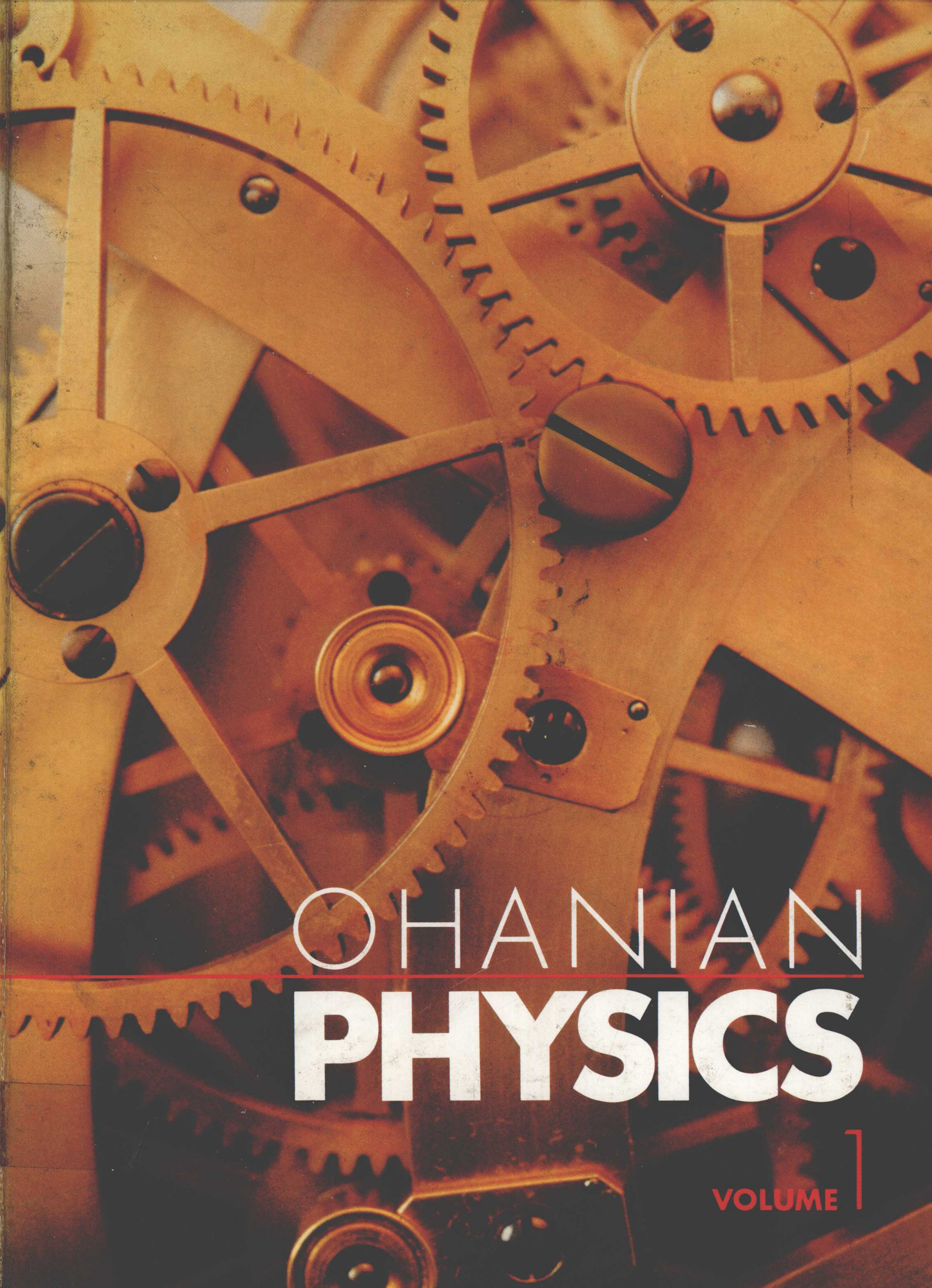
OHANIAN
PHYSICS
VOLUME 1

Physics

Hans C. Ohanian

UNION COLLEGE AND

RENSSELAER POLYTECHNIC INSTITUTE

VOLU

W · W · NORTON & COMPANY
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To Susan Farnsworth Ohanian, writer,
who gently tried to teach me some of her craft.

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Preface

This is a textbook for a two- or three-semester calculus-based physics course for science and engineering students. My main objectives in writing this book were to present a contemporary, modern view of classical mechanics and electromagnetism, and to offer the student a glimpse of what is going on in physics today. Thus, throughout the book, I encourage students to keep in mind the atomic structure of matter and to think of the material world as a multitude of restless electrons, protons, and neutrons. For instance, in the mechanics chapters, I emphasize that all macroscopic bodies are systems of particles; and in the electricity chapters, I introduce the concepts of positive and negative charge by referring to protons and electrons, not by referring to the antiquated procedure of rubbing glass rods with silk rags (which, according to experts on triboelectricity, can give the wrong sign if the silk has been thoroughly cleaned). I try to make sure that students are always aware of the limitations of the nineteenth-century fiction that matter and electric charge are continua. Blind reliance on this fiction has often been justified by the claim that engineering students need physics as a tool, and that the atomic structure of matter is of little concern to them. But if physics is a tool, it is also a work of art, and its style cannot be dissociated from its function. In this book I give a physicist's view of physics, because I believe that it is fitting that all students should gain some appreciation for the artistic style of the toolmaker.

The book contains two kinds of chapters: *core* chapters and *interlude* chapters. The 41 core chapters cover the essential topics of introductory physics: mechanics of particles, rigid bodies, and fluids; oscillations; wave motion; heat and thermodynamics; electricity and magnetism; optics; and quanta. They also include a chapter on special relativity, but this chapter is optional, as are a few sections of some other chapters (these are clearly marked in the table of contents and in the text). The 12 interludes present some of the fascinating discoveries and applications of physics today: crystal structure and symmetry, ionizing radiation, elementary particles, the expansion of the universe, general relativity, energy resources, fields and quanta, fission, atmospheric electricity, plasmas, superconductivity, and lasers. All of these interludes are optional — they rely on the core chapters, but the core chapters do not rely on them.

In order to accommodate students who are taking an introductory calculus course concurrently, derivatives are used slowly and hesitantly at first (Chapter 2), and routinely later on. Likewise, the use of integrals is postponed as far as possible (Chapter 7), and they come into heavy use only in the second volume (after Chapter 21). For students who need a review of calculus, Appendix 5 contains a concise primer on derivatives and integrals.

The organization of the core chapters is fairly traditional, with some innovations. I deviate from tradition by an early introduction of angular momentum, starting with the angular momentum of a particle instead of the angular momentum of a rigid body (Chapter 5). In my experience, for many students the first chapters are an expanded review of high-school physics, and students can profit from some new concepts at this stage (teachers who prefer to introduce angular momentum in conjunction with rigid bodies may postpone Section 5.6 until later). More notably, I start the study of magnetism (Chapter 30) with the law for the magnetic force between two moving point charges; this magnetic force is no more complicated than the force between two current elements, and the crucial advantage is that magnetism can be developed from the magnetic-force law in much the same way as electricity is developed from Coulomb's Law. This approach is consistent with the underlying philosophy of the book: particles are primary entities and should always be treated first, whereas macroscopic bodies and currents are composite entities which should be treated later. As another innovation, I include a simple derivation of the electric radiation field of an accelerated charge (Chapter 35); this calculation relies on Richtmeyer and Kennard's clever analysis of the kinks in the electric field lines of an accelerated charge (a set of computer-generated film loops available from the Educational Development Center shows how such kinks propagate along the field lines; these film loops tie in very well with the calculations of Chapter 35).

The chapters include generous collections of solved examples (about 275 altogether) and of problems (about 1700 altogether). Answers to the even-numbered problems are given in Appendix 11. The problems are grouped by sections, with the most difficult problems at the end of each section (exceptionally challenging problems are marked with an asterisk). I have tried to make the problems interesting to the student by drawing on realistic examples from technology, sports, and everyday life. Many of the problems are based on data extracted from engineering handbooks, car-repair manuals, *Jane's Book of Aircraft, The Guinness Book of World Records,* newspaper reports, etc. Many other problems deal with atoms and subatomic particles; these are intended to reinforce the atomistic view of the material world. In some cases, cognoscenti will perhaps consider the use of classical physics somewhat objectionable in a problem that really ought to be handled by quantum mechanics. But I believe that the advantages of familiarization with atomic quantities and magnitudes outweigh the disadvantages of a naïve use of classical mechanics.

Each chapter also includes a collection of qualitative questions intended to stimulate thought and to test the grasp of basic concepts (some of these questions are discussion questions that do not have a unique answer). Moreover, each chapter contains a brief summary of the main physical quantities and laws introduced in it. The virtue of these summaries lies in their brevity. They include essential definitions and equations, but no restatements of arguments or additional explanations, because the statements in the body of each chapter are adequate.

The inspiration for the 12 interlude chapters grew out of my unhappiness over a paradox afflicting the typical undergraduate physics curriculum: liberal-arts students in a nonmathematical physics course often get to see more of the beauty and excitement of the physics of today than science and engineering students in a calculus-based physics course. While liberal-arts students get a glimpse of quarks, black holes, or the Big Bang, science and engineering students are expected to calculate the motion of blocks on top of other blocks sliding down an inclined plane, or the motion of a baseball thrown in some direction or another by a man (or woman) riding in an elevator. To some extent this is unavoidable — science and engineering students need to learn and practice classical mechanics and electromagnetism, and they have little time left for dabbling in the arcane mysteries of contemporary physics. Nevertheless, most teachers will occasionally find an hour or two to tell their students a little of what is going on in physics today. I wrote the interludes to lend encouragement and support to such excursions to the frontiers of physics.

My choices of topics for the 12 interludes reflect the interests expressed by my students. Over the years, I have often been asked: When will we get to black holes? or Are you going to tell us about quarks? and I came to feel that such curiosity must not be allowed to whither away. Obviously, in the typical introductory course it will be impossible to cover all of the interludes (I have usually covered two per term), but the broad range of topics will permit teachers to select according to their own tastes. The interludes are mainly descriptive rather than analytic. In them, I try to avoid formulas and instead give the students a qualitative feeling for the underlying physics, keeping the discussion simple so that students can read them on their own. Thus, the interludes could be used for supplementary reading, not necessarily accompanied by lectures. For the inquisitive student, each interlude includes a collection of qualitative questions and an extensive annotated list of further readings.

The predominant system of units used in this text is SI. However, since American engineers continue to work with the British system, the text also includes examples and problems with these units. In the abbreviations for the units, I follow the dictates of the Conférence Générale des Poids et Mesures of 1971, although I deplore the majestic stupidity of the decision to replace the old, self-explanatory abbreviations amp, coul, nt, sec, °K by an alphabet soup of cryptic symbols A, C, N, s, K, etc. For the sake of clarity, I spell out the names of units in full whenever the abbreviations are likely to lead to ambiguity and confusion.

An excellent study guide for this book has been written by Professors Van E. Neie (Purdue University) and Peter J. Riley (University of Texas, Austin). This guide includes for every chapter a brief introduction laying out the objectives; a list of key terms for review; detailed commentaries on each of the main ideas; and a large collection of interesting sample problems, which alternate between worked problems (with full solutions) and guided problems (which provide step-by-step schemes that lead students to the solutions).

The book has been seven years in the making. The original manuscript went through several revisions, based both on my own experience with students at Union College and on extensive reviews and class testing at several other institutions. A preliminary edition of this book, reproduced photographically from typescript, was used in classes by Professors John R. Boccio (Swarthmore College), A. Douglas Davis (Eastern Illinois University), J. David Gavenda, (University of Texas, Austin), Frank Moscatelli (Swarthmore College), Harvey S. Picker (Trinity College), Peter J. Riley (University of Texas, Austin), Kenneth L. Schick (Union College), and Mark P. Silverman (Trinity College). The experience gained in these class tests permitted me to make many improvements. I am grateful to both teachers and students for sharing their reactions to the book with me.

I have greatly benefited from many comments by reviewers who carefully read my manuscript and suggested corrections and alterations. I am indebted to Professors John R. Boccio (Swarthmore College), Roger W. Clapp, Jr. (University of South Florida), A. Douglas Davis (Eastern Illinois University), Anthony P. French (Massachusetts Institute of Technology), J. David Gavenda (University of Texas, Austin), Roger D. Kirby (University of Nebraska), Roland M. Lichtenstein (Rensselaer Polytechnic Institute), Richard T. Mara (Gettysburg College), John T. Marshall (Louisiana State University), Harvey S. Picker (Trinity College), and Peter J. Riley (University of Texas, Austin) for very detailed, comprehensive reviews; and I am indebted to Professors John R. Albright (Florida State University), Frank A. Ferrone (Drexel University), James R. Gaines (Ohio State University), Michael A. Guillen (Harvard University), Walter Knight (University of California, Berkeley), Jean P. Krisch (University of Michigan), Hermann Nann (Indiana University), Norman Pearlman (Purdue University), P. Bruce Pipes (Dartmouth College), Jack Prince (Bronx Community College), Gerald A. Smith (Michigan State University), Julia A. Thompson and David Kraus (University of Pittsburgh), and Gary A. Williams (University of California, Los Angeles) for briefer reviews. I am also indebted to the experts who reviewed the interludes: Professors Edmond Brown (Rensselaer Polytechnic Institute; "The Architecture of Crystals"), Priscilla W. Laws (Dickinson College; "Radiation and Life"), Stephen Gasiorowicz (University of Minnesota; "Elementary Particles"), Alan H. Guth (Massachusetts Institute of Technology; "The Big Bang and the Expansion of the Universe"), Donald F. Kirwan (University of Rhode Island; "Energy, Entropy, and the Environment"), Malvin Ruderman (Columbia University; "Forces, Fields, and Quanta"), Irving Kaplan (Massachusetts Institute of Technology; "Nuclear Fission"), Bernard Vonnegut (State University of New York at Albany; "Atmospheric Electricity"), Sam Cohen (Princeton University Plasma Physics Laboratory; "Plasma"), and Margaret L. A. MacVicar (Massachusetts Institute of Technology; "Superconductivity").

I thank Dr. Richard D. Deslattes and Dr. Barry N. Taylor of the National Bureau of Standards for information on units, standards, and

precision measurements. I thank some of my colleagues at Union College: Professor C. C. Jones prepared the beautiful photographs of interference and diffraction by light (Chapters 38 and 39); Professor Barbara C. Boyer gave valuable advice and assistance on photographs dealing with biological material; and the staff of the library helped me find many a tidbit of information needed for an example or a problem. Michael Rooks and Ben Hu independently checked the solutions to the problems and proposed corrections for some problems they found insoluble.

I thank the editorial staff of W. W. Norton & Co., who worked long and hard to bring all the pieces of this book together: Drake McFeely, editor, who gave the manuscript the most meticulous attention and with sharp eyes spotted many a sentence that required rephrasing and clarification; Christopher Lang, who guided the project through its early stages; Alicia Salomon, copy editor, who corrected subtle errors of grammar and enforced stylistic consistency; and Amy Boesky, Lori Jones, and Natalie Goldstein, who searched out many of the fascinating photographs that add interest to this book. And it is a pleasure to thank Terry Hynes for the typing of the first draft of the text from my handwritten manuscript; she was always eager to improve my style and skillfully supplied all those words and endings of words that my pen, somehow, left out when my thoughts raced ahead of my hand.

H. C. O.
February 1985

THE WORLD OF PHYSICS

Physics is the study of matter. In a very literal sense, physics is the greatest of all natural sciences: it encompasses the smallest particles, such as electrons and quarks; and it also encompasses the largest bodies, such as galaxies and the entire universe. The smallest particles and the largest bodies differ in size by a factor of more than 10^{40}! In the following pictures we will survey the world of physics and attempt to develop some rough feeling for the sizes of things in this world. This preliminary survey sets the stage for our explanations of the mechanisms that make things behave in the way they do. Such explanations are at the heart of physics, and they are the concern of the later chapters of this book.

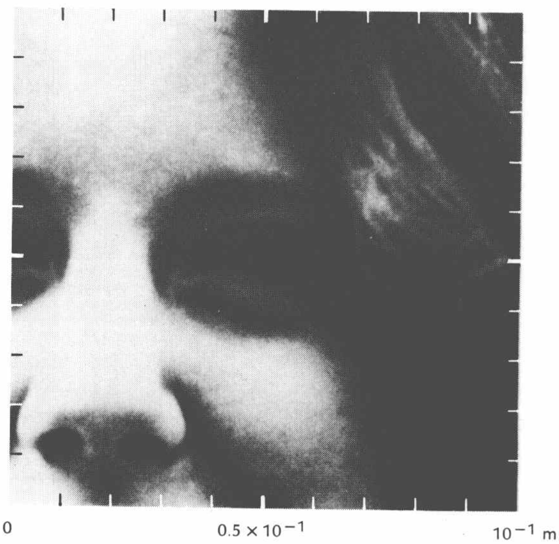
The pictures fall into two sequences. In the first sequence we zoom out: we begin with a picture of a woman's face and proceed step by step to pictures of the entire Earth, the Solar System, the Galaxy, and the universe. This ascending sequence contains 27 pictures, with the scale decreasing in steps of factors of 10.

In the second sequence we zoom in: we again begin with a picture of the face and close in on the eye, the retina, the rod cells, the molecules, the atoms, and the subatomic particles. This descending sequence contains 15 pictures, with the scale increasing in steps of factors of 10.

Most of our pictures are photographs. Many of these have only become available in recent years; they were taken by high-flying U-2 aircraft, Landsat satellites, astronauts on the Moon, or sophisticated electron microscopes. For some of our pictures no photographs are available and we have to rely, instead, on carefully prepared drawings.

PART I: THE LARGE-SCALE WORLD

SCALE 1:1.5 This is Charlotte, an intelligent biped of the planet Earth, Solar System, Orion Arm, Milky Way Galaxy, Local Group, Local Supercluster. She is made of 5.1×10^{27} atoms, with 1.8×10^{28} electrons, the same number of protons, and 1.4×10^{28} neutrons.



0 0.5×10^0 10^0 m

SCALE 1:1.5 × 10 Charlotte has a height of 1.7 meters and a mass of 55 kilograms. Her chemical composition (by mass) is 65% oxygen, 18.5% carbon, 9.5% hydrogen, 3.3% nitrogen, 1.5% calcium, 1% phosphorus, and 0.35% of other elements.

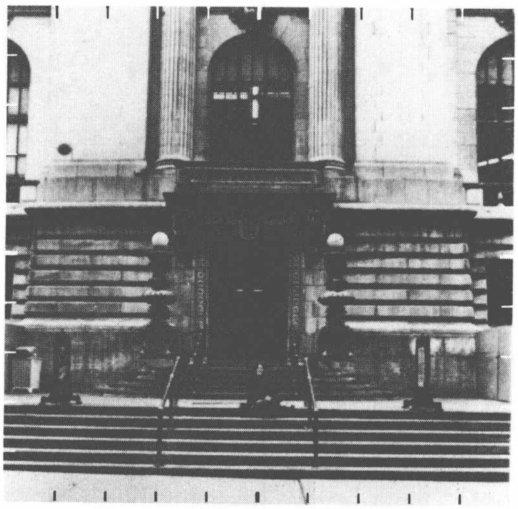
The matter in Charlotte's body and the matter in her immediate environment occur in three states of aggregation: *solid, liquid,* and *gas.* All these forms of matter are made of atoms and molecules, but solid, liquid, and gas are qualitatively different because the arrangements of the atomic and molecular building blocks are different.

In a solid each building block occupies a definite place. When a solid is assembled out of molecular or atomic building blocks, these blocks are locked in place once and for all and they cannot move or drift about except with great difficulty. This rigidity of the arrangement is what makes the aggregate hard — it makes a solid "solid." In a liquid the molecular or atomic building blocks are not rigidly connected. They are thrown together at random and they move about fairly freely, but there is enough adhesion between neighboring blocks to prevent the liquid from dispersing. Finally, in a gas the molecules or atoms are almost completely independent of one another. They are distributed at random over the volume of the gas and are separated by appreciable distances, coming in touch only occasionally during collisions. A gas will disperse spontaneously if it is not held in confinement by a container or by some restraining force.

The molecules of a gas are forever moving around at high speed. For example, at a temperature of 0°C the average speed of a molecule of nitrogen in air is about 450 meters/second, faster than the speed of sound. The speed of molecules is directly related to the temperature: the speed increases if the air is heated and decreases if the air is cooled. The molecules of a liquid also move; their speeds are not very different from those of the molecules of a gas. However, since there is little space between the molecules in a liquid, the motion is continually interrupted by collisions. Because of these frequent collisions, the path of a molecule consists of a series of random zigzags and the molecule takes a long time to wander from one part of the liquid to another. Even in a solid there is some motion of the building blocks. But the motion of each atom or molecule is merely a vibration around its assigned position — the atom behaves as if kept on a short leash and although it moves back and forth at a high speed, it never strays beyond some tight limits.

If one regards the motion of the atoms of a gas in a container as analogous to the bouncing of a few dice in a shaker, then the motion of atoms in a liquid is analogous to the random wandering of the dice in a shaker that has been loosely but completely filled with dice; and the motion of atoms in a solid is analogous to the impotent rattling of the dice in a shaker that has been tightly and regularly packed full of dice.

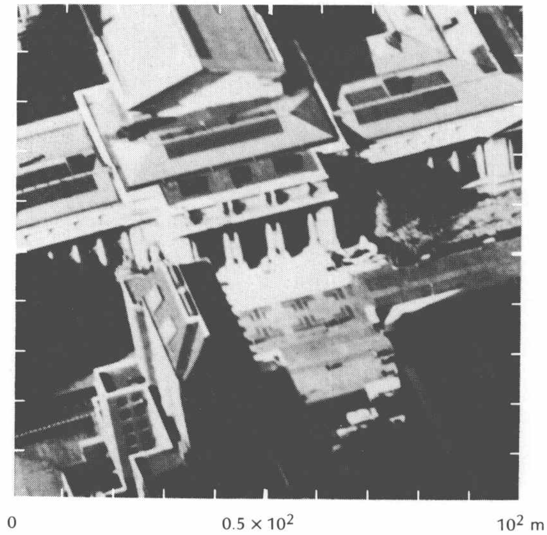
The eternal, dancing motion of the atoms is the key to the transformations of state from solid to liquid to gas and vice versa. If we heat a solid, the vibrational motion becomes more violent and the atoms or molecules finally shake themselves out of place — the solid softens and melts, turning into a liquid. If we heat this resulting liquid further, the motion ultimately becomes so violent that the adhesion between the atoms or molecules cannot prevent some of them from escaping from the surface of the liquid. Gradually more and more escape — the liquid evaporates, turning into a gas.



0 0.5×10^1 10^1 m

SCALE 1:1.5 × 10² The building behind Charlotte is the New York Public Library, one of the largest libraries on Earth. This library holds 9,300,000 volumes, containing roughly 10% of the total accumulated knowledge of our terrestrial civilization.

SCALE 1:1.5 × 10³ The New York Public Library is located at the corner of Fifth Avenue and 42nd Street, in the middle of New York City.

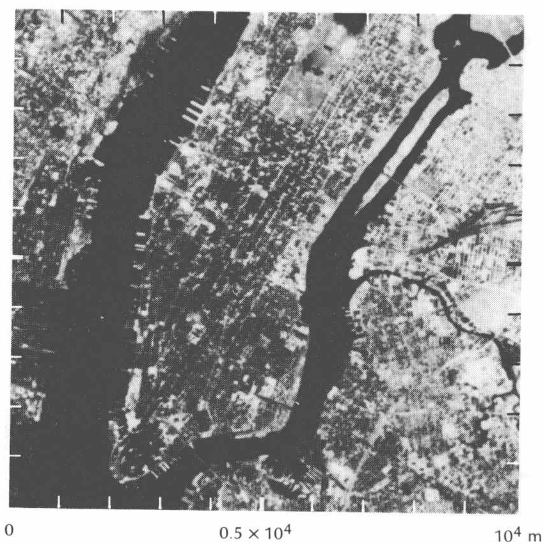


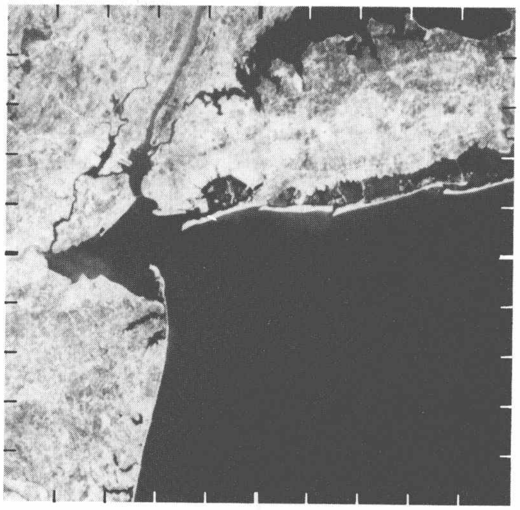
SCALE 1:1.5 × 10⁴ This aerial photograph shows an area of 1 kilometer × 1 kilometer in the vicinity of the New York Public Library. The streets in this part of the city are laid out in a regular rectangular pattern. The library is the building in the park in the upper middle of the picture. The Empire State Building shows up in the lower left of the picture. This skyscraper is 381 meters high and it casts a long shadow. Completed in 1930, it was for many years the tallest building in the world. Although the concrete and steel used in its construction are usually thought of as rigid materials, they have some elasticity — in a strong wind the top of the Empire State Building sways as much as 20 centimeters to a side.

This photograph was taken from an airplane flying at an altitude of 3658 meters. North is at the top of the photograph.

SCALE 1:1.5 × 10⁵ This photograph shows a large portion of New York City. We can recognize the library and its park as a small rectangular patch slightly above the center of the picture. The central mass of land is the island of Manhattan, with the Hudson River on the left and the East River on the right. Three bridges over the East River connect Manhattan with other parts of the city. The hundred-year-old Brooklyn Bridge is the southernmost of these bridges. It was the first steel-wire suspension bridge ever built and it stands as a spectacular and graceful achievement of nineteenth-century engineering.

This aerial photograph was taken by a U-2 aircraft flying at an altitude of about 20,000 meters.

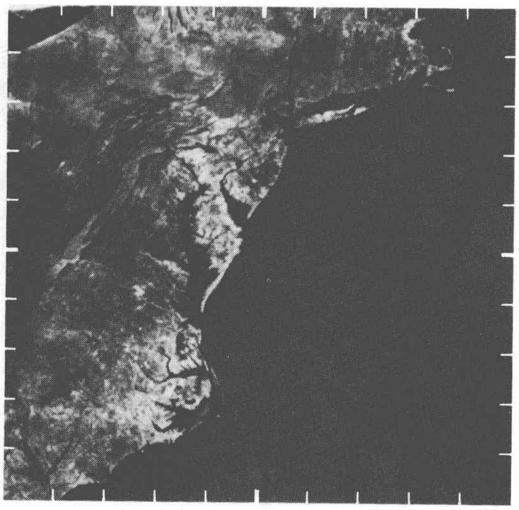




0 0.5×10^5 10^5 m

SCALE 1:1.5 × 10^6 In this photograph, Manhattan is in the upper left quadrant. On this scale, we can no longer distinguish the pattern of streets in the city. However, we can clearly distinguish many highways, bridges, and causeways. For example, the thin white line crossing the dark water south of the tip of Manhattan is the Verrazano-Narrows Bridge. With a center span of 1300 m, it is one of the longest suspension bridges in the world. The vast expanse of water in the lower right of the picture is part of the Atlantic Ocean. The mass of land in the upper right is Long Island, with Long Island Sound to the north of it. Parallel to the south shore of Long Island we can see a string of very narrow islands; they almost look man-made. These are barrier islands; they are heaps of sand piled up by ocean waves in the course of thousands of years.

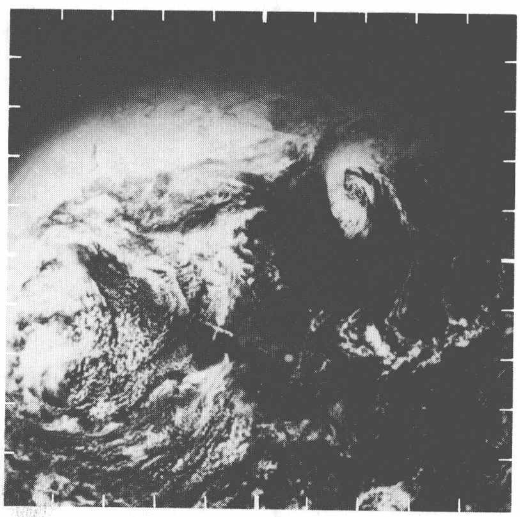
This photograph was taken by a Landsat satellite orbiting the Earth at an altitude of 920 kilometers.



0 0.5×10^6 10^6 m

SCALE 1:1.5 × 10^7 Here we see the eastern coast of the United States, from Cape Cod to Cape Fear. Cape Cod is the hook near the northern end of the coastline, and Cape Fear is the promontory near the southern end of the coastline. If we move along the coast starting at the north, we first come to Long Island; then to Delaware Bay and Chesapeake Bay, two deep indentations in the coastline; and then to Cape Hatteras, at the extreme end of the large bulge of land thrusting eastward into the Atlantic. Several rivers show up as thin, dark lines: the Hudson running due south from the northern edge of the photograph, the Delaware flowing into Delaware Bay, and the Susquehanna and Potomac flowing into Chesapeake Bay. The wrinkles in the land west of Chesapeake Bay are the Appalachian Mountains. Note that on this scale no signs of human habitation are visible. However, at night the lights of large cities would stand out clearly.

This picture is a mosaic, assembled by joining together many Landsat photographs such as the one above.



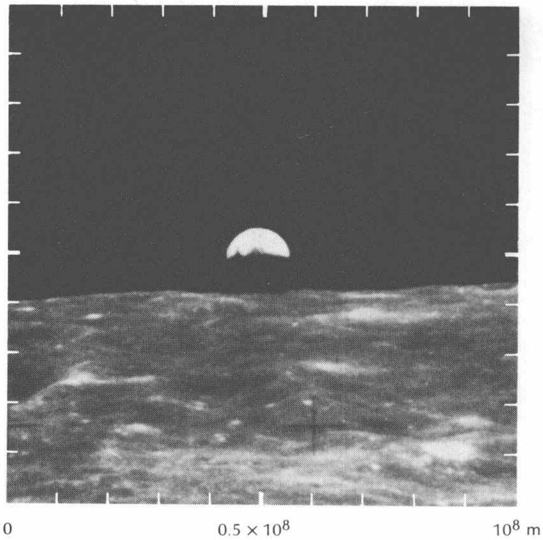
0 0.5×10^7 10^7 m

SCALE 1:1.5 × 10^8 In this photograph, taken by the Apollo 16 astronauts during their trip to the Moon, we see a large part of the Earth. Through the gap in the clouds in the lower middle of the picture, we can see the coast of California and Mexico. We can recognize the peninsula of Baja California and the Gulf of California. In the middle right of the photograph we can recognize the Gulf of Mexico. Charlotte's location, the East Coast of the United States, is covered by a big system of swirling clouds in the upper right of the photograph.

Note that a large part of the area visible in this photograph is ocean. About 71% of the surface of the Earth is ocean; only 29% is land. The atmosphere covering this surface is about 100 kilometers thick; on the scale of this photograph, its thickness is about 0.7 millimeter. Seen from a large distance, the predominant colors of the planet Earth are blue (oceans) and white (clouds).

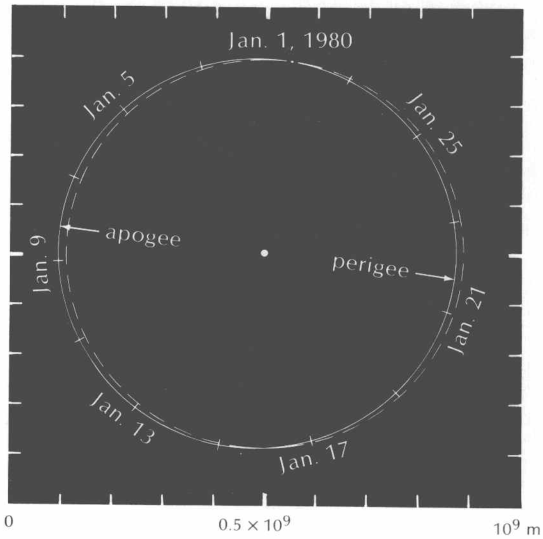
SCALE 1:1.5 $\times 10^9$ This photograph of the Earth was taken by the Apollo 16 astronauts standing on the surface of the Moon. Sunlight is striking the Earth from the top of the picture.

As is obvious from this and from the preceding photograph, the Earth is a sphere. Its radius is 6.38×10^6 meters and its mass is 5.98×10^{24} kilograms. Its chemical composition (by mass) is 38.6% iron, 28.6% oxygen, 14.4% silicon, 11.1% magnesium, 3.0% nickel, 1.6% sulfur, 1.3% aluminum, and 1.3% of other elements.



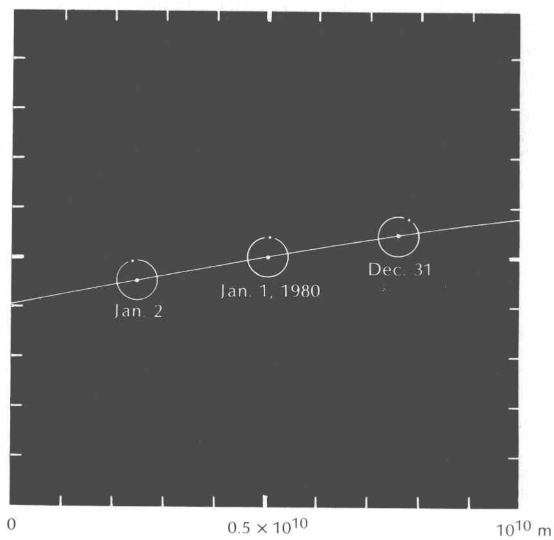
SCALE 1:1.5 $\times 10^{10}$ In this picture we see the Earth, the Moon, and its orbit. This picture is a drawing, not a photograph; none of our manned spacecraft has traveled sufficiently far away to take a photograph of such a panoramic view. (Many of the pictures on the following pages are also drawings.) As in the preceding picture, the Sun is far below the bottom of the picture. The position of the Moon is that of January 1, 1980. On this day, the Moon was almost full.

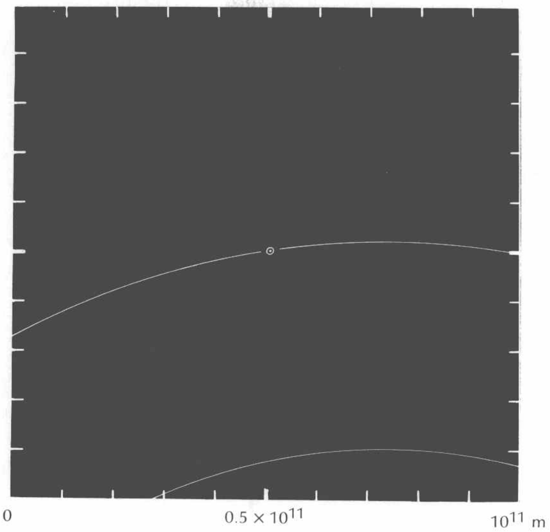
The orbit of the Moon around the Earth is an *ellipse*, but an ellipse that is very close to a circle. The solid curve in the picture is the orbit of the Moon and the dashed curve is a circle; by comparing these two curves we can see how much the ellipse deviates from a circle. The point on the ellipse closest to the Earth is called the *perigee* and the point farthest from the Earth is called the *apogee*. The distance between the Moon and the Earth is roughly 30 times the diameter of the Earth. The Moon takes 27.3 days to travel once around the Earth.



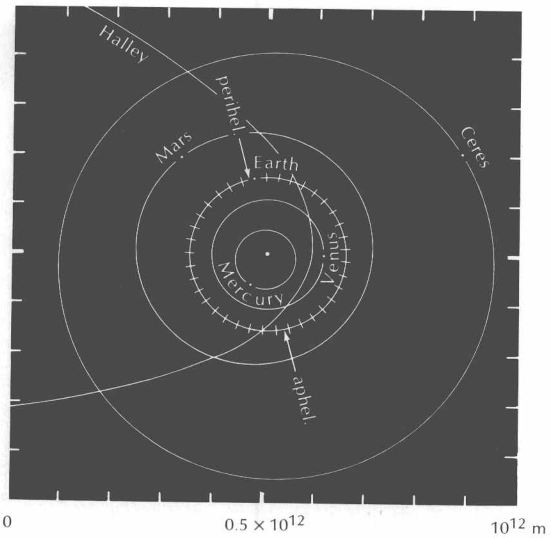
SCALE 1:1.5 $\times 10^{11}$ This picture shows the Earth, the Moon, and portions of their orbits around the Sun. On this scale, both the Earth and the Moon look like small dots. Again, the Sun is far below the bottom of the picture. In the middle, we see the Earth and the Moon in their positions for January 1, 1980. On the right and on the left we see, respectively, the positions for 1 day before and 1 day after this date.

Note that the net motion of the Moon consists of the combination of two simultaneous motions: the Moon orbits around the Earth, which in turn orbits around the Sun. The net orbit of the Moon is only slightly more curved than the orbit of the Earth.





SCALE 1:1.5 × 10¹² Here we see the orbits of the Earth and of Venus. However, Venus itself is beyond the edge of the picture. The small circle is the orbit of the Moon. The dot representing the Earth is much larger than what it should be, although the draftsman has drawn it as minuscule as possible. On this scale, even the Sun is quite small; if it were included in this picture, it would be only 1 millimeter across.



SCALE 1:1.5 × 10¹³ This picture shows the positions of the Sun and the inner planets: Mercury, Venus, Earth, and Mars. The positions of the planets are those of January 1, 1980. The orbits of all these planets are ellipses, but they are close to circles. The point of the orbit nearest to the Sun is called the *perihelion* and the point farthest from the Sun is called the *aphelion*. The Earth reaches perihelion about January 3 and aphelion about July 6 of each year.

All the planets travel around their orbits in the same direction: counterclockwise in our picture. The marks along the orbit of the Earth indicate the successive positions at intervals of 10 days. The orbits of the planets are not quite in the same plane. In the picture, we see the orbit of the Earth exactly face on; the orbits of the other planets are slightly tilted, but this tilt is not shown in the picture.

Beyond the orbit of Mars, a large number of asteroids orbit around the Sun. The four largest of these asteroids are Ceres, Pallas, Juno, and Vesta; the first of these has been included in our picture, but the others have been omitted to prevent excessive clutter. Furthermore, a large number of comets orbit around the Sun. Most of these have pronounced elliptical orbits. The comet Halley has been included in our picture.

The Sun is a sphere of radius 6.96×10^8 meters. On the scale of the picture, the Sun looks like a very small dot, even smaller than the dot drawn here. The mass of the Sun is 1.99×10^{30} kilograms. Its chemical composition (by mass) is 75% hydrogen, 23% helium, 0.8% oxygen, 0.4% carbon, 0.2% nitrogen, and about 0.6% of other elements. Since most of the mass of the universe is found inside of stars like the Sun, hydrogen and helium are the most abundant atoms in the universe. All the other atoms taken together account for less than 2% of the mass in the universe. Thus, the chemical elements found on the Earth and in our bodies must be regarded as mere traces, mere impurities. We are made of very rare stuff.

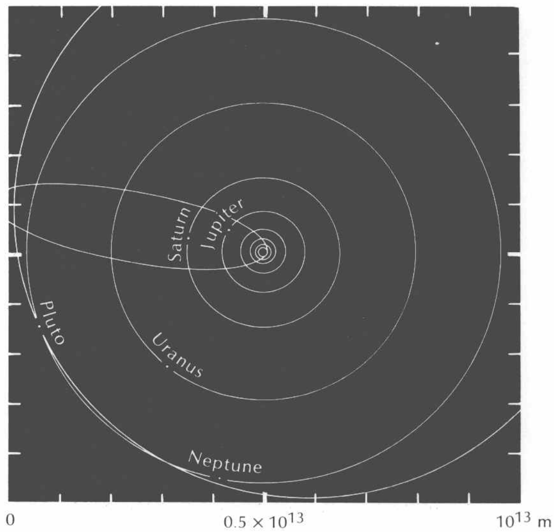
The matter in the Sun is in the *plasma* state, sometimes called the fourth state of matter. Plasma is a very hot gas in which violent collisions between the atoms in their random thermal motion have fragmented the atoms, ripping electrons off them. An atom that has lost one or more electrons is called an *ion*. Thus, plasma consists of a mixture of electrons and ions, all milling about at high speed and engaging in frequent collisions. These collisions are accompanied by the emission of light, making the plasma luminous.

In our universe plasma is by far the most abundant state of matter. Inside ordinary stars, such as the Sun, the temperature is so high that almost all atoms are ionized; only near the surface of the star can some atoms survive intact. Thus, all the stars are giant balls of plasma. Since most of the matter is found in stars, plasma is the predominant form of matter in the universe. Only a small fraction of matter is in the form of solids, liquids, and gases; these three states of matter are only found in planets, in neutron stars (pulsars), and in interstellar clouds of dust and gas.

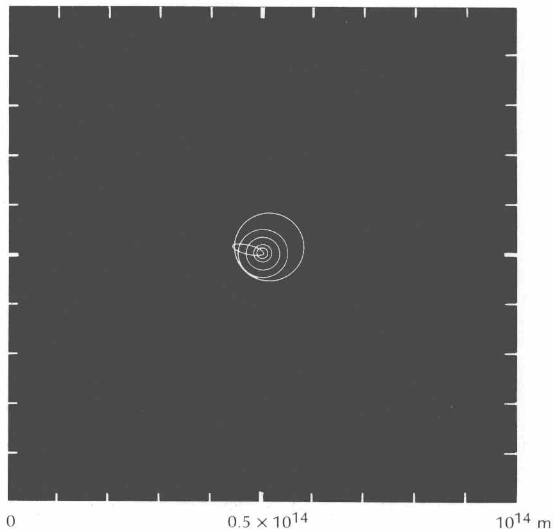
SCALE 1:1.5 × 10¹⁴ This picture shows the positions of the outer planets of the Solar System: Jupiter, Saturn, Uranus, Neptune, and Pluto. On this scale, the orbits of the inner planets are barely visible. As in our other pictures, the positions of the planets are those of January 1, 1980.

The outer planets move slowly and their orbits are very large; thus they take a long time to go once around their orbit. The extreme case is that of Pluto, which takes 248 years to complete one orbit.

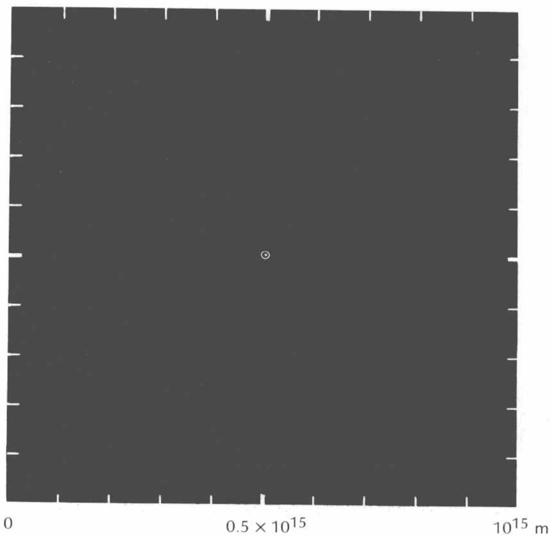
Uranus, Neptune, and Pluto are so far away and so faint that their discovery only became possible through the use of telescopes. Uranus was discovered in 1781, Neptune in 1846, and the tiny Pluto in 1930.

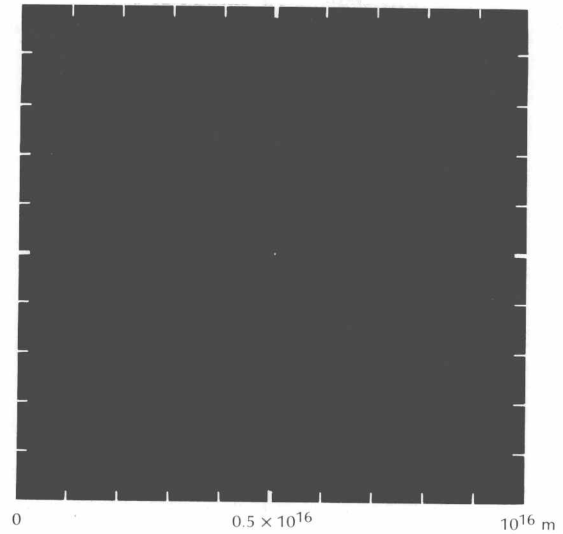


SCALE 1:1.5 × 10¹⁵ We see now that the Solar System is surrounded by a vast expanse of empty space. Actually, this space is not quite empty. The Solar System is encircled by a large cloud of millions of comets whose orbits crisscross the sky in all directions. Furthermore, the interstellar space in this picture and in the succeeding pictures contains traces of gas and of dust. The interstellar gas is mainly hydrogen; its density is typically 1 atom per cubic centimeter.

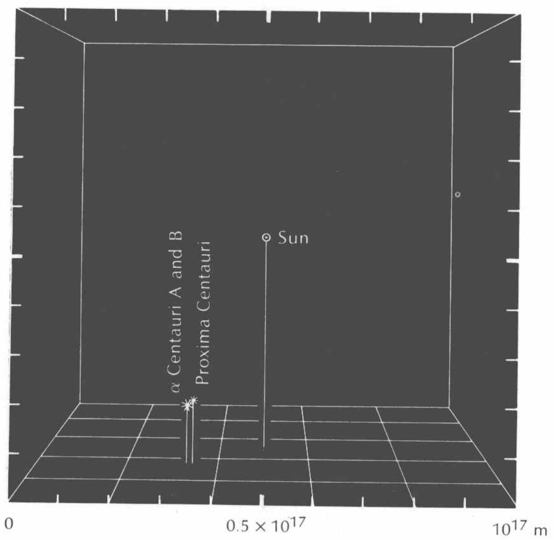


SCALE 1:1.5 × 10¹⁶ More empty space. The small circle is the orbit of Pluto.





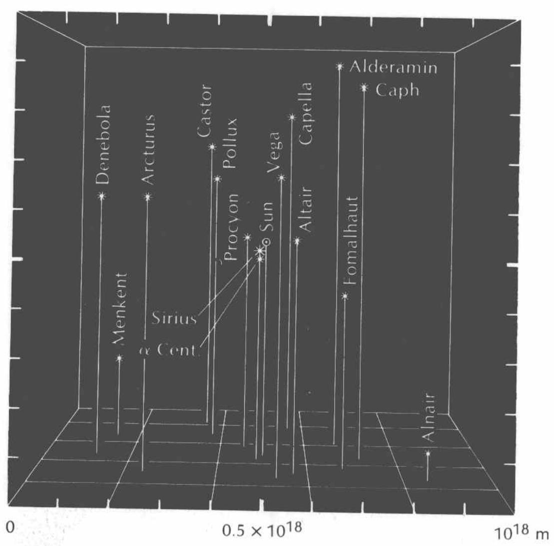
SCALE 1:1.5 × 10^{17} And more empty space. On this scale, the Solar System looks like a minuscule dot, 0.1 millimeter across.



SCALE 1:1.5 × 10^{18} Here, at last, we see the stars nearest to the Sun. The picture shows all the stars within a cubical box 10^{17} meters × 10^{17} meters × 10^{17} meters centered on the Sun: Alpha Centauri A, Alpha Centauri B, and Proxima Centauri. All three are in the constellation Centaurus, near the Southern Cross.

The star closest to the Sun is Proxima Centauri. This is a very faint, reddish star (a "red dwarf"), at a distance of 4.0 × 10^{16} meters from the Sun. Astronomers like to express stellar distances in light-years: Proxima Centauri is 4.2 light-years from the Sun, which means light takes 4.2 years to travel from this star to the Sun.

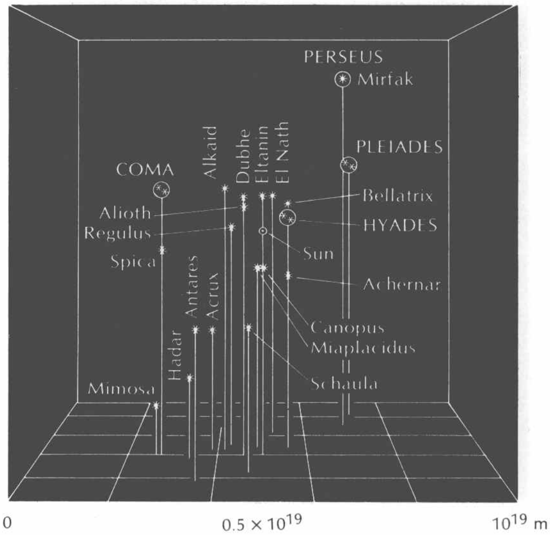
Proxima Centauri is too faint to be seen by the naked eye. The nearest stars that can be seen by the naked eye are Alpha Centauri A and Alpha Centauri B. The former is a bright star quite similar to our Sun; the latter is a fainter, orange star. These two stars are so close together that we need to use a telescope to distinguish between them. They form a double star, continually orbiting around each other. This double star is at a distance of 4.3 light-years from the Sun.



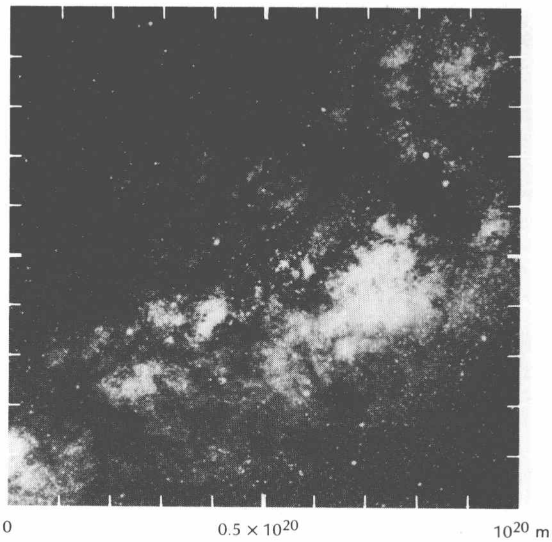
SCALE 1:1.5 × 10^{19} This picture displays the brightest stars within a cubical box 10^{18} meters × 10^{18} meters × 10^{18} meters centered on the Sun. There are many more stars in this box besides those shown — the total number of stars in this box is close to 2000.

Sirius is the brightest of all the stars in the night sky. If it were at the same distance from the Earth as the Sun, it would be 28 times brighter than the Sun. Sirius has a much fainter companion very close to it.

SCALE 1:1.5 × 10^{20} Here we expand our box to 10^{19} meters × 10^{19} meters × 10^{19} meters, again showing only the brightest stars and omitting many others. The total number of stars within this box is close to 2 million. We recognize several clusters of stars in this picture: the Pleiades Cluster, the Hyades Cluster, the Coma Berenices Cluster, and the Perseus Cluster. Each of these has hundreds of stars crowded into a fairly small patch of sky.



SCALE 1:1.5 × 10^{21} Now there are so many stars in our field of view that they appear to form clouds of stars. There are about a million stars in this photograph, and there are many more stars too faint to show up distinctly. Although this photograph is not centered on the Sun, it simulates what we would see if we could look toward the Solar System from very far away. The photograph shows a view of the Milky Way in the direction of the constellation Sagittarius. When we look from our Solar System in this direction, we see the clouds of stars in the neighboring spiral arm of our Galaxy (the next picture shows a galaxy and its spiral arms). This neighboring arm is the Sagittarius Spiral Arm; the cloud of stars in which our Sun is located belongs to the *Orion Spiral Arm*.



SCALE 1:1.5 × 10^{22} This is the galaxy NGC 5457 with its clouds of stars arranged in spiral arms wound around a central bulge. It is a spiral galaxy. The bright central bulge is the nucleus of the galaxy; it has a more or less spherical shape. The surrounding region, with the spiral arms, is the disk of the galaxy. This disk is quite thin; it has a thickness of only about 3% of its diameter. The stars making up the disk circle around the galactic center in a counterclockwise direction.

Our Sun is in a spiral galaxy of roughly similar shape and size: the *Galaxy of the Milky Way*. The total number of stars in this galaxy is about 10^{11}. The Sun is in one of the spiral arms, roughly one-third inward from the edge of the disk toward the center. The Sun takes about 250 million years to complete one circuit around the galactic center. Recent observations of the galactic center with radiotelescopes suggest that there is a large black hole at the center, a black hole several million times as massive as the Sun.

This photograph, like the remaining photographs of this section, was made with the great 5-meter telescope on Mt. Palomar.