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**PRIFYSGOL CYMRU
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STEFFAN**

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Mae'r Copi Digidol hwn ac unrhyw gopi digidol neu argraffedig a ddarparwyd ar eich cyfer neu a wnaed gennych o dan amodau'r Drwydded i'w defnyddio ar gyfer y Cwrs Astudio hwn. Gallwch gadw copïau o'r fath ar ddiwedd y cwrs, ond ar gyfer eich defnydd personol yn unig.

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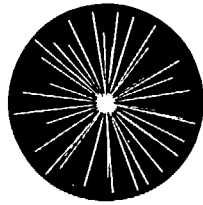
Rhaid i bob copi (gan gynnwys copïau electronaidd) gynnwys yr Hysbysiad Hawlfraint hwn a rhaid eu dinistrio a/neu eu dileu os a phan fyynnir hynny gan Brifysgol Cymru Llanbedr Pont Steffan.

Ac eithrio'r hyn y darperir ar ei gyfer gan gyfraith hawlfraint, ni chaniateir unrhyw gopïo, storio na dosbarthu pellach (gan gynnwys trwy e-bost) heb ganiatâd y deiliad hawlfraint.

Mae gan yr awdur (term sy'n cynnwys artistiaid a chrëwyr gweledol eraill) hawliau moesol yn y gwaith ac ni all staff na myfyrwyr beri, na chaniatáu, i'r gwaith gael ei wyrdroi, ei lurgunio na'i newid mewn unrhyw ffordd arall, nac i gael ei drin yn ddifriol mewn unrhyw ffordd, a fyddai'n niweidiol i anrhydedd neu enw da'r awdur.

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Chapter I

THE SHORES OF THE COSMIC OCEAN

The first men to be created and formed were called the Sorcerer of Fatal Laughter, the Sorcerer of Night, Unkempt, and the Black Sorcerer . . . They were endowed with intelligence, they succeeded in knowing all that there is in the world. When they looked, instantly they saw all that is around them, and they contemplated in turn the arc of heaven and the round face of the earth . . . [Then the Creator said]: "They know all . . . what shall we do with them now? Let their sight reach only to that which is near; let them see only a little of the face of the earth! . . . Are they not by nature simple creatures of our making? Must they also be gods?"

—The Popol Vuh of the Quiché Maya

Have you comprehended the expanse of the earth?
Where is the way to the dwelling of light,
And where is the place of darkness . . . ?

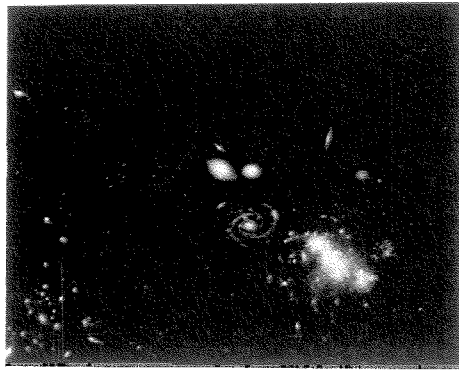
—The Book of Job

It is not from space that I must seek my dignity, but from the government of my thought. I shall have no more if I possess worlds. By space the universe encompasses and swallows me up like an atom; by thought I comprehend the world.

—Blaise Pascal, *Pensées*

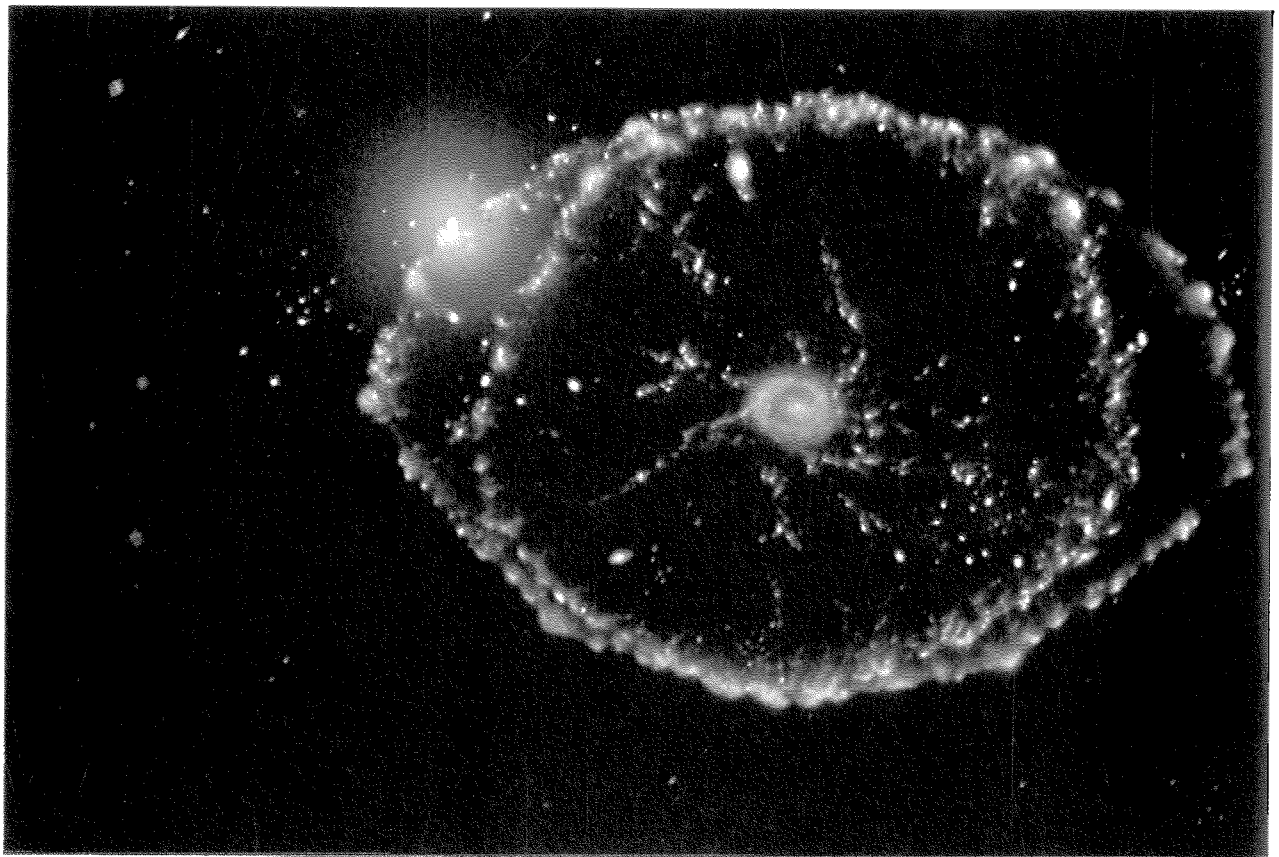
The known is finite, the unknown infinite; intellectually we stand on an islet in the midst of an illimitable ocean of inexplicability. Our business in every generation is to reclaim a little more land.

—T. H. Huxley, 1887



A more extended cluster of galaxies, including (bottom right) an irregular galaxy. Painting by Adolf Schaller and Rick Sternbach.

A rare ring galaxy, with one of its constituent stars glowing blue in a supernova explosion. Painting by Adolf Schaller.



THE COSMOS IS ALL THAT IS OR EVER WAS OR EVER WILL BE. Our feeblest contemplations of the Cosmos stir us—there is a tingling in the spine, a catch in the voice, a faint sensation, as if a distant memory, of falling from a height. We know we are approaching the greatest of mysteries.

The size and age of the Cosmos are beyond ordinary human understanding. Lost somewhere between immensity and eternity is our tiny planetary home. In a cosmic perspective, most human concerns seem insignificant, even petty. And yet our species is young and curious and brave and shows much promise. In the last few millennia we have made the most astonishing and unexpected discoveries about the Cosmos and our place within it, explorations that are exhilarating to consider. They remind us that humans have evolved to wonder, that understanding is a joy, that knowledge is prerequisite to survival. I believe our future depends on how well we know this Cosmos in which we float like a mote of dust in the morning sky.

Those explorations required skepticism and imagination both. Imagination will often carry us to worlds that never were. But without it, we go nowhere. Skepticism enables us to distinguish fancy from fact, to test our speculations. The Cosmos is rich beyond measure—in elegant facts, in exquisite interrelationships, in the subtle machinery of awe.

The surface of the Earth is the shore of the cosmic ocean. From it we have learned most of what we know. Recently, we have waded a little out to sea, enough to dampen our toes or, at most, wet our ankles. The water seems inviting. The ocean calls. Some part of our being knows this is from where we came. We long to return. These aspirations are not, I think, irreverent, although they may trouble whatever gods may be.

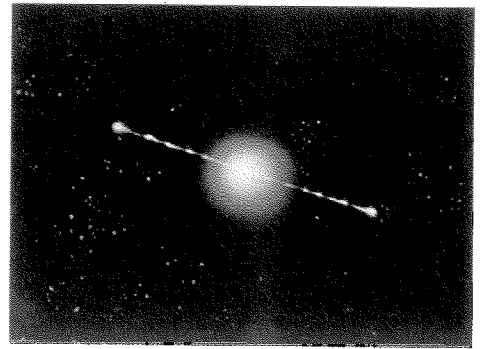
The dimensions of the Cosmos are so large that using familiar units of distance, such as meters or miles, chosen for their utility on Earth, would make little sense. Instead, we measure distance with the speed of light. In one second a beam of light travels 186,000 miles, nearly 300,000 kilometers or seven times around the Earth. In eight minutes it will travel from the Sun to the Earth. We can say the Sun is eight light-minutes away. In a year, it crosses nearly ten trillion kilometers, about six trillion miles, of intervening space. That unit of length, the distance light goes in a year, is called a light-year. It measures not time but distances—enormous distances.

The Earth is a place. It is by no means the only place. It is not even a typical place. No planet or star or galaxy can be typical, because the Cosmos is mostly empty. The only typical place is within the vast, cold, universal vacuum, the everlasting night of intergalactic space, a place so strange and desolate that, by comparison, planets and stars and galaxies seem achingly rare and lovely. If we were randomly inserted into the Cosmos, the chance that we would find ourselves on or near a planet would be less than one in a billion trillion trillion* (10^{33} , a one followed by 33 zeroes). In everyday life such odds are called compelling. Worlds are precious.

From an intergalactic vantage point we would see, strewn like sea froth on the waves of space, innumerable faint, wispy tendrils of light. These are the galaxies. Some are solitary wanderers; most inhabit communal clusters, huddling together, drifting endlessly in the great cosmic dark. Before us is the Cosmos on the grandest scale we know. We are in the realm of the nebulae, eight billion light-years from Earth, halfway to the edge of the known universe.

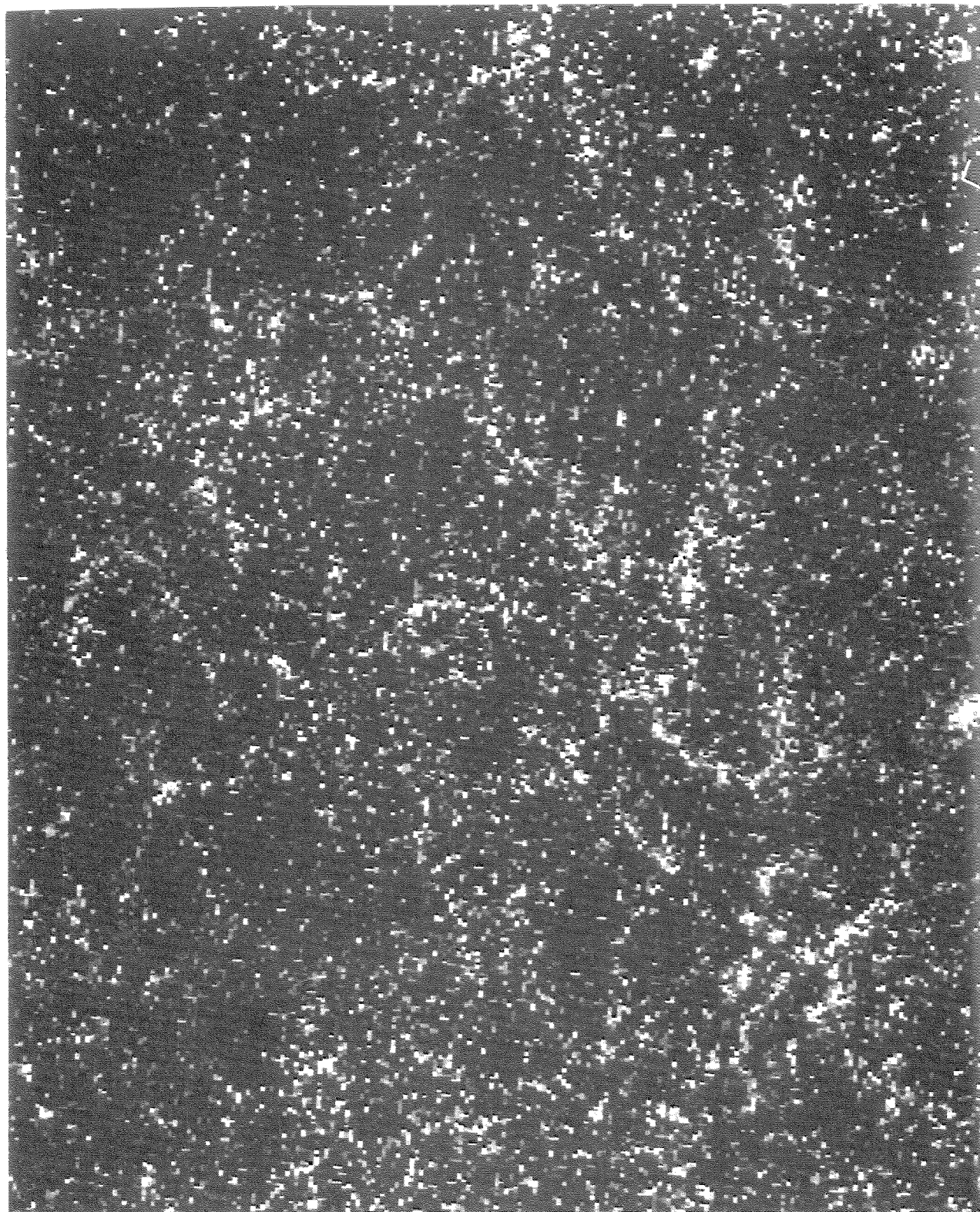
A galaxy is composed of gas and dust and stars—billions upon billions of stars. Every star may be a sun to someone. Within a galaxy are stars and worlds and, it may be, a proliferation of living things and intelligent beings and spacefaring civilizations. But from afar, a galaxy reminds me more of a collection of lovely found objects—seashells, perhaps, or corals, the productions of Nature laboring for aeons in the cosmic ocean.

There are some hundred billion (10^{11}) galaxies, each with, on



Exploding radio galaxy with symmetrical jets. Painting by Adolf Schaller.

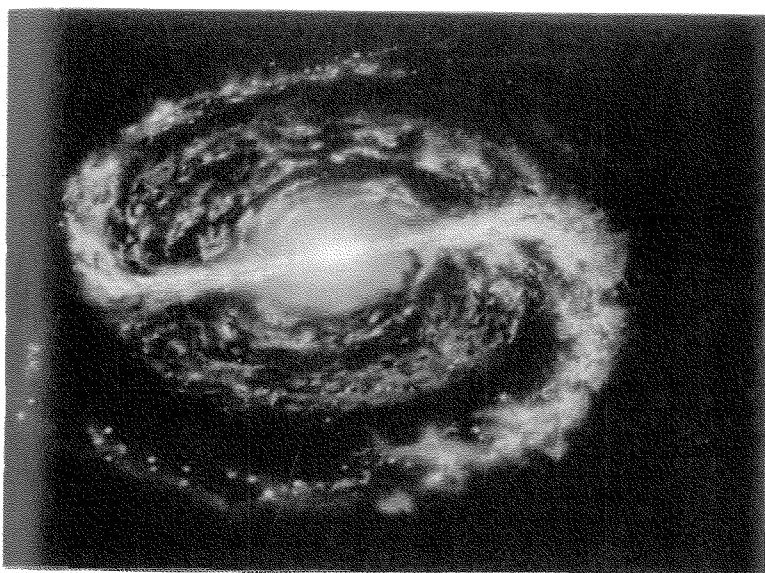
* We use the American scientific convention for large numbers: one billion = 1,000,000,000 = 10^9 ; one trillion = 1,000,000,000,000 = 10^{12} , etc. The exponent counts the number of zeroes after the one.



The large-scale texture of the Cosmos: a small sampling from a map of the million brightest galaxies, all within a billion light-years distance from the Earth. Each little square is a galaxy containing billions of stars. The map is based on a telescopic survey, taking twelve years to complete, by Donald Shane and Carl Wirtanen at the University of California's Lick Observatory. Courtesy Stewart Brand.

the average, a hundred billion stars. In all the galaxies, there are perhaps as many planets as stars, $10^{11} \times 10^{11} = 10^{22}$, ten billion trillion. In the face of such overpowering numbers, what is the likelihood that only one ordinary star, the Sun, is accompanied by an inhabited planet? Why should we, tucked away in some forgotten corner of the Cosmos, be so fortunate? To me, it seems far more likely that the universe is brimming over with life. But we humans do not yet know. We are just beginning our explorations. From eight billion light-years away we are hard pressed to find even the cluster in which our Milky Way Galaxy is embedded, much less the Sun or the Earth. The only planet we are sure is inhabited is a tiny speck of rock and metal, shining feebly by reflected sunlight, and at this distance utterly lost.

But presently our journey takes us to what astronomers on Earth like to call the Local Group of galaxies. Several million



A barred spiral galaxy, so-called from the bar of stars and dust which transects the core. Painting by Jon Lomberg.



A typical spiral galaxy. Painting by Jon Lomberg.

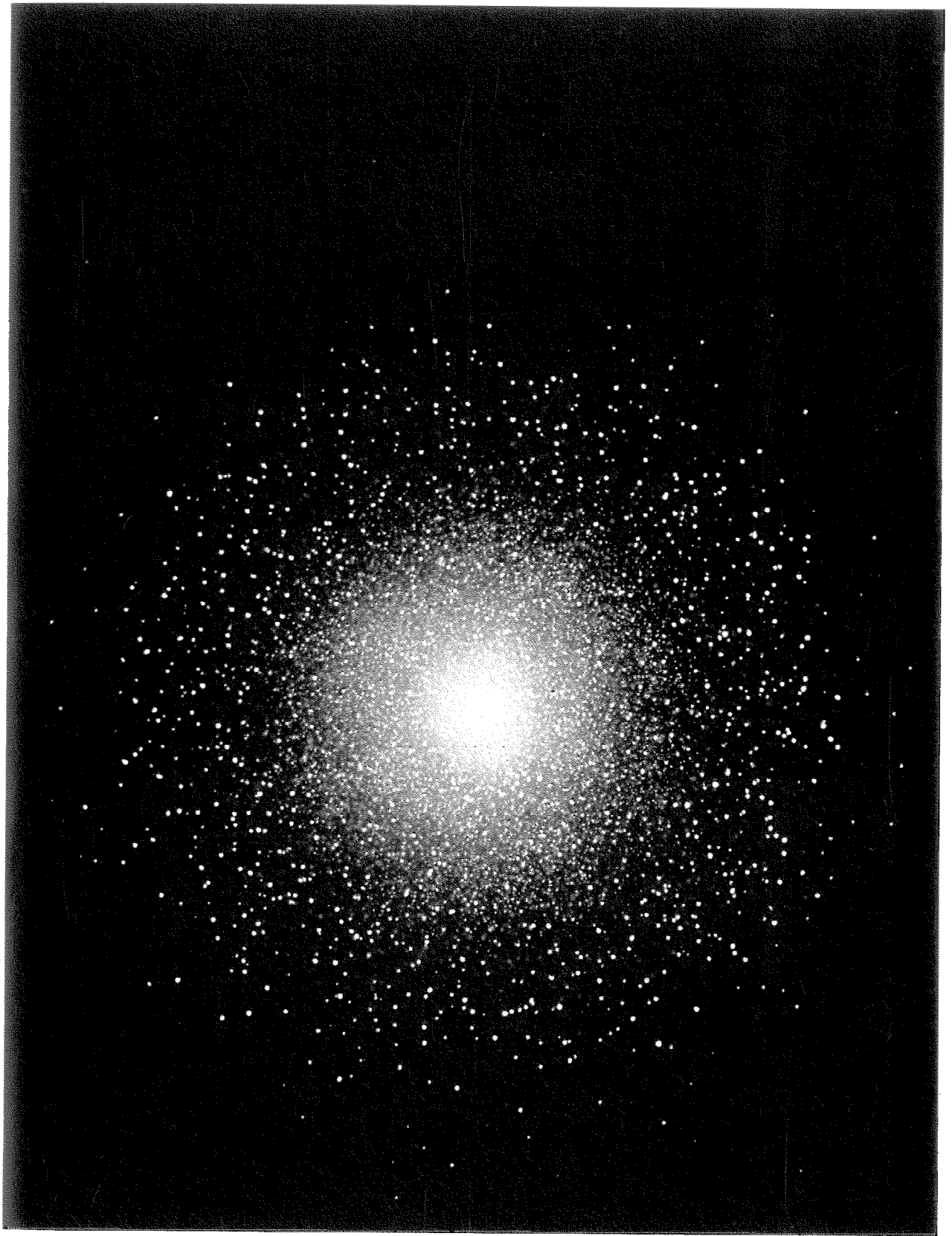
light-years across, it is composed of some twenty constituent galaxies. It is a sparse and obscure and unpretentious cluster. One of these galaxies is M31, seen from the Earth in the constellation Andromeda. Like other spiral galaxies, it is a huge pinwheel of stars, gas and dust. M31 has two small satellites, dwarf elliptical galaxies bound to it by gravity, by the identical law of physics that tends to keep me in my chair. The laws of nature are the same throughout the Cosmos. We are now two million light-years from home.

Beyond M31 is another, very similar galaxy, our own, its spiral arms turning slowly, once every quarter billion years. Now, forty thousand light-years from home, we find ourselves falling toward the massive center of the Milky Way. But if we wish to find the Earth, we must redirect our course to the remote outskirts of the Galaxy, to an obscure locale near the edge of a distant spiral arm.

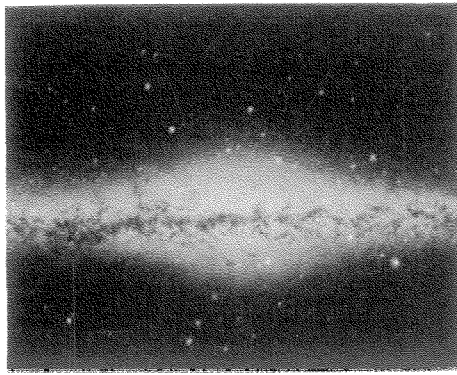
Our overwhelming impression, even between the spiral arms, is of stars streaming by us—a vast array of exquisitely self-luminous stars, some as flimsy as a soap bubble and so large that they could contain ten thousand Suns or a trillion Earths; others the

The Milky Way from slightly above the plane of its spiral arms, which are illuminated by billions of hot, young blue stars. The galactic core, illuminated by older, redder stars, is seen in the distance. Painting by Jon Lomberg.

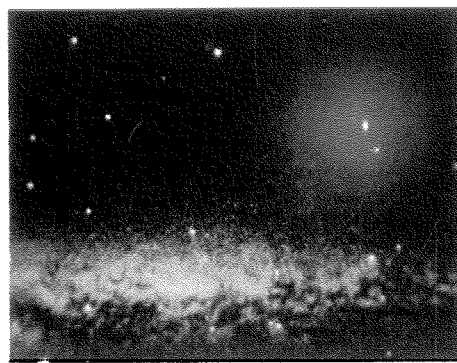




A globular cluster of stars, orbiting the galactic core. Painting by Anne Norcia.



The core of the Milky Way Galaxy, seen edge-on. Painting by Adolf Schaller.



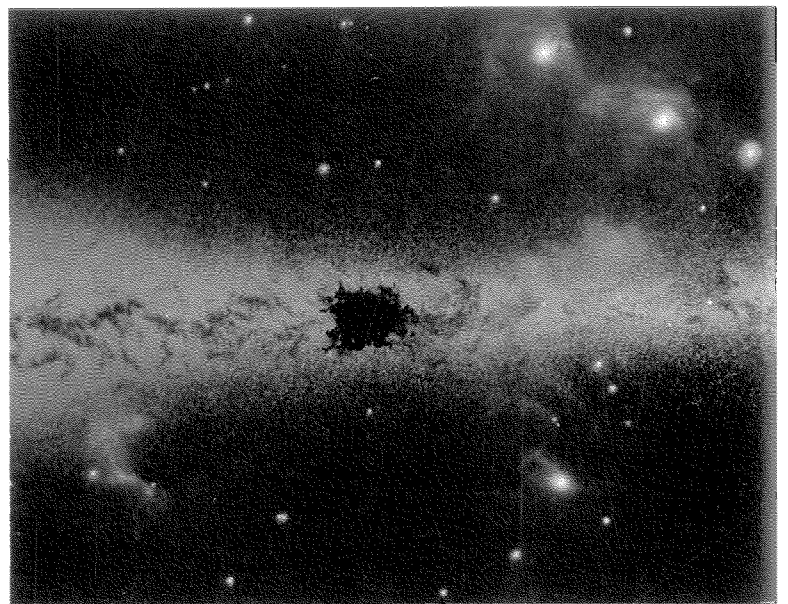
A red giant star (*foreground*) and a spiral arm in the distance, seen edge-on. Painting by John Allison and Adolf Schaller.

A black dust cloud, and stars embedded in gaseous nebulosities; behind them is the Milky Way, edge-on. Painting by Adolf Schaller and John Allison.

size of a small town and a hundred trillion times denser than lead. Some stars are solitary, like the Sun. Most have companions. Systems are commonly double, two stars orbiting one another. But there is a continuous gradation from triple systems through loose clusters of a few dozen stars to the great globular clusters, resplendent with a million suns. Some double stars are so close that they touch, and starstuff flows between them. Most are as separated as Jupiter is from the Sun. Some stars, the supernovae, are as bright as the entire galaxy that contains them; others, the black holes, are invisible from a few kilometers away. Some shine with a constant brightness; others flicker uncertainly or blink with an unfaltering rhythm. Some rotate in stately elegance; others spin so feverishly that they distort themselves to oblateness. Most shine mainly in visible and infrared light; others are also brilliant sources of X-rays or radio waves. Blue stars are hot and young; yellow stars, conventional and middle-aged; red stars, often elderly and dying; and small white or black stars are in the final throes of death. The Milky Way contains some 400 billion stars of all sorts moving with a complex and orderly grace. Of all the stars, the inhabitants of Earth know close-up, so far, but one.

Each star system is an island in space, quarantined from its neighbors by the light-years. I can imagine creatures evolving into glimmerings of knowledge on innumerable worlds, every one of them assuming at first their puny planet and paltry few suns to be all that is. We grow up in isolation. Only slowly do we teach ourselves the Cosmos.

Some stars may be surrounded by millions of lifeless and rocky worldlets, planetary systems frozen at some early stage in their evolution. Perhaps many stars have planetary systems rather like our own: at the periphery, great gaseous ringed planets and icy moons, and nearer to the center, small, warm, blue-white, cloud-



covered worlds. On some, intelligent life may have evolved, reworking the planetary surface in some massive engineering enterprise. These are our brothers and sisters in the Cosmos. Are they very different from us? What is their form, biochemistry, neurobiology, history, politics, science, technology, art, music, religion, philosophy? Perhaps some day we will know them.

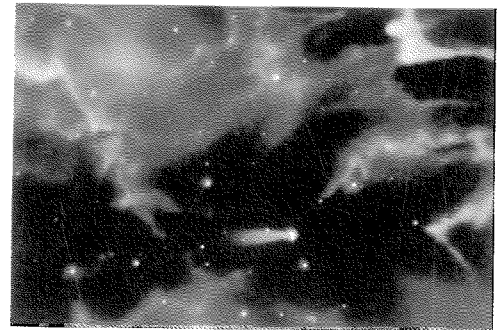
We have now reached our own backyard, a light-year from Earth. Surrounding our Sun is a spherical swarm of giant snowballs composed of ice and rock and organic molecules: the cometary nuclei. Every now and then a passing star gives a tiny gravitational tug, and one of them obligingly careens into the inner solar system. There the Sun heats it, the ice is vaporized, and a lovely cometary tail develops.

We approach the planets of our system, largish worlds, captives of the Sun, gravitationally constrained to follow nearly circular orbits, heated mainly by sunlight. Pluto, covered with methane ice and accompanied by its solitary giant moon Charon, is illuminated by a distant Sun, which appears as no more than a bright point of light in a pitch-black sky. The giant gas worlds, Neptune, Uranus, Saturn—the jewel of the solar system—and Jupiter all have an entourage of icy moons. Interior to the region of gassy planets and orbiting icebergs are the warm, rocky provinces of the inner solar system. There is, for example, the red planet Mars, with soaring volcanoes, great rift valleys, enormous planet-wide sandstorms, and, just possibly, some simple forms of life. All the planets orbit the Sun, the nearest star, an inferno of hydrogen and helium gas engaged in thermonuclear reactions, flooding the solar system with light.

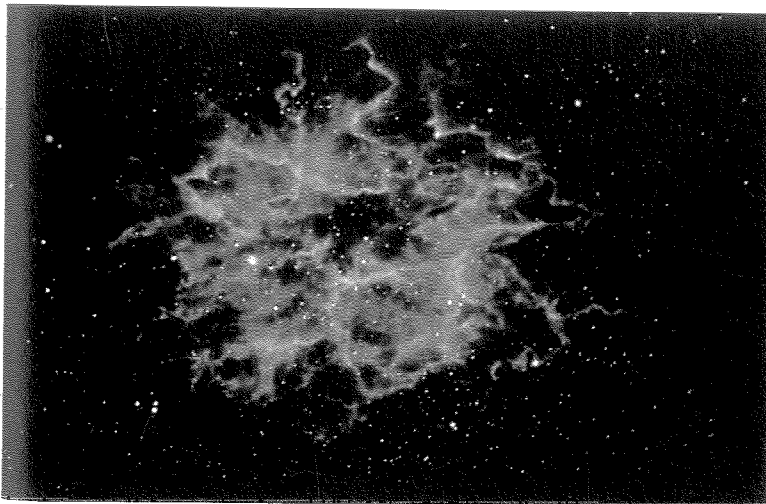
Finally, at the end of all our wanderings, we return to our tiny, fragile, blue-white world, lost in a cosmic ocean vast beyond our most courageous imaginings. It is a world among an immensity of others. It may be significant only for us. The Earth is our home, our parent. Our kind of life arose and evolved here. The human species is coming of age here. It is on this world that we devel-



The interior of a black dust cloud, where young stars are just beginning to shine. Nearby icy planets are evaporating and the released gas is being blown away, like a comet's tail. Painting by Adolf Schaller.



A rapidly rotating, flashing pulsar at the center of a supernova remnant. Painting by John Allison.



The nebula, or illuminated gas cloud, surrounding a supernova explosion. Painting by John Allison.

The other side of the Orion Nebula, unobservable from Earth. The three blue stars comprise the belt of Orion in the conventional terrestrial constellation. Painting by John Allison.



An approach to the interior of the Great Nebula in Orion. The gas is shining in several colors, stimulated by the light of hot stars. Part of the nebula is obscured by a cloud of absorbing dust. The Orion Nebula can be seen from the Earth with the naked eye. Painting by John Allison.



oped our passion for exploring the Cosmos, and it is here that we are, in some pain and with no guarantees, working out our destiny.

Welcome to the planet Earth—a place of blue nitrogen skies, oceans of liquid water, cool forests and soft meadows, a world positively rippling with life. In the cosmic perspective it is, as I have said, poignantly beautiful and rare; but it is also, for the moment, unique. In all our journeying through space and time, it is, so far, the only world on which we know with certainty that the matter of the Cosmos has become alive and aware. There must be many such worlds scattered through space, but our search for them begins here, with the accumulated wisdom of the men and women of our species, garnered at great cost over a million years. We are privileged to live among brilliant and passionately inquisitive people, and in a time when the search for knowledge is generally prized. Human beings, born ultimately of the stars and now for a while inhabiting a world called Earth, have begun their long voyage home.

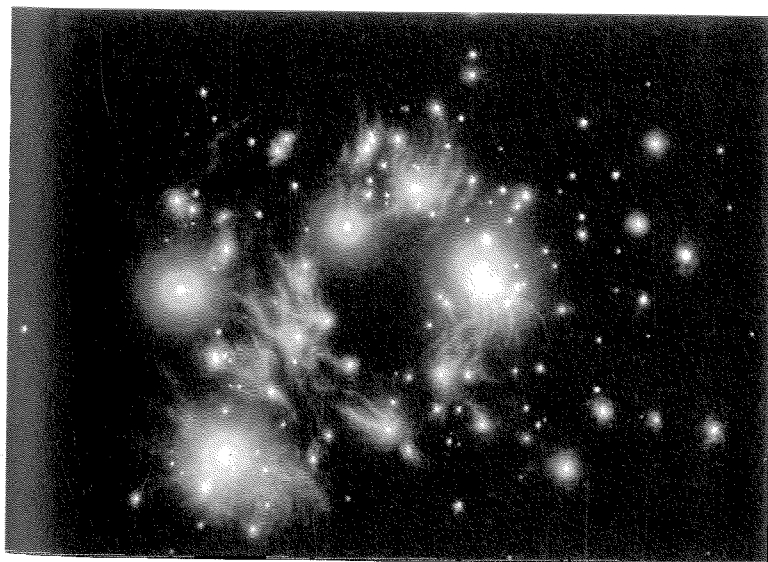
The discovery that the Earth is a *little* world was made, as so



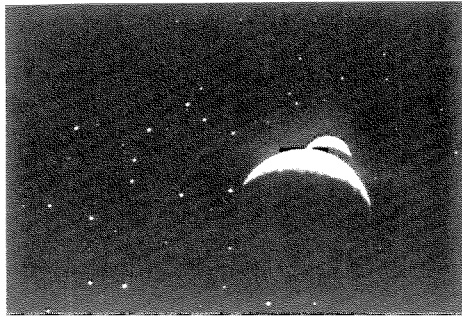
We emerge through the dark dust of the Orion Nebula to its hidden interior, brilliantly illuminated by hot young stars. Painting by John Allison.



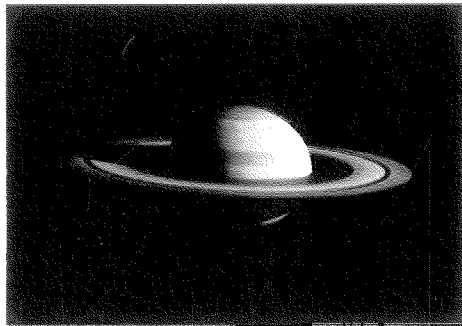
The Trapezium, four newly hatched stars in the Orion Nebula. Painting by John Allison.



The Pleiades, young stars that have recently left the nebulae in which they were born, still trailing clouds of illuminated dust. Painting by Adolf Schaller.



Pluto, covered with methane frost, and its giant moon Charon. Usually the outermost planet, Pluto's orbit has recently carried it interior to the orbit of Neptune. Painting by John Allison.



Saturn. Model by Adolf Schaller, Rick Sternbach and John Allison.



Io, the innermost large moon of Jupiter. Model by Don Davis.

many important human discoveries were, in the ancient Near East, in a time some humans call the third century B.C., in the greatest metropolis of the age, the Egyptian city of Alexandria. Here there lived a man named Eratosthenes. One of his envious contemporaries called him "Beta," the second letter of the Greek alphabet, because, he said, Eratosthenes was second best in the world in everything. But it seems clear that in almost everything Eratosthenes was "Alpha." He was an astronomer, historian, geographer, philosopher, poet, theater critic and mathematician. The titles of the books he wrote range from *Astronomy* to *On Freedom from Pain*. He was also the director of the great library of Alexandria, where one day he read in a papyrus book that in the southern frontier outpost of Syene, near the first cataract of the Nile, at noon on June 21 vertical sticks cast no shadows. On the summer solstice, the longest day of the year, as the hours crept toward midday, the shadows of temple columns grew shorter. At noon, they were gone. A reflection of the Sun could then be seen in the water at the bottom of a deep well. The Sun was directly overhead.

It was an observation that someone else might easily have ignored. Sticks, shadows, reflections in wells, the position of the Sun—of what possible importance could such simple everyday matters be? But Eratosthenes was a scientist, and his musings on these commonplaces changed the world; in a way, they made the world. Eratosthenes had the presence of mind to do an experiment, actually to observe whether in Alexandria vertical sticks cast shadows near noon on June 21. And, he discovered, sticks do.

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? (See p. 16.)

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.*

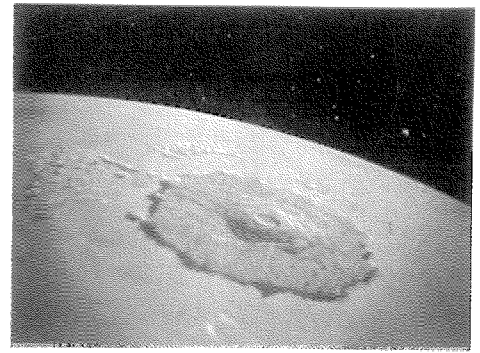
This is the right answer. Eratosthenes' only tools were sticks, eyes, feet and brains, plus a taste for experiment. With them he deduced the circumference of the Earth with an error of only a few percent, a remarkable achievement for 2,200 years ago. He was the first person accurately to measure the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

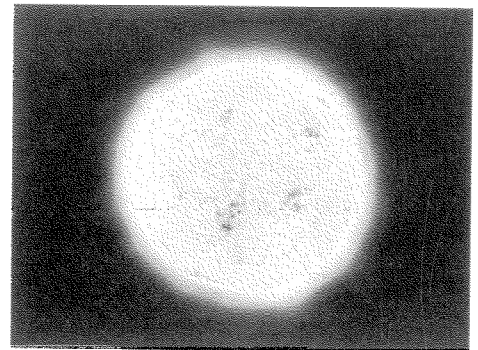
After Eratosthenes' discovery, many great voyages were attempted by brave and venturesome sailors. Their ships were tiny. They had only rudimentary navigational instruments. They used dead reckoning and followed coastlines as far as they could. In an unknown ocean they could determine their latitude, 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 earlier have been recounted as sailors and navigators, practical men of the world, gambled their lives on the mathematics of a scientist from Alexandria?

In Eratosthenes' time, globes were constructed portraying the Earth as viewed from space; they were essentially correct in the well-explored Mediterranean but became more and more inaccurate the farther they strayed from home. Our present knowledge of the Cosmos shares this disagreeable but inevitable feature. In

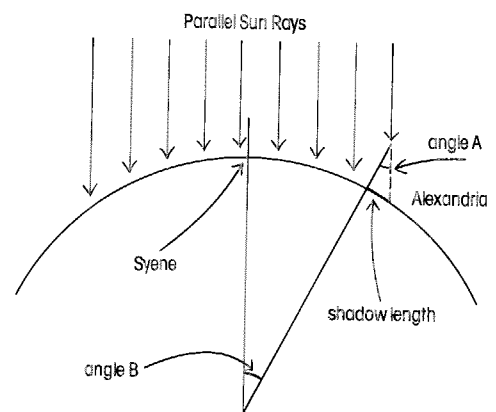
* Or if you like to measure things in miles, the distance between Alexandria and Syene is about 500 miles, and $500 \text{ miles} \times 50 = 25,000$ miles.



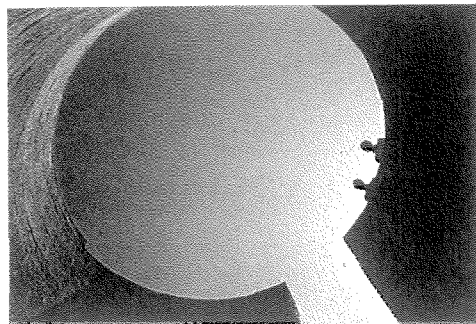
Olympus Mons (Mount Olympus), a giant volcanic construct, 30 kilometers high and 500 kilometers across, on the surface of Mars. Model by Don Davis.



A portrait of the Sun. Painting by Anne Norcia.



From the shadow length in Alexandria, the angle A can be measured. But from simple geometry ("if two parallel straight lines are transected by a third line, the alternate interior angles are equal"), angle B equals angle A. So by measuring the shadow length in Alexandria, Eratosthenes concluded that Syene was $A = B = 7^\circ$ away on the circumference of the Earth.



Looking up from the bottom of the well in ancient Syene, near present-day Abu Simbel, in Egypt, which according to local tradition is the origin of Eratosthenes' study of the circumference of the Earth.

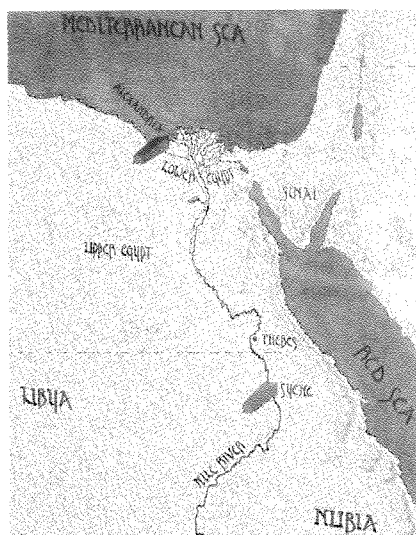
the first century, the Alexandrian geographer Strabo wrote:

Those who have returned from an attempt to circumnavigate the Earth do not say they have been prevented by an opposing continent, for the sea remained perfectly open, but, rather, through want of resolution and scarcity of provision. . . . Eratosthenes says that if the extent of the Atlantic Ocean were not an obstacle, we might easily pass by sea from Iberia to India. . . . It is quite possible that in the temperate zone there may be one or two habitable Earths. . . . Indeed, if [this other part of the world] is inhabited, it is not inhabited by men such as exist in our parts, and we should have to regard it as another inhabited world.

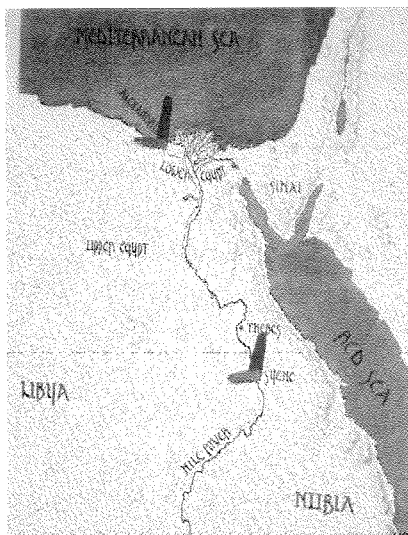
Humans were beginning to venture, in almost every sense that matters, to other worlds.

The subsequent exploration of the Earth was a worldwide endeavor, including voyages from as well as to China and Polynesia. The culmination was, of course, the discovery of America by Christopher Columbus and the journeys of the following few centuries, which completed the geographical exploration of the Earth. Columbus' first voyage is connected in the most straightforward way with the calculations of Eratosthenes. Columbus was fascinated by what he called "the Enterprise of the Indies," a project to reach Japan, China and India not by following the coastline of Africa and sailing East but rather by plunging boldly into the unknown Western ocean—or, as Eratosthenes had said with startling prescience, "to pass by sea from Iberia to India."

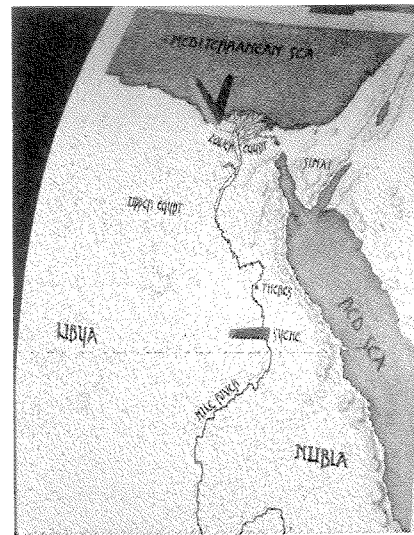
Columbus had been an itinerant peddler of old maps and an



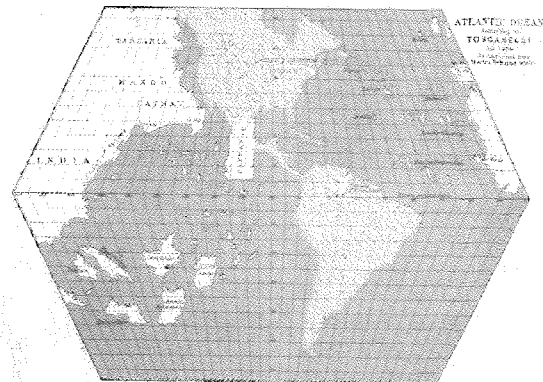
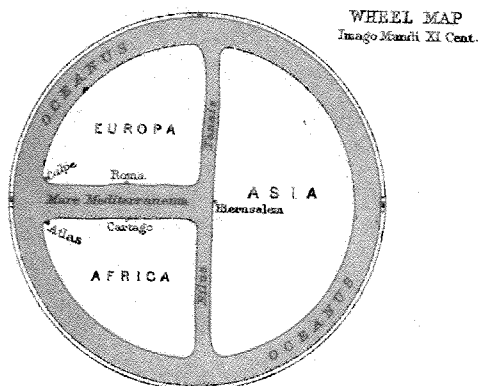
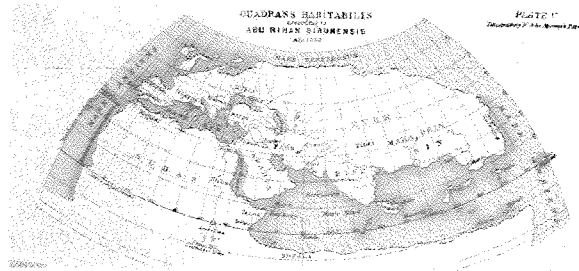
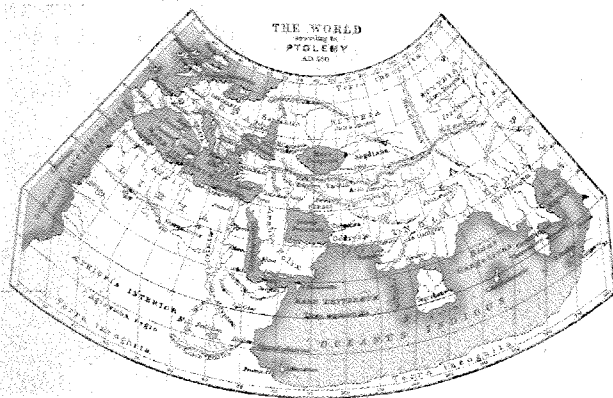
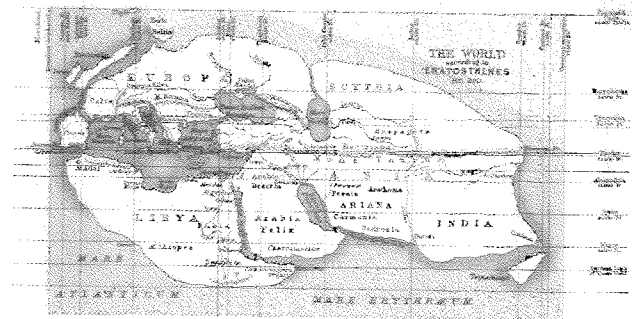
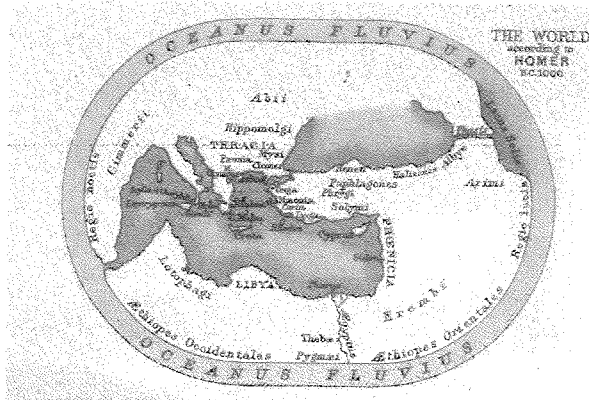
A flat map of ancient Egypt. When the Sun is directly overhead, vertical obelisks cast no shadows in Alexandria or in Syene.



A flat map of ancient Egypt. When the Sun is not directly overhead, vertical obelisks cast shadows of equal length in Alexandria and in Syene.



A curved map of ancient Egypt. The Sun can be directly overhead in Syene but not in Alexandria, thus accounting for the fact that the obelisk in Syene casts no shadow, while that in Alexandria casts a pronounced shadow.



assiduous reader of the books by and about the ancient geographers, including Eratosthenes, Strabo and Ptolemy. But for the Enterprise of the Indies to work, for ships and crews to survive the long voyage, the Earth had to be smaller than Eratosthenes had said. Columbus therefore cheated on his calculations, as the examining faculty of the University of Salamanca quite correctly pointed out. He used the smallest possible circumference of the Earth and the greatest eastward extension of Asia he could find in all the books available to him, and then exaggerated even those. Had the Americas not been in the way, Columbus' expeditions would have failed utterly.

The Earth is now thoroughly explored. It no longer promises new continents or lost lands. But the technology that allowed us

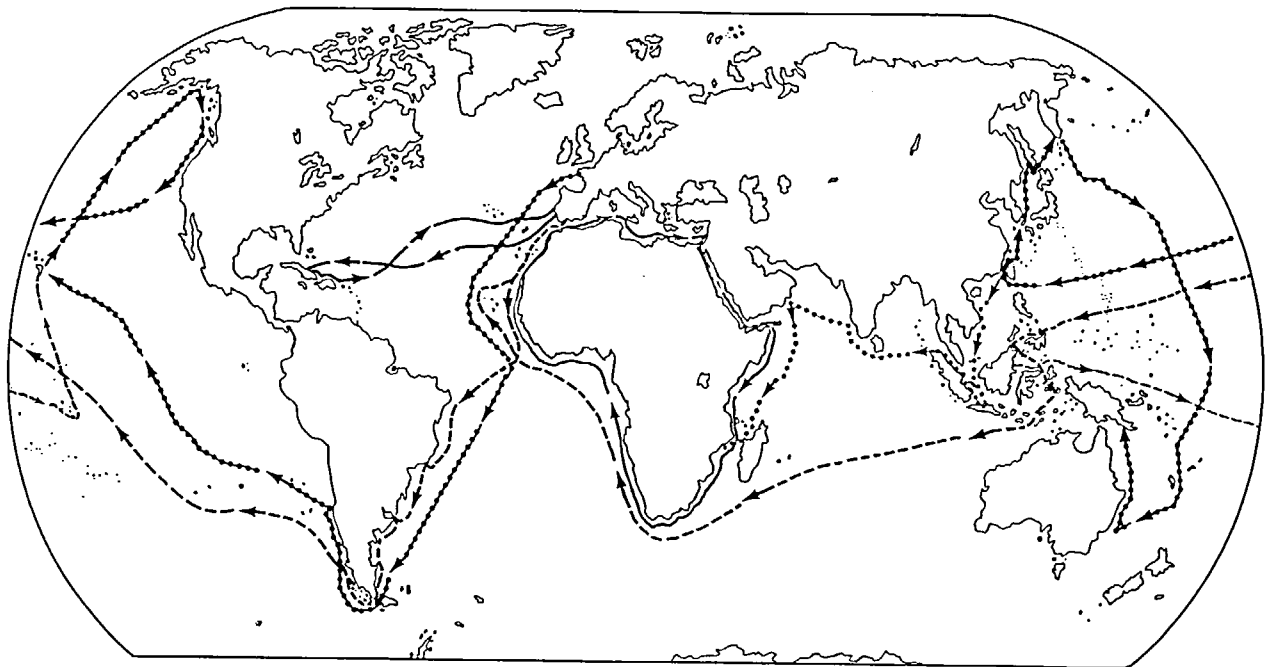
Maps of the world. In the time of Homer, the world was thought to extend no farther than the basin of the Mediterranean (which means "middle of the Earth"), surrounded by a world ocean. Significant improvements were added by Eratosthenes and by Ptolemy. By the eleventh century, ancient geographical knowledge had been well-preserved (and extended to China) by the Arabs, but almost totally lost among the Europeans, who imagined a flat Earth centered on Jerusalem. The last map before the discovery of America (shown in outline) is that of the Florentine astronomer Toscanelli. Columbus probably carried Toscanelli's map with him on his first voyage. The name America, commemorating Columbus' friend Amerigo Vespucci, was suggested in Waldseemüller's (1507) book, *An Introduction to Cosmography*. Reproduced courtesy Scottish Geographical Magazine.

to explore and inhabit the most remote regions of the Earth now permits us to leave our planet, to venture into space, to explore other worlds. Leaving the Earth, we are now able to view it from above, to see its solid spherical shape of Eratosthenian dimensions and the outlines of its continents, confirming that many of the ancient mapmakers were remarkably competent. What a pleasure such a view would have given to Eratosthenes and the other Alexandrian geographers.

It was in Alexandria, during the six hundred years beginning around 300 B.C., that human beings, in an important sense, began the intellectual adventure that has led us to the shores of space. But of the look and feel of that glorious marble city, nothing remains. Oppression and the fear of learning have obliterated almost all memory of ancient Alexandria. Its population was marvelously diverse. Macedonian and later Roman soldiers, Egyptian priests, Greek aristocrats, Phoenician sailors, Jewish merchants, visitors from India and sub-Saharan Africa—everyone, except the vast slave population—lived together in harmony and mutual respect for most of the period of Alexandria's greatness.

The city was founded by Alexander the Great and constructed by his former bodyguard. Alexander encouraged respect for alien cultures and the open-minded pursuit of knowledge. According to tradition—and it does not much matter whether it really happened—he descended beneath the Red Sea in the world's first diving bell. He encouraged his generals and soldiers to marry Persian and Indian women. He respected the gods of other nations. He collected exotic lifeforms, including an elephant for Aristotle, his teacher. His city was constructed on a lavish scale, to be the world center of commerce, culture and learning. It was graced with broad avenues thirty meters wide, elegant architecture and statuary, Alexander's monumental tomb, and an enormous lighthouse, the Pharos, one of the seven wonders of the ancient world.

But the greatest marvel of Alexandria was the library and its associated museum (literally, an institution devoted to the specialties of the Nine Muses). Of that legendary library, the most that survives today is a dank and forgotten cellar of the Serapeum, the library annex, once a temple and later reconsecrated to knowledge. A few moldering shelves may be its only physical remains. Yet this place was once the brain and glory of the greatest city on the planet, the first true research institute in the history of the world. The scholars of the library studied the entire Cosmos. *Cosmos* is a Greek word for the order of the universe. It is, in a way, the opposite of *Chaos*. It implies the deep interconnectedness of all things. It conveys awe for the intricate and subtle way in which the universe is put together. Here was a community of scholars, exploring physics, literature, medicine, astronomy, geography, philosophy, mathematics, biology, and



- | | |
|-------------------------------------|-------------------------------|
| —— Phoenician/Egyptian, c. 600 BC | —— Columbus, 1492 |
| ----- Polynesian, c. 2000 years ago | ----- Magellan/Del Cano, 1520 |
| Cheng Ho, c. 1430 AD | La Pérouse, 1785 |

engineering. Science and scholarship had come of age. Genius flourished there. The Alexandrian Library is where we humans first collected, seriously and systematically, the knowledge of the world.

In addition to Eratosthenes, there was the astronomer Hipparchus, who mapped the constellations and estimated the brightness of the stars; Euclid, who brilliantly systematized geometry and told his king, struggling over a difficult mathematical problem, "There is no royal road to geometry"; Dionysius of Thrace, the man who defined the parts of speech and did for the study of language what Euclid did for geometry; Herophilus, the physiologist who firmly established that the brain rather than the heart is the seat of intelligence; Heron of Alexandria, inventor of gear trains and steam engines and the author of *Automata*, the first book on robots; Apollonius of Perga, the mathematician who demonstrated the forms of the conic sections*—ellipse, parabola and hyperbola—the curves, as we now know, followed in their orbits by the planets, the comets and the stars; Archimedes, the greatest mechanical genius until Leonardo da Vinci; and the astronomer and geographer Ptolemy, who compiled much of what is today the pseudoscience of astrology: his Earth-centered

Exploratory routes of some of the great voyages of discovery.

*So called because they can be produced by slicing through a cone at various angles. Eighteen centuries later, the writings of Apollonius on conic sections would be employed by Johannes Kepler in understanding for the first time the movement of the planets.



Serapis, a synthetic god, combining Greek and Egyptian attributes, introduced into Egypt by Ptolemy I in the third century B.C. He holds a scepter as Cerberus, the three-headed dog of the underworld, waits at his feet.



Alexander the Great, with crook and flail, and pharaonic headgear, as he might have appeared in the Library of Alexandria.



The lost books of Aristarchus, as they might have been stored on the shelves of the Alexandrian Library.

universe held sway for 1,500 years, a reminder that intellectual capacity is no guarantee against being dead wrong. And among those great men was a great woman, Hypatia, mathematician and astronomer, the last light of the library, whose martyrdom was bound up with the destruction of the library seven centuries after its founding, a story to which we will return.

The Greek Kings of Egypt who succeeded Alexander were serious about learning. For centuries, they supported research and maintained in the library a working environment for the best minds of the age. It contained ten large research halls, each devoted to a separate subject; fountains and colonnades; botanical gardens; a zoo; dissecting rooms; an observatory; and a great dining hall where, at leisure, was conducted the critical discussion of ideas.

The heart of the library was its collection of books. The organizers combed all the cultures and languages of the world. They sent agents abroad to buy up libraries. Commercial ships docking in Alexandria were searched by the police—not for contraband, but for books. The scrolls were borrowed, copied and then returned to their owners. Accurate numbers are difficult to estimate, but it seems probable that the Library contained half a million volumes, each a handwritten papyrus scroll. What happened to all those books? The classical civilization that created them disintegrated, and the library itself was deliberately destroyed. Only a small fraction of its works survived, along with a few pathetic scattered fragments. And how tantalizing those bits and pieces are! We know, for example, that there was on the library shelves a book by the astronomer Aristarchus of Samos, who argued that the Earth is one of the planets, which like them orbits the Sun, and that the stars are enormously far away. Each of these conclusions is entirely correct, but we had to wait nearly two thousand years for their rediscovery. If we multiply by a hundred thousand our sense of loss for this work of Aristarchus, we begin to appreciate the grandeur of the achievement of classical civilization and the tragedy of its destruction.

We have far surpassed the science known to the ancient world. But there are irreparable gaps in our historical knowledge. Imagine what mysteries about our past could be solved with a borrower's card to the Alexandrian Library. We know of a three-volume history of the world, now lost, by a Babylonian priest named Berossus. The first volume dealt with the interval from the Creation to the Flood, a period he took to be 432,000 years or about a hundred times longer than the Old Testament chronology. I wonder what was in it.

The ancients knew that the world is very old. They sought to look into the distant past. We now know that the Cosmos is far older than they ever imagined. We have examined the universe in space and seen that we live on a mote of dust circling a humdrum star in the remotest corner of an obscure galaxy. And



if we are a speck in the immensity of space, we also occupy an instant in the expanse of ages. We now know that our universe—or at least its most recent incarnation—is some fifteen or twenty billion years old. This is the time since a remarkable explosive event called the Big Bang. At the beginning of this universe, there were no galaxies, stars or planets, no life or civilizations, merely a uniform, radiant fireball filling all of space. The passage from the Chaos of the Big Bang to the Cosmos that we are beginning to know is the most awesome transformation of matter and energy that we have been privileged to glimpse. And until we find more intelligent beings elsewhere, we are ourselves the most spectacular of all the transformations—the remote descendants of the Big Bang, dedicated to understanding and further transforming the Cosmos from which we spring.

The Great Hall of the ancient Library of Alexandria in Egypt. A reconstruction based on scholarly evidence.

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