 'flavors', as their properties have been termed in a poignant attempt to make the subnuclear world a little more like home. Are quarks the ultimate constituents of matter, or are they too composed of still smaller and *more* elementary particles? Will we ever come to an end in our understanding of the nature of matter, or is there an infinite regression into more and more fundamental particles? This is one of the great unsolved problems in science.

The transmutation of the elements was pursued in medieval laboratories in a quest called alchemy. Many alchemists believed that all matter was a mixture of four elementary substances: water, air, earth and fire, an ancient Ionian speculation. By altering the relative proportions of earth and fire, say, you would be able, they thought, to change copper into gold. The field swarmed with charming frauds and con men, such as Cagliostro and the Count of Saint-Germain, who pretended not only to transmute the elements but also to hold the secret of immortality. Sometimes gold was hidden in a wand with a false bottom, to appear miraculously in a crucible at the end of some arduous experimental demonstration. With wealth and immortality the bait, the European nobility found itself transferring large sums to the practitioners of this dubious art. But there were more serious alchemists such as Paracelsus and even Isaac Newton. The money was not altogether wasted - new chemical elements, such as phosphorous, antimony and mercury, were discovered. In fact, the origin of modern chemistry can be traced directly to these experiments.

But the idea seemed so bizarre that it was generally ignored until quite recently. Then, to the astonishment of many, including many astronomers, evidence was actually found for the existence of black holes in space. The Earth's atmosphere is opaque to X-rays. To determine whether astronomical objects emit such short wavelengths of light, an X-ray telescope must be carried aloft. The first X-ray observatory was an admirably international effort, orbited by the United States from an Italian launch platform in the Indian Ocean off the coast of Kenya and named Uhuru, the Swahili word for 'freedom'. In 1971, Uhuru discovered a remarkably bright X-ray source in the constellation of Cygnus, the Swan, flickering on and off a thousand times a second. The source, called Cygnus X-1, must therefore be very small. Whatever the reason for the flicker, information on when to turn on and off can cross Cyg X-1 no faster than the speed of light, 300,000 km/sec. Thus Cyg X-1 can be no larger than [300,000 km/sec] x [(1/ 1000) sec] = 300 kilometers across. Something the size of an asteroid is a brilliant, blinking source of X-rays, visible over interstellar distances. What could it possibly be? Cyg X-1 is in precisely the same place in the sky as a hot blue supergiant star, which reveals itself in visible light to have a massive close but unseen companion that gravitationally tugs it first in one direction and then in another. The companion's mass is about ten times that of the Sun. The supergiant is an unlikely source of X-rays, and it is tempting to identify the companion inferred in visible light with the source detected in X-ray light. But an invisible object weighing ten times more than the Sun and collapsed into a volume the size of an asteroid can only be a black hole. The X-rays are plausibly generated by friction in the disk of gas and dust accreted around Cyg X-1 from its supergiant companion. Other stars called V861 Scorpii, GX339-4, SS433, and Circinus X-2 are also candidate black holes. Cassiopeia A is the remnant of a supernova whose light should have reached the Earth in the seventeenth century, when there were a fair number of astronomers. Yet no one reported the explosion. Perhaps, as I. S. Shklovskii has suggested, there is a black hole hiding there, which ate the exploding stellar core and damped the fires of the supernova. Telescopes in space are the means for checking these shards and fragments of data that may be the spoor, the trail, of the legendary black hole.

A helpful way to understand black holes is to think about the curvature of space. Consider a flat, flexible, lined two-dimensional surface, like a piece of graph paper made of rubber. If we drop a small mass, the surface is deformed or puckered. A marble rolls around the pucker in an orbit like that of a planet around the Sun. In this interpretation, which we owe to Einstein, gravity is a distortion in the fabric of space. In our example, we see two-dimensional space warped by mass into a third physical dimension. Imagine we live in a three-dimensional universe, locally distorted by matter into a fourth physical dimension that we cannot perceive directly. The greater the local mass, the more intense the local gravity, and the more severe the pucker, distortion or warp of space. In this analogy, a black hole is a kind of bottomless pit. What happens if you fall in? As seen from the outside, you would take an infinite amount of time to fall in, because all your clocks - mechanical and biological would be perceived as having stopped. But from *your* point of view, all your clocks would be ticking away normally. If you could somehow survive the gravitational tides and radiation flux, and (a likely assumption) if the black hole were rotating, it is just possible that you might emerge in another part of space-time - somewhere else in space, somewhere else in time. Such worm holes in space, a little like those in an apple, have been seriously suggested, although they have by no means been proved to exist. Might gravity tunnels provide a kind of interstellar or intergalactic subway, permitting us to travel to

> Before heaven and earth had taken form all was vague and amorphous . . . That which was clear and light drifted up to become heaven, while that which was heavy and turbid solidified to become earth. It was very easy for the pure, fine material to come together, but extremely difficult for the heavy, turbid material to solidify. Therefore heaven was completed first and earth assumed shape after. When heaven and earth were joined in emptiness and all was unwrought simplicity, then without having been created things came into being. This was the Great Oneness. All things issued from this Oneness but all became different . . .
>
> - Huai-nan Tzu, China (around first century B.C.)

These myths are tributes to human audacity. The chief difference between them and our modern scientific myth of the Big Bang is that science is self-questioning, and that we can perform experiments and observations to test our ideas. But those other creation stories are worthy of our deep respect.

Every human culture rejoices in the fact that there are cycles in nature. But how, it was thought, could such cycles come about unless the gods willed them? And if there are cycles in the years of humans, might there not be cycles in the aeons of the gods? The Hindu religion is the only one of the world's great faiths dedicated to the idea that the Cosmos itself undergoes an immense, indeed an infinite, number of deaths and rebirths. It is the only religion in which the time scales correspond, no doubt by accident, to those of modern scientific cosmology. Its cycles run from our ordinary day and night to a day and night of Brahma, 8.64 billion years long, longer than the age of the Earth or the Sun and about half the time since the Big Bang. And there are much longer time scales still.

There is the deep and appealing notion that the universe is but the dream of the god who, after a hundred Brahma years, dissolves himself into a dreamless sleep. The universe dissolves with him - until, after another Brahma century, he stirs, recomposes himself and begins again to dream the great cosmic dream. Meanwhile, elsewhere, there are an infinite number of other universes, each with its own god dreaming the cosmic dream. These great ideas are tempered by another, perhaps still greater. It is said that men may not be the dreams of the gods, but rather that the gods are the dreams of men.

In India there are many gods, and each god has many manifestations. The Chola bronzes, cast in the eleventh century, include several different incarnations of the god Shiva. The most elegant and sublime of these is a representation of the creation of the universe at the beginning of each cosmic cycle, a motif known as the cosmic dance of Shiva. The god, called in this manifestation Nataraja, the Dance King, has four hands. In the upper right hand is a drum whose sound is the sound of creation. In the upper left hand is a tongue of flame, a reminder that the universe, now newly created, will billions of years from now be utterly destroyed.

These profound and lovely images are, I like to imagine, a kind of premonition of modern astronomical ideas.* Very likely, the universe has been expanding since the Big Bang, but it is by no means clear that it will continue to expand forever. The expansion may gradually slow, stop and reverse itself. If there is less than a certain critical amount of matter in the universe, the gravitation of the receding galaxies will be insufficient to stop the expansion, and the universe will run away forever. But if there is more matter than we can see - hidden away in black holes, say, or in hot but invisible gas between the galaxies -

which conducts the basic biological functions, including the rhythms of life - heartbeat and respiration. According to a provocative insight by Paul MacLean, the higher functions of the brain evolved in three successive stages. Capping the brainstem is the R-complex, the seat of aggression, ritual, territoriality and social hierarchy, which evolved hundreds of millions of years ago in our reptilian ancestors. Deep inside the skull of every one of us there is something like the brain of a crocodile. Surrounding the R-complex is the limbic system or mammalian brain, which evolved tens of millions of years ago in ancestors who were mammals but not yet primates. It is a major source of our moods and emotions, of our concern and care for the young.

And finally, on the outside, living in uneasy truce with the more primitive brains beneath, is the cerebral cortex, which evolved millions of years ago in our primate ancestors. The cerebral cortex, where matter is transformed into consciousness, is the point of embarkation for all our cosmic voyages. Comprising more than two-thirds of the brain mass, it is the realm of both intuition and critical analysis. It is here that we have ideas and inspirations, here that we read and write, here that we do mathematics and compose music. The cortex regulates our conscious lives. It is the distinction of our species, the seat of our humanity. Civilization is a product of the cerebral cortex.

The language of the brain is not the DNA language of the genes. Rather, what we know is encoded in cells called neurons - microscopic electrochemical switching elements, typically a few hundredths of a millimeter across. Each of us has perhaps a hundred billion neurons, comparable to the number of stars in the Milky Way Galaxy. Many neurons have thousands of connections with their neighbors. There are something like a hundred trillion, 10^{14}, such connections in the human cerebral cortex.

Charles Sherrington imagined the activities in the cerebral cortex upon awakening:

> [The cortex] becomes now a sparkling field of rhythmic flashing points with trains of traveling sparks hurrying hither and thither. The brain is waking and with it the mind is returning. It is as if the Milky Way entered upon some cosmic dance. Swiftly the [cortex] becomes an enchanted loom where millions of flashing shuttles weave a dissolving pattern, always a meaningful pattern though never an abiding one; a shifting harmony of sub-patterns. Now as the waking body rouses, sub-patterns of this great harmony of activity stretch down into the unlit tracks of the [lower brain]. Strings of flashing and traveling sparks engage the links of it. This means that the body is up and rises to meet its waking day.

Even in sleep, the brain is pulsing, throbbing and flashing with the complex business of human life - dreaming, remembering, figuring things out. Our thoughts, visions and fantasies have a physical reality. A thought is made of hundreds of electrochemical impulses. If we were shrunk to the level of the neurons, we might witness elaborate, intricate, evanescent patterns. One might be the spark of a memory of the smell of lilacs on a country road in childhood. Another might be part of an anxious all-points bulletin: ‘Where did I leave the keys?’

There are many valleys in the mountains of the mind, convolutions that greatly increase the surface area available in the cerebral cortex for information storage in a skull of limited size. The neurochemistry of the brain is astonishingly busy, the circuitry of a machine more wonderful than any devised by humans. But there is no evidence that its functioning is due to anything more than the 10^{14} neural connections that build an elegant nation, ancient or modern, has conceived the art of architecture on such a sublime, great, and imposing style, as the ancient Egyptians. They ordered everything to be done for people who are a hundred feet high.

* Fourier is now famous for his study of the propagation of heat in solids, used today to understand the surface properties of the planets, and for his investigation of waves and other periodic motion - a branch of mathematics known as Fourier analysis.

On the walls and columns of Karnak, at Dendera, everywhere in Egypt, Champollion delighted to find that he could read the inscriptions almost effortlessly. Many before him had tried and failed to decipher the lovely hieroglyphics, a word that means 'sacred carvings.' Some scholars had believed them to be a kind of picture code, rich in murky metaphor, mostly about eyeballs and wavy lines, beetles, bumblebees and birds - especially birds. Confusion was rampant. There were those who deduced that the Egyptians were colonists from ancient China. There were those who concluded the opposite. Enormous folio volumes of spurious translations were published. One interpreter glanced at the Rosetta stone, whose hieroglyphic inscription was then still undeciphered, and instantly announced its meaning. He said that the quick decipherment enabled him 'to avoid the systematic errors which invariably arise from prolonged reflection.' You get better results, he argued, by not thinking too much. As with the search for extraterrestrial life today, the unbridled speculation of amateurs had frightened many professionals out of the field.

Champollion resisted the idea of hieroglyphs as pictorial metaphors. Instead, with the aid of a brilliant insight by the English physicist Thomas Young, he proceeded something like this: The Rosetta stone had been uncovered in 1799 by a French soldier working on the fortifications of the Nile Delta town of Rashid, which the Europeans, largely ignorant of Arabic, called Rosetta. It was a slab from an ancient temple, displaying what seemed clearly to be the same message in three different writings: in hieroglyphics at top, in a kind of cursive hieroglyphic called demotic in the middle, and, the key to the enterprise, in Greek at the bottom. Champollion, who was fluent in ancient Greek, read that the stone had been inscribed to commemorate the coronation of Ptolemy V Epiphanes, in the spring of the year 196 B.C. On this occasion the king released political prisoners, remitted taxes, endowed temples, forgave rebels, increased military preparedness and, in short, did all the things that modern rulers do when they wish to stay in office.

The Greek text mentions Ptolemy many times. In roughly the same positions in the hieroglyphic text is a set of symbols surrounded by an oval or cartouche. This, Champollion reasoned, very probably also denotes Ptolemy. If so, the writing could not be fundamentally pictographic or metaphorical; rather, most of the symbols must stand for letters or syllables. Champollion also had the presence of mind to count up the number of Greek words and the number of individual hieroglyphs in what were presumably equivalent texts. There were many fewer of the former, again suggesting that the hieroglyphs were mainly letters and syllables. But which hieroglyphs correspond to which letters? Fortunately, Champollion had available to him an obelisk, which had been excavated at Philae, that included the hieroglyphic equivalent of the Greek name Cleopatra. Ptolemy begins with P; the first symbol in the cartouche is a square. Cleopatra has for its fifth letter a P, and in the Cleopatra cartouche in the fifth position is the same square. P it is. The fourth letter in Ptolemy is an L. It is represented by the lion. The second letter of Cleopatra is an L and, in hieroglyphics, here is a lion again. The eagle is an A, appearing twice in civilization in space, but do not make, at least for a while, physical contact with them. In this case there is no way for the transmitting civilization to know whether we have received the message. If we find the contents offensive or frightening, we are not obliged to reply. But if the message contains valuable information, the consequences for our own civilization will be stunning - insights on alien science and technology, art, music, politics, ethics, philosophy and religion, and most of all, a profound deprovincialization of the human condition. We will know what else is possible.

Because we will share scientific and mathematical insights with any other civilization, I believe that understanding the interstellar message will be the easiest part of the problem. Convincing the U.S. Congress and the Council of Ministers of the U.S.S.R. to fund a search for extraterrestrial intelligence is the hard part.* In fact, it may be that civilizations can be divided into two great categories: one in which the scientists are unable to convince nonscientists to authorize a search for extraplanetary intelligence, in which energies are directed exclusively inward, in which conventional perceptions remain unchallenged and society falters and retreats from the stars; and another category in which the grand vision of contact with other civilizations is shared widely, and a major search is undertaken.

* Or other national organs. Consider this pronouncement from a British Defence Department spokesman as reported in the London *Observer* for February 26, 1978: ‘Any messages transmitted from outer space are the responsibility of the BBC and the Post Office. It is their responsibility to track down illegal broadcasts.’

This is one of the few human endeavors where even a failure is a success. If we were to carry out a rigorous search for extraterrestrial radio signals encompassing millions of stars and heard nothing, we would conclude that galactic civilizations were at best extremely rare, a calibration of our place in the universe. It would speak eloquently of how rare are the living things of our planet, and would underscore, as nothing else in human history has, the individual worth of every human being. If we were to succeed, the history of our species and our planet would be changed forever.

It would be easy for extraterrestrials to make an unambiguously artificial interstellar message. For example, the first ten prime numbers - numbers divisible only by themselves and by one - are 1, 2, 3, 5, 7, 11, 13, 17, 19, 23. It is extremely unlikely that any natural physical process could transmit radio messages containing prime numbers only. If we received such a message we would deduce a civilization out there that was at least fond of prime numbers. But the most likely case is that interstellar communication will be a kind of palimpsest, like the palimpsests of ancient writers short of papyrus or stone who superimposed their messages on top of preexisting messages. Perhaps at an adjacent frequency or a faster timing, there would be another message, which would turn out to be a primer, an introduction to the language of interstellar discourse. The primer would be repeated again and again because the transmitting civilization would have no way to know when we turned in on the message. And then, deeper in the palimpsest, underneath the announcement signal and the primer, would be the real message. Radio technology permits that message to be inconceivably rich. Perhaps when we tuned in, we would find ourselves in the midst of Volume 3,267 of the *Encyclopaedia Galactica*.

We would discover the nature of other civilizations. There would be many of them, each composed of organisms astonishingly different from anything on this planet. They