ED 161 721 SE 025 185

AUTHOR Page, Lou Williams; Page, Thornton
TITLE Apollo-Soyuz Pamphlet No. 5: The Earth from Orbit. Apollo-Soyuz Experiments in Space.
INSTITUTION National Aeronautics and Space Administration, Washington, D.C.
REPORT NO NASA-EP-137
PUB DATE Oct 77
NOTE 66p.; For related documents, see SE 025 181-189; Photographs may not reproduce well; Contains occasional marginal legibility in Figures
AVAILABLE FROM Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock No. 033-800-00688-8; Available in sets only - $10.00)

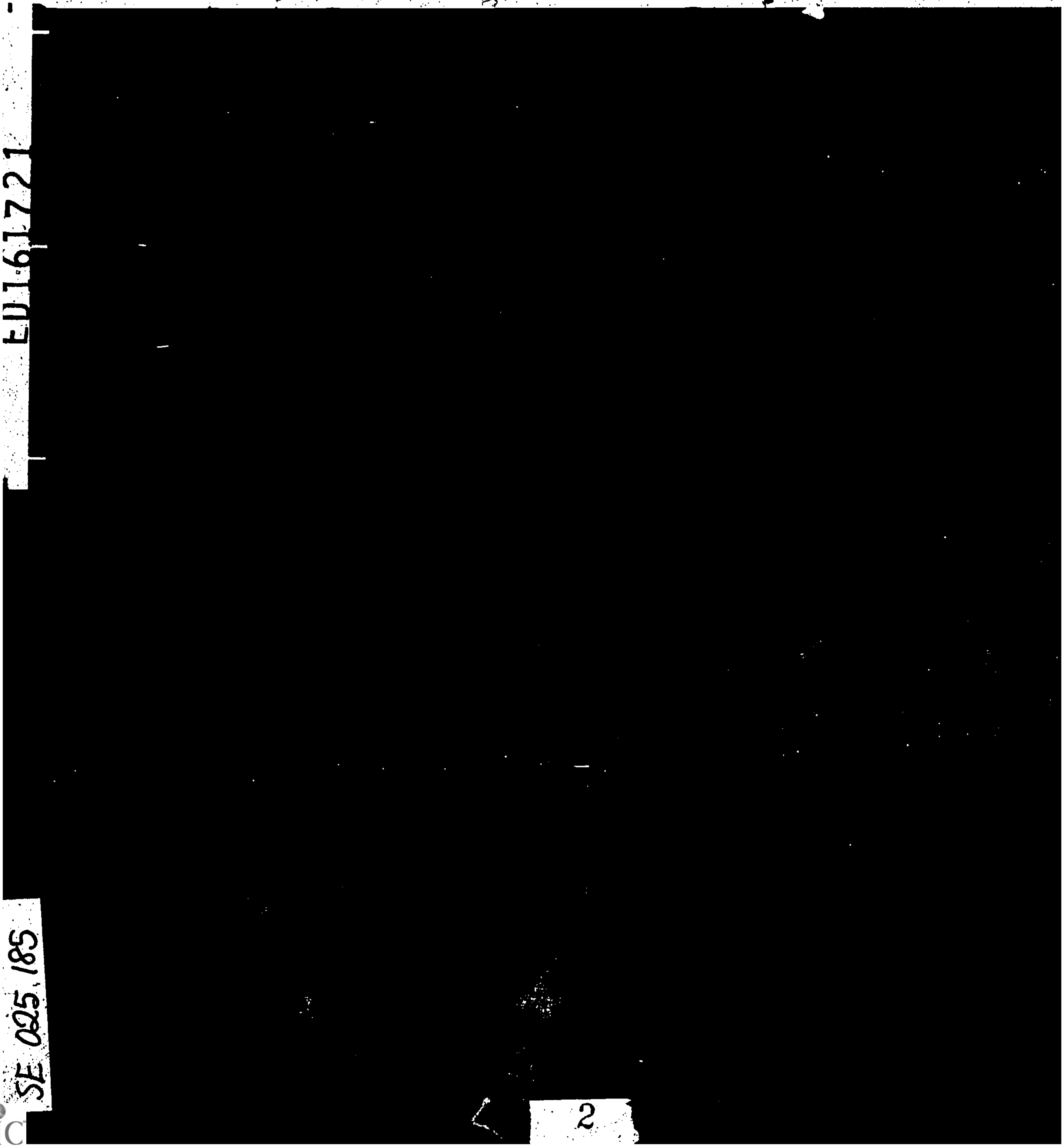
EDRS PRICE MF-$0.83 HC-$3.50 Plus Postage.
DESCRIPTORS Aerospace Education; College Science; *Earth Science; Higher Education; *Instructional Materials; Learning Activities; *Physical Sciences; *Science Education; Secondary Education; Secondary School Science; Space Sciences; *Supplementary Textbooks
IDENTIFIERS National Aeronautics and Space Administration

ABSTRACT

This booklet is the fifth in a series of nine that describe the Apollo-Soyuz mission and experiments. This set is designed as a curriculum supplement for high school and college teachers, supervisors, curriculum specialists, textbook writers, and the general public. These booklets provide sources of ideas, examples of the scientific method, references to standard textbooks, and descriptions of space experiments. There are numerous photographs and diagrams, as well as questions for discussion (with answers) and a glossary of terms. This pamphlet discusses observations of the earth's surface from space, aerosols that affect climate and weather on earth, and the oxygen and nitrogen in the outer atmosphere. (MA)

# Apollo-Soyuz Pamphlet No. 5:

# The Earth from Orbit



**Apollo-Soyuz Experiments In Space**

This is one of a series of nine curriculum-related pamphlets for Teachers and Students of Space Science

Titles in this series of pamphlets include:

EP-133 Apollo-Soyuz Pamphlet No. 1: The Flight
EP-134 Apollo-Soyuz Pamphlet No. 2: X-Rays, Gamma-Rays
EP-135 Apollo-Soyuz Pamphlet No. 3: Sun, Stars, In Between
EP-136 Apollo-Soyuz Pamphlet No. 4: Gravitational Field
EP-137 Apollo-Soyuz Pamphlet No. 5: The Earth from Orbit
EP-138 Apollo-Soyuz Pamphlet No. 6: Cosmic Ray Dosage
EP-139 Apollo-Soyuz Pamphlet No. 7: Biology in Zero-G
EP-140 Apollo-Soyuz Pamphlet No. 8: Zero-G Technology
EP-141 Apollo-Soyuz Pamphlet No. 9: General Science

On The Cover

The Arabian Peninsula and the Red Sea
as Viewed from Apollo-Soyuz

## Apollo-Soyuz Pamphlet No. 5:

# The Earth from Orbi[illegible]

Prepared by Lou Williams Page and Thornton Page From Investigators' Reports of Experimental Results and With the Help of Advising Teachers

NASA
National Aeronautics and
Space Administration
Washington, D.C. 20546
October 1977

For sale by the Superintendent of Documents,
U.S. Government Printing Office, Washington, D.C. 20402
(9-Part Set; Sold in Sets Only)
Stock Number 033-800-00688-8

# Preface

The Apollo-Soyuz Test Project (ASTP), which flew in July 1975, aroused considerable public interest; first, because the space rivals of the late 1950's and 1960's were working together in a joint endeavor, and second, because their mutual efforts included developing a space rescue system. The ASTP also included significant scientific experiments, the results of which can be used in teaching biology, physics, and mathematics in schools and colleges.

This series of pamphlets discussing the Apollo-Soyuz mission and experiments is a set of curriculum supplements designed for teachers, supervisors, curriculum specialists, and textbook writers as well as for the general public. Neither textbooks nor courses of study, these pamphlets are intended to provide a rich source of ideas, examples of the scientific method, pertinent references to standard textbooks, and clear descriptions of space experiments. In a sense, they may be regarded as a pioneering form of teaching aid. Seldom has there been such a forthright effort to provide, directly to teachers, curriculum-relevant reports of current scientific research. High school teachers who reviewed the texts suggested that advanced students who are interested might be assigned to study one pamphlet and report on it to the rest of the class. After class discussion, students might be assigned (without access to the pamphlet) one or more of the "Questions for Discussion" for formal or informal answers, thus stressing the application of what was previously covered in the pamphlets.

The authors of these pamphlets are Dr. Lou Williams Page, a geologist, and Dr. Thornton Page, an astronomer. Both have taught science at several universities and have published 14 books on science for schools, colleges, and the general reader, including a recent one on space science.

Technical assistance to the Pages was provided by the Apollo-Soyuz Program Scientist, Dr. R. Thomas Giuli, and by Richard R. Baldwin, W. Wilson Lauderdale, and Susan N. Montgomery, members of the group at the NASA Lyndon B. Johnson Space Center in Houston which organized the scientists' participation in the ASTP and published their reports of experimental results.

Selected teachers from high schools and universities throughout the United States reviewed the pamphlets in draft form. They suggested changes in wording, the addition of a glossary of terms unfamiliar to students, and improvements in diagrams. A list of the teachers and of the scientific investigators who reviewed the texts for accuracy follows this Preface.

This set of Apollo-Soyuz pamphlets was initiated and coordinated by Dr. Frederick B. Tuttle, Director of Educational Programs, and was supported by the NASA Apollo-Soyuz Program Office, by Leland J. Casey, Aerospace Engineer for ASTP, and by William D. Nixon, Educational Programs Officer, all of NASA Headquarters in Washington, D.C.

6

Appreciation is expressed to the scientific investigators and teachers who reviewed the draft copies; to the NASA specialists who provided diagrams and photographs; and to J. K. Holcomb, Headquarters Director of ASTP operations, and Chester M. Lee, ASTP Program Director at Headquarters, whose interest in this educational endeavor made this publication possible.

7

# Teachers And Scientific Investigators Who Reviewed the Text

Harold L. Adair, Oak Ridge National Laboratory, Oak Ridge, Tenn.
Lynette Aey, Norwich Free Academy, Norwich, Conn.
J. Vernon Bailey, NASA Lyndon B. Johnson Space Center, Houston, Tex.
Stuart Bowyer, University of California at Berkeley, Berkeley, Calif.
Bill Wesley Brown, California State University at Chico, Chico, Calif.
Ronald J. Bruno, Creighton Preparatory School, Omaha, Nebr.
T. F. Budinger, University of California at Berkeley, Berkeley, Calif.
Robert F. Collins, Western States Chiropractic College, Portland, Oreg.
B. Sue Criswell, Baylor College of Medicine, Houston, Tex.
T. M. Donahue, University of Michigan, Ann Arbor, Mich.
David W. Eckert, Greater Latrobe Senior High School, Latrobe, Pa.
Lyle N. Edge, Blanco High School, Blanco, Tex.
Victor B. Eichler, Wichita State University, Wichita, Kans.
Farouk El-Baz, Smithsonian Institution, Washington, D.C.
D. Jerome Fisher, Emeritus, University of Chicago, Phoenix, Ariz.
R. T. Giuli, NASA Lyndon B. Johnson Space Center, Houston, Tex.
M. D. Grossi, Smithsonian Astrophysical Observatory, Cambridge, Mass.
Wendy Hindin, North Shore Hebrew Academy, Great Neck, N.Y.
Tim C. Ingoldsby, Westside High School, Omaha, Nebr.
Robert H. Johns, Academy of the New Church, Bryn Athyn, Pa.
D. J. Larson, Jr., Grumman Aerospace, Bethpage, N.Y.
M. D. Lind, Rockwell International Science Center, Thousand Oaks, Calif.
R. N. Little, University of Texas, Austin, Tex.
Sarah Manly, Wade Hampton High School, Greenville, S.C.
Katherine Mays, Bay City Independent School District, Bay City, Tex.
Jane M. Oppenheimer, Bryn Mawr College, Bryn Mawr, Pa.
T. J. Pepin, University of Wyoming, Laramie, Wyo.
H. W. Scheld, NASA Lyndon B. Johnson Space Center, Houston, Tex.
Seth Shulman, Naval Research Laboratory, Washington, D.C.
James W. Skehan, Boston College, Weston, Mass.
B. T. Slater, Jr., Texas Education Agency, Austin, Tex.
Robert S. Snyder, NASA George C. Marshall Space Flight Center, Huntsville, Ala.
Jacqueline D. Spears, Port Jefferson High School, Port Jefferson Station, N.Y.
Robert L. Stewart, Monticello High School, Monticello, N.Y.
Aletha Stone, Fulmore Junior High School, Austin, Tex.
G. R. Taylor, NASA Lyndon B. Johnson Space Center, Houston, Tex.
Jacob I. Trombka, NASA Robert H. Goddard Space Flight Center, Greenbelt, Md.
F. O. Vonbun, NASA Robert H. Goddard Space Flight Center, Greenbelt, Md.
Douglas Winkler, Wade Hampton High School, Greenville, S.C.

# Contents

# Figures

# 1 Introduction

After 4 years of preparation by the U.S. National Aeronautics and Space Administration (NASA) and the U.S.S.R. Academy of Sciences, the Apollo and Soyuz spacecraft were launched on July 15, 1975. Two days later at 16:09 Greenwich mean time on July 17, after Apollo maneuvered into the same orbit as Soyuz, the two spacecraft were docked. The astronauts and cosmonauts then met for the first international handshake in space, and each crew entertained the other crew (one at a time) at a meal of typical American or Russian food. These activities and the physics of reaction motors, orbits around the Earth, and weightlessness (zero-g) are described more fully in Pamphlet I, "The Spacecraft, Their Orbits, and Docking" (EP-133).

Thirty-four experiments were performed while Apollo and Soyuz were in orbit: 23 by astronauts, 6 by cosmonauts, and 5 jointly. These experiments in space were selected from 161 proposals from scientists in nine different countries. They are listed by number in Pamphlet I, and groups of two or more are described in detail in Pamphlets II through IX (EP-134 through EP-141, respectively). Each experiment was directed by a Principal Investigator, assisted by several Co-Investigators, and the detailed scientific results have been published by NASA in two reports: the Apollo-Soyuz Test Project Preliminary Science Report (NASA TM X-58173) and the Apollo-Soyuz Test Project Summary Science Report (NASA SP-412). The simplified accounts given in these pamphlets have been reviewed by the Principal Investigators or one of the Co-Investigators.

For many years, airplanes have photographed the Earth's surface. Color photographs and special filters have given more and more information about the surface—temperatures, conditions of crops and forests, amount of water in the soil, minerals in exposed rocks, and so on. Starting in the mid-1960's, NASA spacecraft have photographed weather patterns and detected water pollution, in addition to obtaining the temperature, crop data, moisture, exposed minerals, and so on. From Skylab in 1973, astronauts noted many more features: wave conditions in the ocean, major geologic formations, and conditions in the upper atmosphere. It was natural for the Apollo-Soyuz Test Project to extend these observations still further.

Apollo and Soyuz were in orbit 222 kilometers above the Earth's surface. From this altitude, observations could be made of broad areas of the Earth and of the atmosphere above the horizon. Although Apollo-Soyuz was above most of the Earth's atmosphere, there was some very low density gas even at that altitude. Three experiments were designed to take advantage of the Apollo-Soyuz view.

Experiment MA-136, Earth Observations and Photography, produced hundreds of photographs, several reels of video tape, and a reel of movie film. Many verbal descriptions were also made by the astronauts. The Principal

Investigator was Farouk El-Baz of the Smithsonian Institution in Washington, D.C. He was assisted by 12 Co-Investigators, who are experts in geology, oceanography, and meteorology. They came from various parts of the United States and one came from India.

Experiment MA-007, Stratospheric Aerosol Measurement, was directed by T. J. Pepin of the University of Wyoming. He and seven Co-Investigators used infrared observations of the setting or rising Sun, as seen from Apollo, to measure the amount of dust and droplets in the lower 150 kilometers of the Earth's atmosphere.

Experiment MA-059, Ultraviolet Absorption, measured the densities of atomic oxygen and nitrogen 222 kilometers above the Earth's surface. The Principal Investigator was T. M. Donahue of the University of Michigan. He was assisted by five Co-Investigators.

# 2 Observations of the Earth's Surface

Aerial photographs of portions of the Earth are routinely taken from airplanes, often for making maps or surveys. Orbiting spacecraft like Apollo-Soyuz or the earlier Skylab have three main advantages over airplanes as camera mounts. First, the higher spacecraft can "see" a larger area and can therefore record broader features, such as the remains of an old volcano or a huge eddy in the sea. Second, the spacecraft is almost perfectly steady; there are no gusts of wind or "bumpy air" to toss it around like an airplane, thus smearing the photographs. Third, the spacecraft follows a precise orbit over a "track" that runs straight across the ground. Although the spacecraft moves much more rapidly than an airplane, modern cameras are fast and some are built to compensate for the spacecraft velocity.

Farouk El-Baz, the Principal Investigator for Experiment MA-136, strongly favors astronauts' visual observations with "backup" photography. He points out several cases where astronauts glimpsed features that did not show up on the photographs, and other cases where astronauts chose the time when the lighting was just right to take photographs that would show what the astronauts were seeing.

The Earth observations were carefully planned to provide information needed by geologists for studies of mountains, rivers, deserts, and continental drift. Other information helped oceanographers to study sea currents and meteorologists to study tropical storms and hurricanes (Fig. 2.1). Most of these studies provide direct benefits to us ground-based residents on Earth.

## A Cameras, Lenses, and Film

One objective of Experiment MA-136 was to check the effectiveness of different cameras for photographing various features from orbit. Five cameras and seven different lenses were provided on Apollo. The largest camera was a Hasselblad reflex (Swiss built, see Fig. 2.2), with 70-millimeter film and two lenses, one with a focal length of 250 millimeters and the other of 50 millimeters. The focal length of the lens determines the size or scale of the photograph: the larger the focal length, the greater the enlargement (Fig. 2.3). The field of view, however, is larger (on 70-millimeter film) when the shorter lens is used. The 50-millimeter lens was used for wide-angle views, and the 250-millimeter lens was used for large-scale, high-resolution photographs.

Another Hasselblad camera had 60- and 100-millimeter lenses and was mounted firmly on a bracket to take mapping photographs through one Apollo window. This camera had an "intervalometer" to time the exposures so that each photograph overlapped the preceding one by 60 percent. Every point along the groundtrack was thus photographed at least twice, once from each of two points in Apollo's orbit several hundred kilometers apart. Pairs of these overlapping photographs yield stereoscopic views from which trained specialists can "interpret" such information as heights of clouds and mountains and depths of canyons.

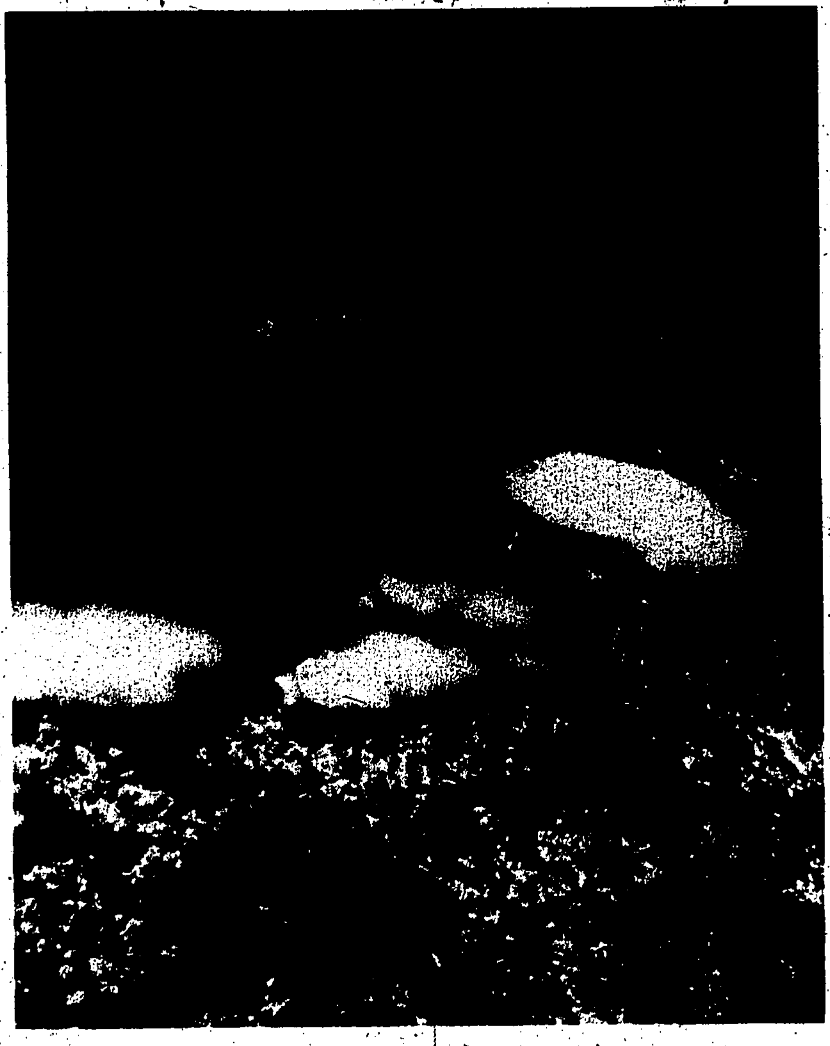
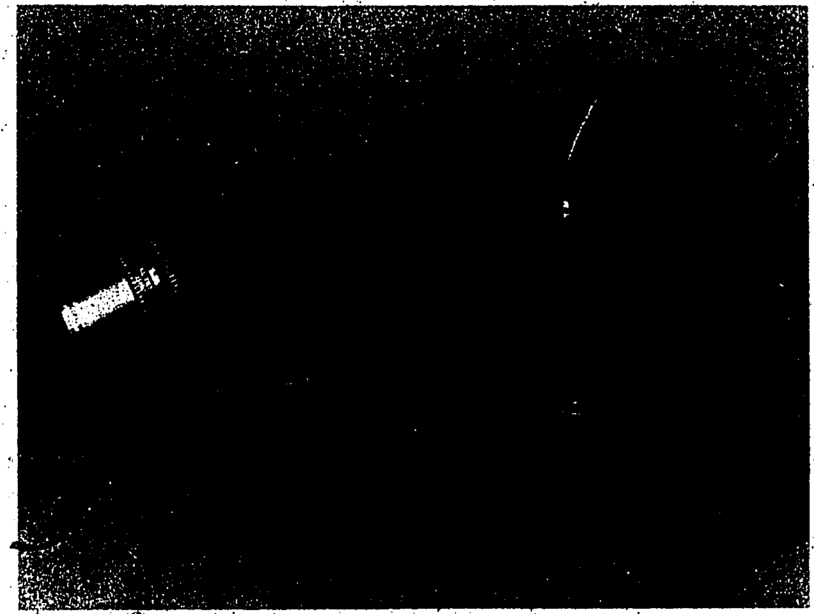


**Figure 2.1** This photograph of an unusual cloud system was taken along the western coast of Mexico looking westward over the Gulf of California. The land in the background is Baja California.



The 70-millimeter Hasselblad reflex camera system. Figure 2.2

There were two smaller cameras: a 35-millimeter Nikon single-lens reflex camera with a 55-millimeter focal-length lens (Japanese) and a 16-millimeter Mauer movie camera (American). There was also a television camera for real-time broadcasts from Apollo-Soyuz and a video tape recorder to record television views of the Pacific Ocean. The color film used in the cameras was specially prepared for the MA-136 Experiment by Eastman Kodak. A special coating was used on the emulsion to prevent halation by blue light. (Halation is the unrealistic haze around a bright object in a photograph.) More than 1900 photographs were taken from Apollo for the MA-136 Experiment; 75 percent of them are of excellent quality.

## B Earth Features and Astronaut Training

Except for photographs from orbit, we people on the ground never get a clear view of large Earth features. A familiar example is the satellite weather photograph shown on television weather newscasts, which reveals weather

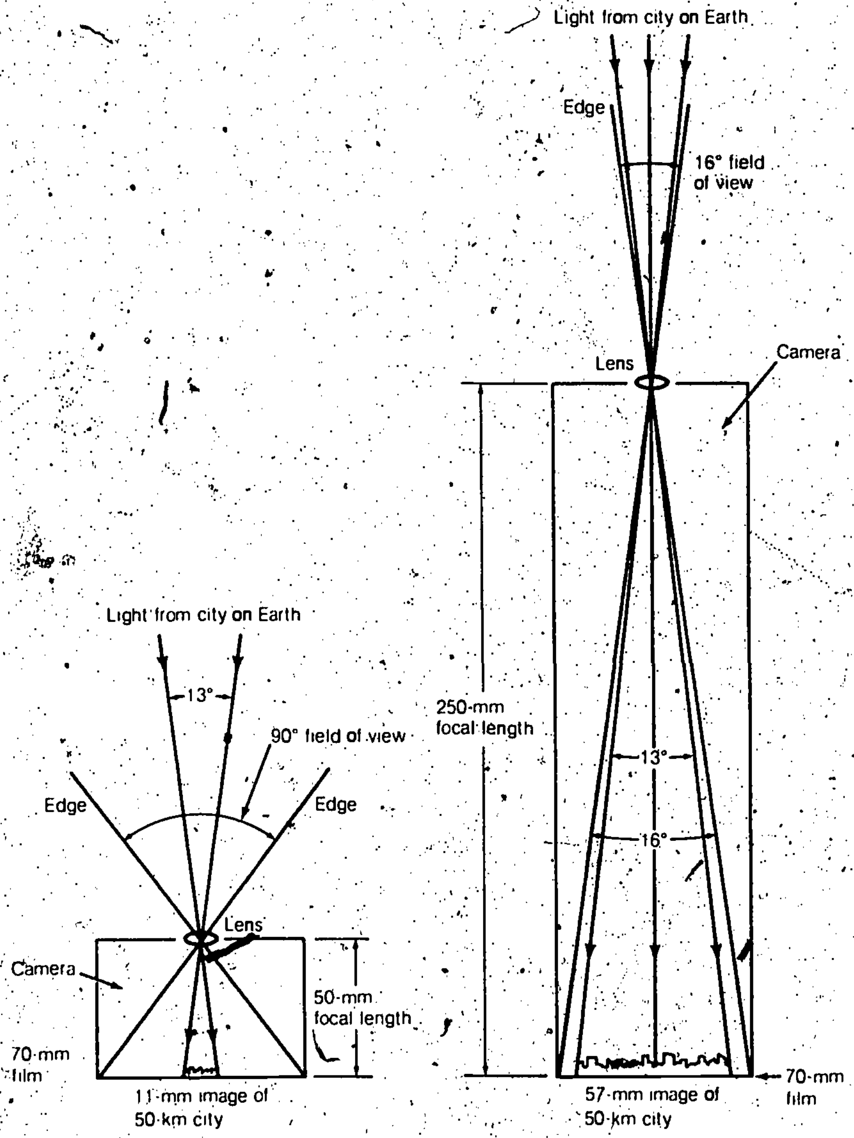


Figure 2.3 Camera focal length, field of view, and photographic scale.

fronts and storm centers far better than any view of the clouds from Earth. Oceanographers plot maps of water currents over small areas, a little bit at a time. However, satellite views of the Gulf Stream along the East Coast of the United States show vivid color contrasts between the colder Atlantic water and the giant eddies in the Gulf Stream near islands and reefs. Geologists also plot small-scale evidence of rifts or fault lines on maps, but they do not always recognize the full extent of these features. Rifts and faults are huge cracks in the Earth's crust where the rock on one side has slipped past the rock on the other side. The slip can be up-down or sideward. The most famous slippage in the United States is the San Andreas Fault, which runs north-to-south in California and is easy to see on satellite photographs.

These topics were discussed in science classes for the astronauts—60 hours of classroom time—during the year before the Apollo-Soyuz mission. The astronauts also had 10 "flyover exercises" during which they flew in airplanes over faults, sea eddies, and desert dunes. They learned how to describe a fault line on a tape recorder and how to judge the color of seawater or desert sand by using a "color wheel." The color wheel onboard Apollo had 54 reddish-brown colors and 54 bluish-green colors on a paper disk. The astronauts selected the color most similar to the seawater or desert sand that they observed and tape-recorded the color-wheel number. These color numbers were important because the color photographs might be underexposed or overexposed and not show the actual colors.

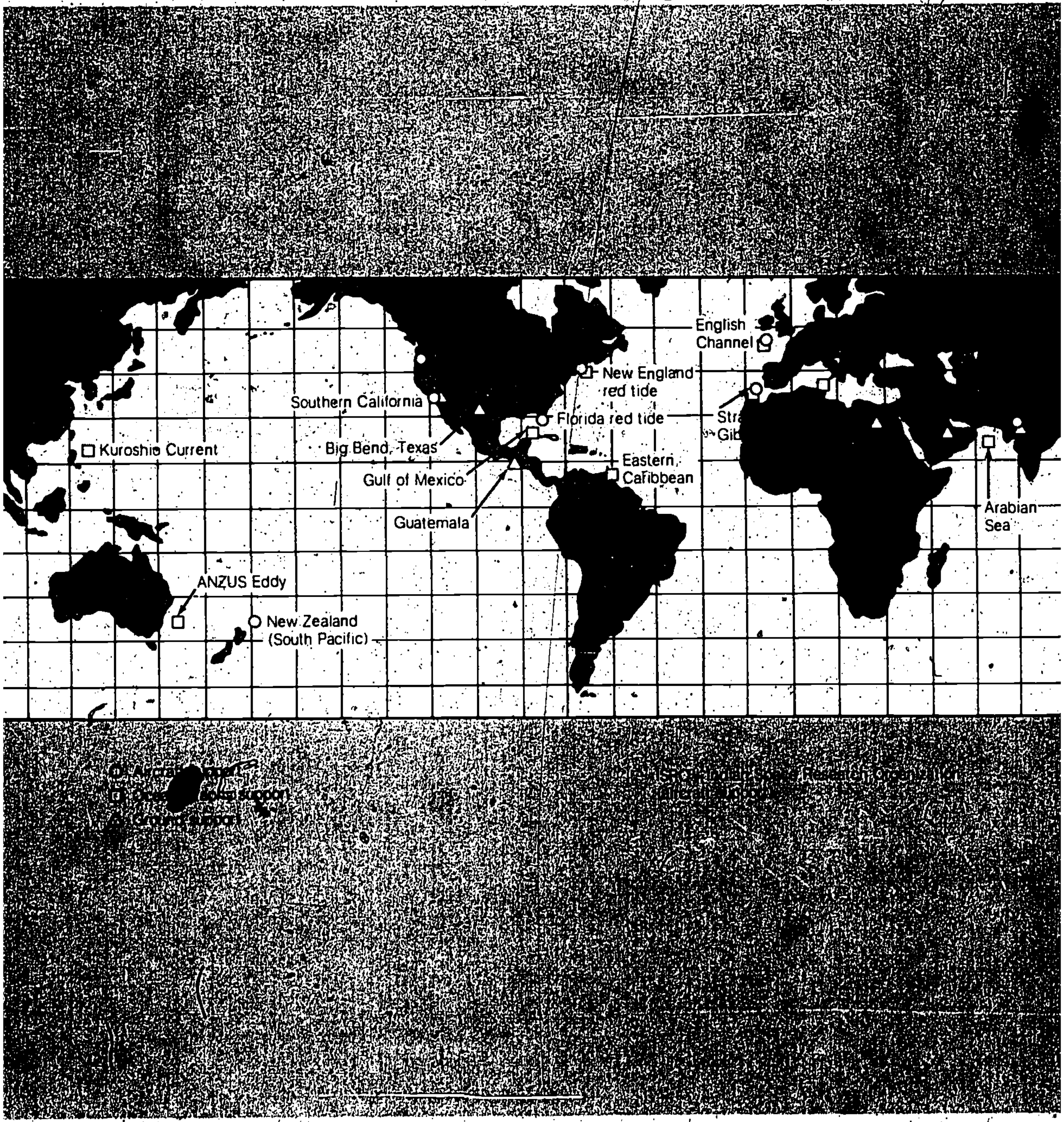
During the aircraft flyover exercises, the astronauts experimented with several pairs of binoculars and finally selected an ×16-power monocular for use on the Apollo-Soyuz flight. This little telescope enlarged what they saw below and helped them to identify features to report or photograph.

The purpose of all this training was to help the Apollo astronauts—Tom Stafford, Deke Slayton, and Vance Brand—become well-informed in geology, oceanography, and meteorology so that they would quickly recognize features of scientific importance.

## Ground Truth

The Principal Investigator had consulted a group of 42 experts to decide what Earth features the astronauts should look for and photograph. Some of these experts were able to have measurements made on the Earth's surface to verify what was seen or photographed from Apollo-Soyuz. For instance, several groups of ships measured sea-surface temperatures, salinity (the amount of salt in the water), water color, red tides (poisonous plankton in the water), water currents, wind velocity, and cloud types. Figure 2.4 shows the 18 areas where such "ground-truth" measurements were made while Apollo-Soyuz

**Figure 2.4** Locations of ground-truth teams for Experiment MA-136, Earth Observations and Photography.



passed overhead. Two airplanes flew across the United States and took photographs from high altitudes to compare with the MA-136 mapping photographs taken at the same time; several other airplanes did the same near New Zealand and England. A team of Egyptian geologists mapped a portion of the Western Desert of Egypt, which was photographed twice by Apollo-Soyuz.

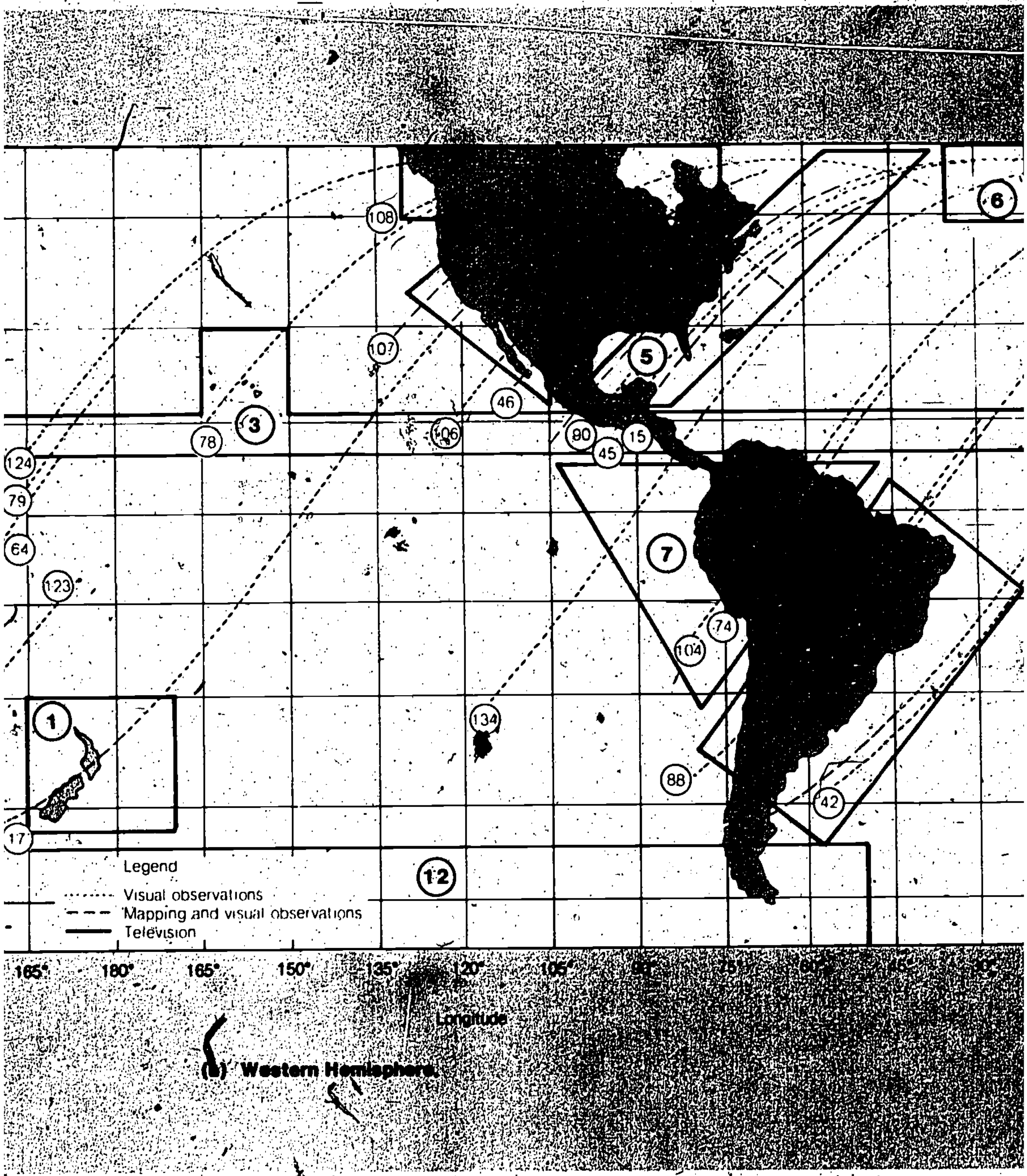
In every case, the MA-136 observations agreed with the local ground-truth data, even though the MA-136 data extended over much larger areas. Some of the ground-truth sites were covered by clouds when Apollo passed, among them the site of the New England red tide off the coast of Maine. (The astronauts viewed red water farther north in the Bay of Fundy but reported it to be reddish-brown muddy water from rivers, not the bright-red color of the plankton in the red tide.)

## D. MA-136 Earth Observations Results

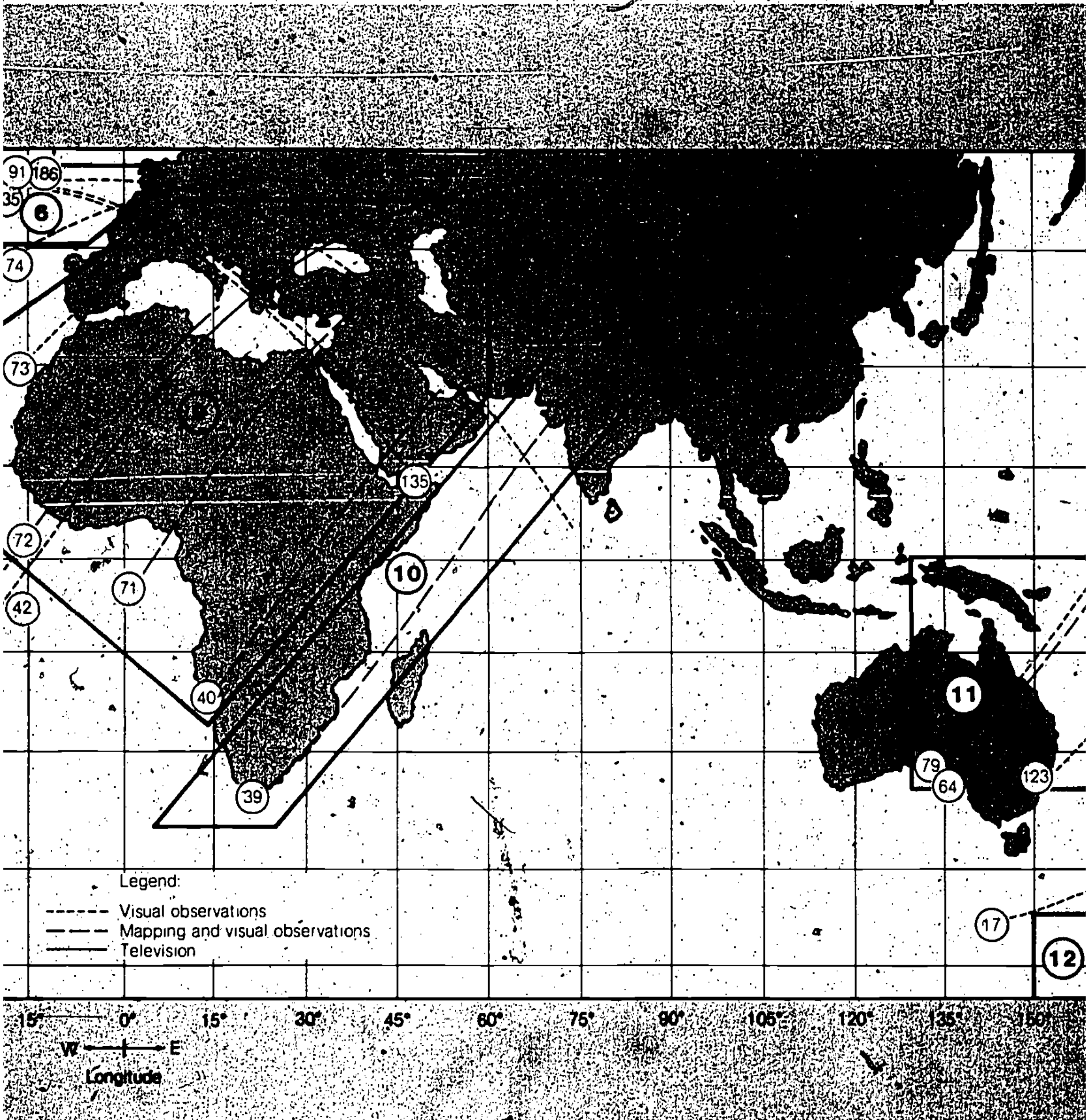
The numerous color photographs and astronaut reports will be studied for years. Several important discoveries have already been made from them, and more may yet be found. Figure 2.5 shows the locations of the visual observations, the photographic mapping observations, and the television video tape recordings. Each numbered area (1 to 12) concerned a specific scientific problem. For instance, area 11 is the huge ANZUS Eddy (for *A*ustralia-*N*ew Zealand-*U*nited *S*tates) off the eastern coast of Australia, and area 9 shows the growing deserts of North Africa.

One important discovery is shown in Figure 2.6, a photograph of the Levantine Rift. For years, scientists had known about this huge crack in the Earth's crust; however, the Apollo-Soyuz MA-136 Experiment revealed its full extent. The rift extends from the Gulf of Aqaba (at the northern end of the Red Sea) northward through the Dead Sea to the Sea of Galilee in Israel, where it splits into three cracks that fan out to the north and northeast. The rift is probably caused by the counterclockwise drift of the Arabian peninsula (away from Africa) around a "pivot" near the Sea of Galilee, where the rift splits. Geologists find more and more evidence that entire continents have "drifted" during many millions of years. For instance, North and South America seem to have drifted very slowly away from Europe and Africa, leaving a basin (the Atlantic Ocean) in between. Along the eastern coast of South America, the types and ages of rocks (and the fossils in them) match those along the western coast of Africa, and the outlines of these two coasts fit

**Figure 2.5** Maps showing the broad locations of the MA-136 Earth observation sites. Small circled numbers represent revolution groundtracks for photographic mapping and visual observation tasks; large circled numbers represent the Earth observation sites.

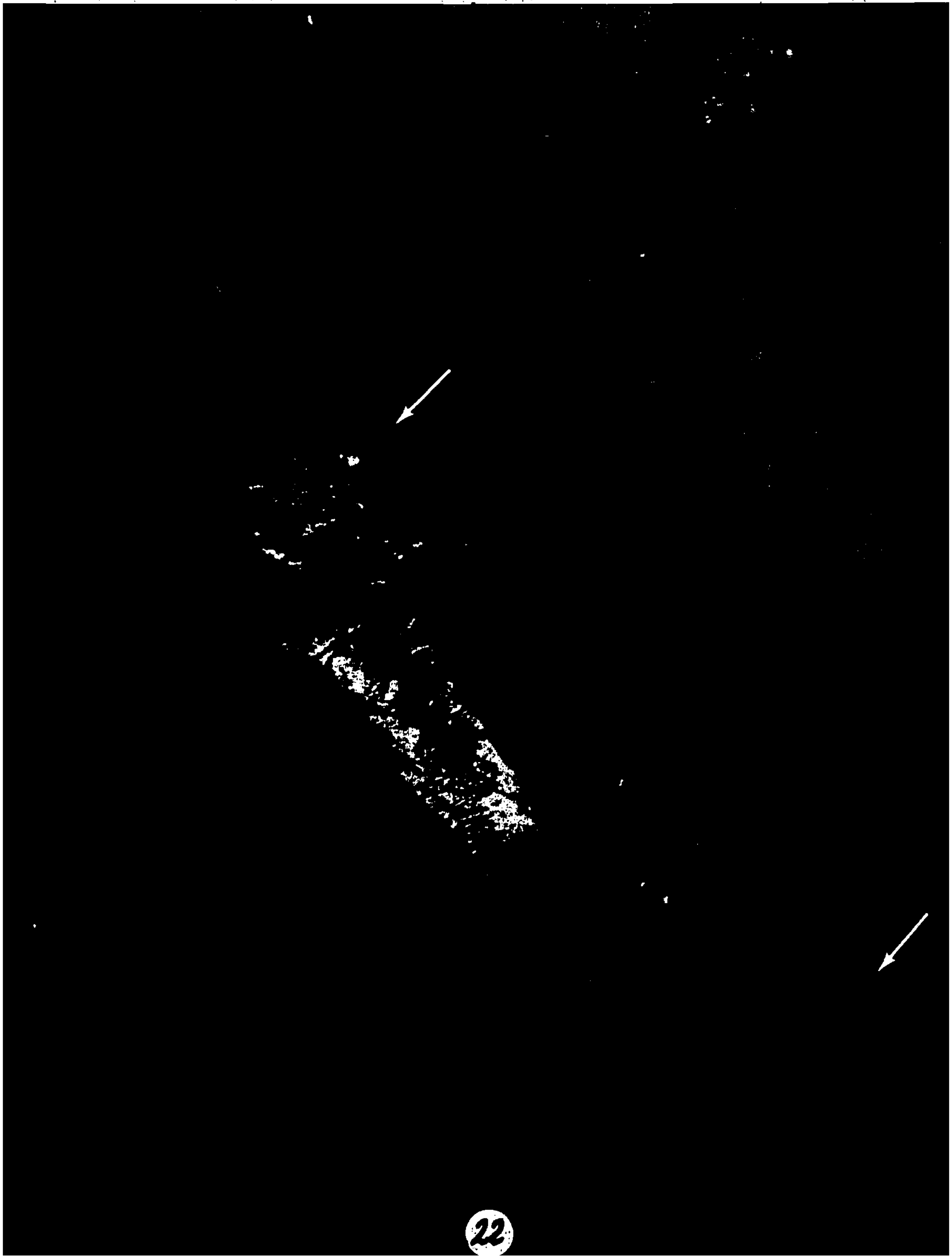


(a) Western Hemisphere



(b) Eastern Hemisphere.

**Figure 2.6** The southern part of the Levantine Rift, extending from the Dead Sea to the Sea of Galilee, is distinguished by the linearity of the Jordan River valley (arrow). To the north, a "fan-shaped" complex system of curved faults characterizes the rift. One prominent fault parallels the Syrian coast and then makes a noticeable bend to the northwest (arrow) towards Turkey.



together like pieces of a jigsaw puzzle. The theory of "continental drift" or "plate tectonics" is a complicated subject.[1] Geologists are looking for more evidence for the theory on MA-136 photographs.

A more rapidly changing feature, the delta of the Nile River, is shown in Figure 2.7. The Nile River flows northward from Egypt into the Mediterranean Sea. Mud from the Nile has slowly formed the delta, and the fresh water of the Nile can be seen in Figure 2.7 mixing with the saltier water of the Mediterranean offshore. The delta of the Orinoco River in Venezuela is shown in Figure 2.8. Muddy river water can be traced for hundreds of kilometers out into the Caribbean Sea and the Atlantic Ocean.

The colors of desert sands, such as those shown in the photograph in Figure 2.9, provide important information about the ages of these sands and the advance of deserts across the countryside. The bright-yellow sand is younger than the red sand. The sharp line to the left of the center of the photograph shows where the yellow sand is moving across the red sand as it is blown westward by winds. Differences between this Apollo-Soyuz photograph and Skylab photographs taken in 1973 will show the rate of advance. The changing pattern of the sand dunes is also being studied.

Photographs of Lake Chad, at the southern edge of the Sahara, show the sand moving in toward the lake. This advance of the desert may dry up Lake Chad and deprive the local inhabitants of water to drink and fish to catch. Other deserts were photographed in Australia and Argentina.

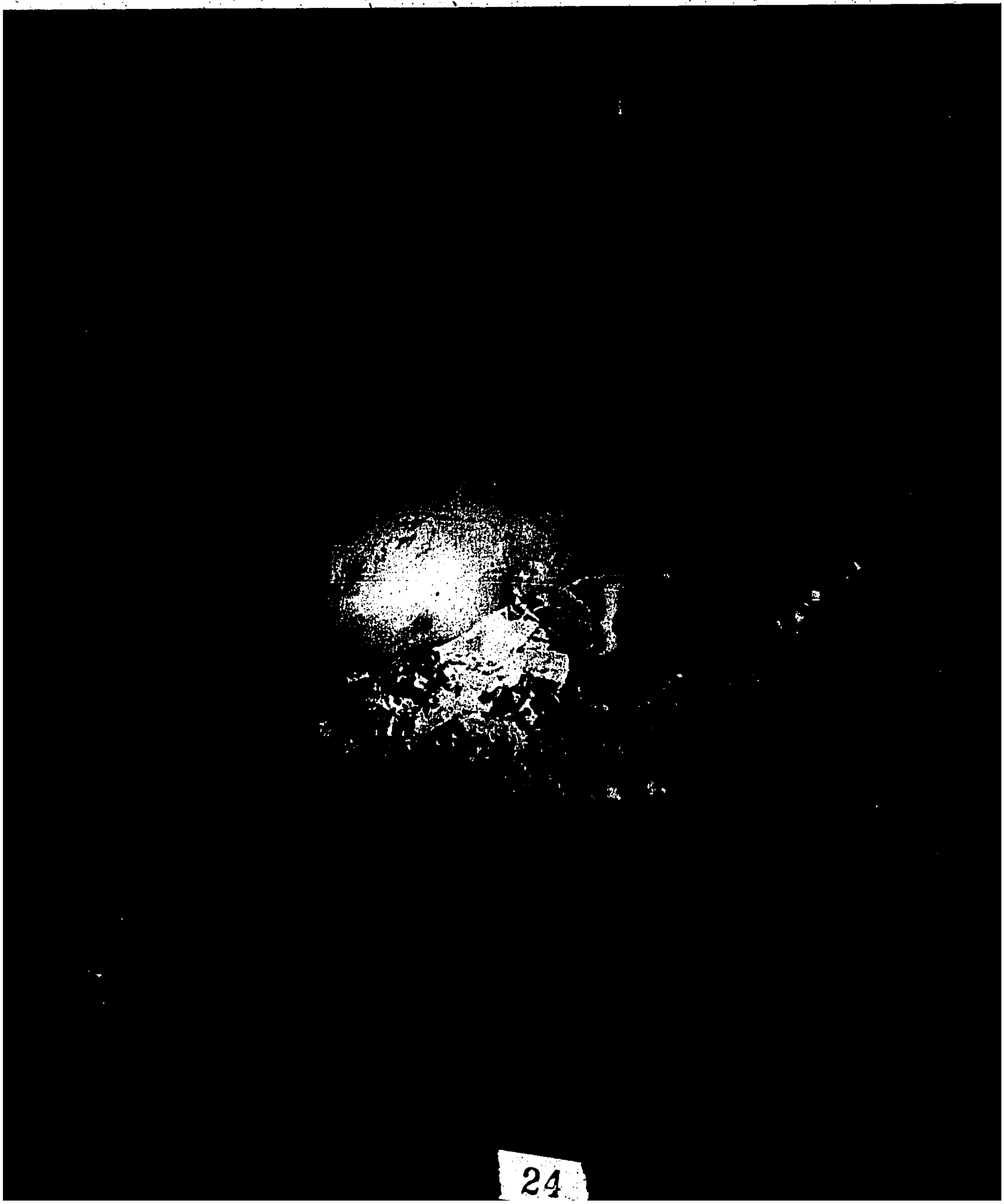
A view of western Spain, including the Strait of Gibraltar, is shown in Figure 2.10, which was photographed when the astronauts saw a series of waves about 60 kilometers long in the otherwise clear blue Atlantic Ocean. These waves are not on the surface but are deep in the water below. They may have formed because of variations in the salinity (saltiness) of the water caused by saltier water pouring out of the Mediterranean Sea through the Strait. The waves were glimpsed only for a moment when the lighting ("Sun glitter") was just right. They could be seen then because light is refracted more by the saltier water.

Several of the mapping runs (Fig. 2.5) covered areas that had not been accurately mapped before. One photograph revealed an ancient meteor crater in Brazil. Others showed snow conditions in the Cascade Mountains and glaciers in other parts of the world. Two tropical storms in the Caribbean Sea and off the coast of Florida and many cloud patterns over land and sea were photographed. One peculiar set of cloud strips is shown in Figure 2.11. No

---

[1] ESCP, Secs. 11-11, 11-12. (Throughout this pamphlet, references will be given to key topics covered in these three standard textbooks: "Investigating the Earth" (ESCP), Houghton Mifflin Company, 1973; "Physical Science Study Committee" (PSSC), fourth edition, D. C. Heath, 1976; and "Project Physics," second edition, Holt, Rinehart and Winston, 1975.)

**Figure 2.7** The Nile Delta is an excellent example of a triangular-shaped delta. Patterns of surface texture and boundary layers in the water are easily seen in the Sun's reflection. They possibly result from a density difference between the freshwater from the Nile and the saltier water of the Mediterranean Sea. Compare this photograph with a map of Egypt.



The deep-brown color of the Orinoco River outflow is caused by both sediments (mud) and rotting plant material. This turbid water was observed by the crew as far north as the island of Barbados.

**Figure 2.8**

**Figure 2.9** There is a color gradient in this downward view of the Simpson Desert in Australia. The long, thin, linear dunes of sand were described by the Apollo crew as "hundreds of parallel road tracks." Such dunes form in bare, sandy areas where the winds come predominantly from one direction. The lines of dunes are perpendicular to this direction.

The direction of sunlight in this photograph has made internal waves visible (lower left). Located off the western coast of Spain, the waves were approximately 50 to 60 kilometers long and were probably caused by variations in salinity.

Figure 2.10

Figure 2.11 Cloud strips off the coast of California.

one understands how they were formed. They are too large to be airplane contrails (streaks of condensed water vapor left behind airplanes flying through humid air), many of which were observed over the Atlantic Ocean.

E

## Questions for Discussion

(Optics, Earth Features, Continental Drift)

1. The normal human eye can resolve[2] (separate) two objects 0.02° apart; that is, you can see separately two lines 0.03 millimeter apart on a paper that is 10 centimeters from your eyes. How far apart would two rivers have to be for the astronauts to see them separately from 220 kilometers altitude? How close could the rivers be if the astronaut used his monocular to see them separately?

2. Apollo-Soyuz had an orbital speed of 7.4 km/sec. The Hasselblad mapping camera with a 100-millimeter lens had a field of view of 38°. To obtain a 60-percent overlap of successive photographs, what interval between exposures would be necessary? If the 60-millimeter lens were used, would the interval be shorter or longer?

3. Which camera-lens combination would you use to get the best resolution of Earth features?

4. If you were an astronaut describing the view shown in Figure 2.6, what aspects would you emphasize? Remember that you are moving at 7.4 km/sec, so your view lasts only a minute or two.

5. A ground-truth team is being sent to the desert shown in Figure 2.9. What measurements would you ask them to make?

6. The American continents are drifting away from Europe and Africa at a rate of about 2 cm/yr. How long ago were they together? (Geologists call the original landmass—North and South America, Europe, Africa, Asia, and Australia—"Pangaea." The southern portion was "Gondwanaland.")

---

[2] PSSC, Sec. 8-8.

# 3 Aerosols That Affect Climate and Weather on Earth

Aerosols are small droplets and dust particles suspended in the air. They are carried to altitudes of 20 to 30 kilometers by winds and atmospheric circulation. Their absorption and scattering of sunlight affects the climate and (at low altitudes) the weather. Experiment MA-007, Stratospheric Aerosol Measurement, used three methods to measure the size, type, and amount of aerosols at high altitudes: (1) counts of particles by microscope detectors carried in a high-altitude balloon, (2) measurements of light scattered back from laser pulses directed up through the atmosphere, and (3) measurements of the Sun's brightness as it rose or set, as seen from Apollo-Soyuz. The first two ground-based methods covered altitudes up to 25 to 30 kilometers at about the same time and in the same area that Apollo-Soyuz observations were being made at altitudes up to 45 to 50 kilometers. The experiment demonstrated that the spacecraft technique is accurate and that it will be useful for determining the amount of aerosols at high altitudes. (Aerosol spray cans produce the same kind of droplets as those detected in Experiment MA-007. It is *not* these *droplets* however, that may reduce the ozone layer; it is the *Freon gas* used in the spray cans. This gas slowly rises through the atmosphere, and some scientists fear that its fluorine and chlorine may cause chemical reactions in the ozone layer. See Figure 4.1.)

A

## The Balloon-Borne Dust-Particle Counter

Balloon flights are made regularly from a U.S. Air Force base near Kansas City, Missouri. One flight was scheduled at the same time that aerosol observations were being made from Apollo at sunset at 01:38 Greenwich mean time (GMT) over Kansas City on July 22, 1975. A cutaway drawing of the particle counter carried on these balloon flights is shown in Figure 3.1. A stream of outside air is pumped through a concentrated light beam, and two microscopes are focused on this point. When an aerosol droplet or dust particle passes through, a bright flash is recorded in each microscope by a photomultiplier at the eye end of the microscope. If both photomultipliers give an electric pulse at the same instant, a "count" is recorded by the electronic circuit. This mechanism is a "coincidence counter" (see Pamphlet II); it uses two detectors to eliminate false counts. (A false count could be recorded by one detector if a cosmic ray passed through the photomultiplier. Another check of false "background" counts was made by filtering the airstream for short intervals every 15 minutes. During these intervals, there should have been *no* counts, and there were none except at very low altitudes.)

The pulse size of the photomultipliers shows how large the droplet or dust particle is simply because a larger particle reflects more light. The electronics were arranged to separately record the particles of 0.3- to 0.5-micrometer diameter (small pulses) and the large particles (large pulses). (One micrometer is only 0.00004 inch.) The particle counts were radioed to the ground, together with the temperature and pressure at each altitude, and were recorded as a function of time. These records show high concentrations of aerosols up to 5 kilometers (16 000 feet), then a sharp drop to about 1 particle/cm$^3$. There was a maximum of about 60 particles/cm$^3$ at 18 kilometers altitude. Above 25 kilometers, the particle count was back down to 1 or 2 particles/cm$^3$ (see dashed line in Fig. 3.2).

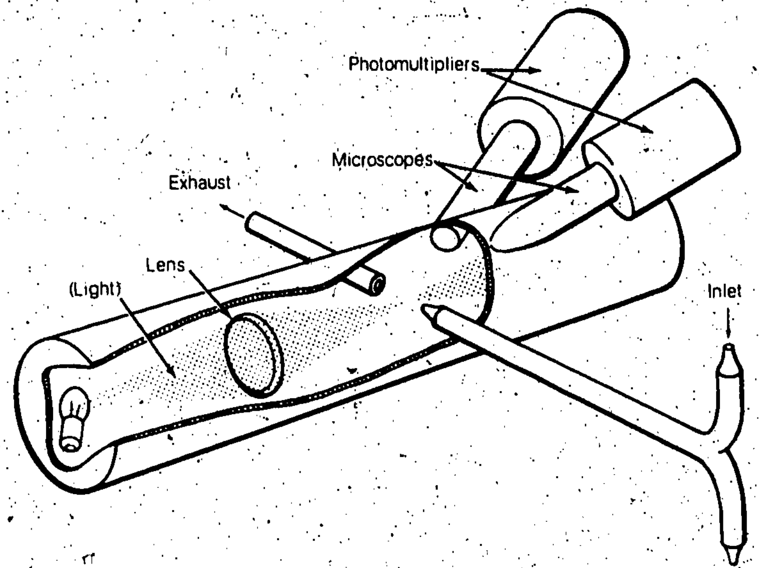


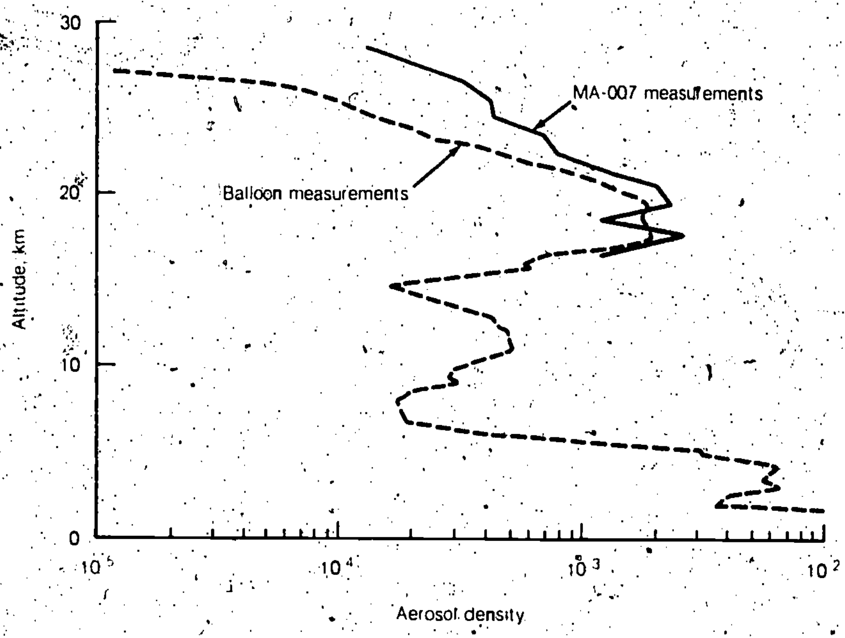
**Figure 3.1** **Schematic drawing of the University of Wyoming dust-particle counter used for ground-truth measurements.**

## B The Laser-Pulse Radar

The "lidar" shown in Figure 3.3 is a 122-centimeter (48-inch) telescope loaned by the NASA Langley Research Center for the MA-007 Experiment. A powerful laser is mounted at the telescope focus and gives extremely short pulses of 30 nanoseconds' duration. A flash of light leaves the telescope, travels up through the nighttime atmosphere, and is scattered back toward the

Earth by dust and aerosols. The scattered light is collected by another telescope and focused on a sensitive detector. The velocity of light is known; therefore, the altitude of the dust and aerosols can be calculated from the round-trip time (160 microseconds for an altitude of 24 kilometers). The difference in color (wavelength) between the scattered light and the laser light is also recorded; it is used to obtain information about the particles, such as size and refractive index.

The lidar was set up at the U.S. Air Force base near Kansas City and used the night before and the night after the observations from Apollo-Soyuz were made. On July 22, the lidar recorded some cirrus clouds at 13 kilometers altitude, as well as aerosols around 20 kilometers. On July 23, there were no high clouds, and the aerosols again were detected at 20 kilometers.



**Aerosol density versus altitude over Kansas City on July 22, 1975. Figure 3.2**

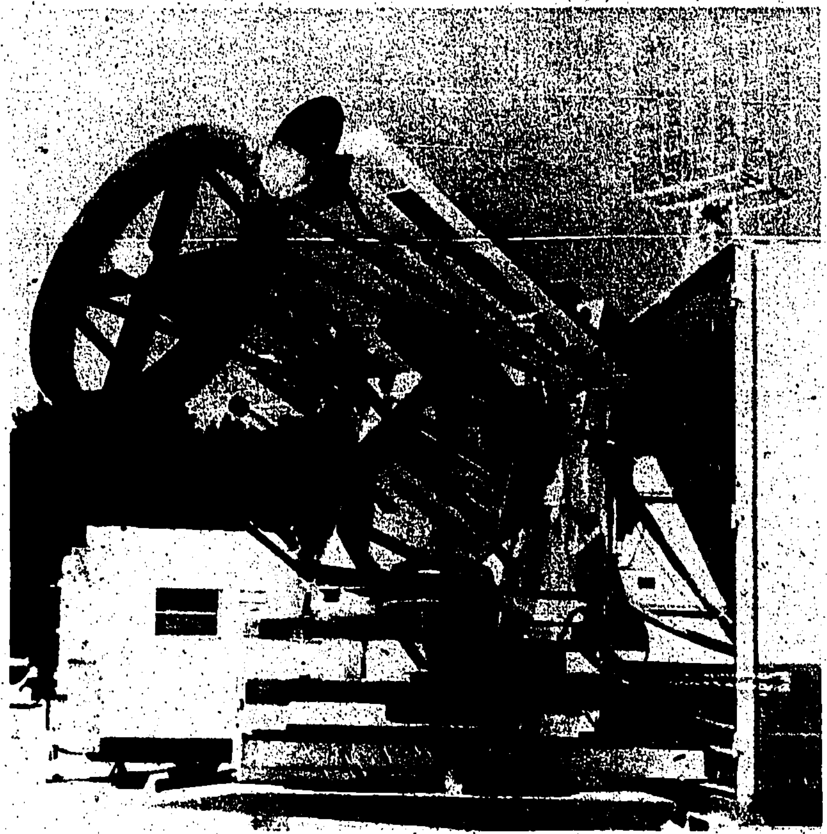
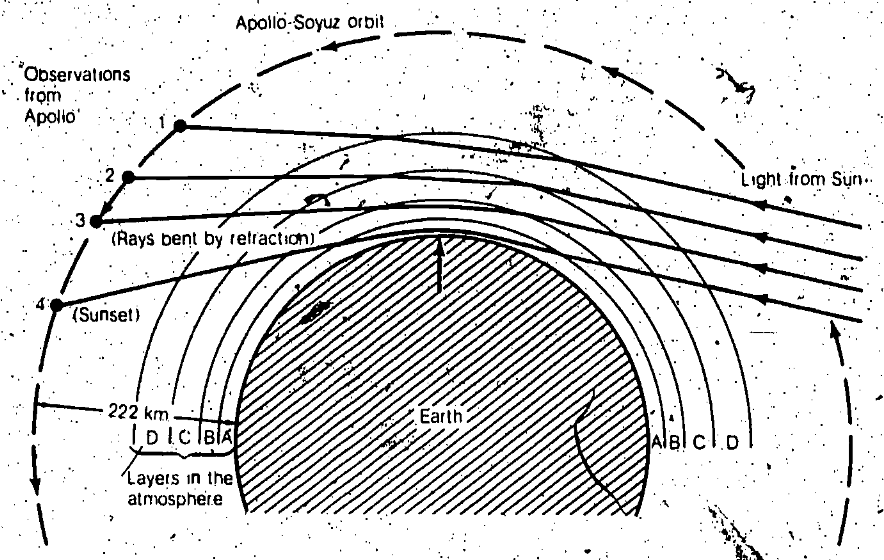


**Figure 3.3** The NASA Langley Research Center 122-centimeter lidar system. It can be used to measure distances to clouds, balloons, and airplanes, as well as to aerosols.

## C MA-007 Measurements and Photographs From Apollo

When light passes through the atmosphere, some of it is absorbed and scattered by aerosols and some of it is scattered by the air molecules to give the blue light of the sky. The atmosphere also bends rays of light, as shown in Figure 3.4. This bending ("refraction") is caused by the increase in air density at lower altitudes. The light travels slightly slower in the denser air and its direction is changed, much like the way a car veers to the right when its



**Schematic diagram of MA-007 sunset observations. (The layers of the atmosphere and the Apollo-Soyuz orbit are exaggerated for clarity.)** **Figure 3.4**

right wheels get into soft mud beside the road and its left wheels are still on smooth pavement. Light from the setting Sun is thus bent downward like the ray to point 4 in Figure 3.4, and the Sun looks higher in the sky than it really is. This refraction by the atmosphere is similar to refraction by a glass prism. The dense air low in the atmosphere is like the thick end of the prism. It slows the light more than does the less dense air at higher altitudes, which corresponds to the thin end of the prism. Just before sunset, the light reaching Apollo at point 4 passed through air in layer A very close to the Earth's surface, as shown by the arrow. This light was affected by aerosols at low altitude. Earlier, light passed through higher altitude air to reach point 3. The MA-007 Experiment used measurements of the Sun's brightness for 1.5 minutes before sunset to estimate the amount of aerosols in layers A, B, C, D, and so on. Of course, the sunlight received at point 4 passed through layers B, C, and D as well as layer A, so the calculation is complicated.

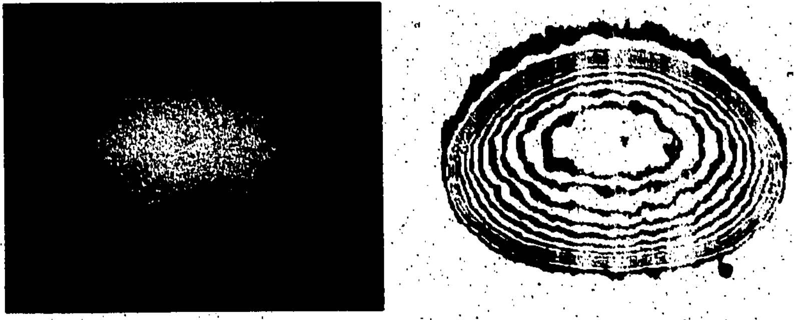
The refraction of the sunlight (bending toward Earth in Fig. 3.4) depends on the change of air density with altitude. The MA-007 scientists measured the refraction on photographs of the Sun taken with the Hasselblad 70-millimeter camera (Sec. 2A) using the 250-millimeter lens, an infrared filter, and special infrared film that recorded light of 8400-angstrom (840-nanometer) wavelength. This gave a sharper photograph than ordinary visible light would have because much of the light scattered by aerosols was filtered out. Figures 3.5(a) and 3.5(b) show one of these photographs and the contours of brightness measured on it. The Sun near the horizon appears to be flattened because the rays near the horizon (from the bottom of the Sun) are refracted more than the rays farther up (from the top of the Sun). This makes the bottom *seem* farther up, as shown by the ray to point 4 in Figure 3.4. Figure 3.5(c) shows the apparent shape of the Sun expected from refraction; it matches Figure 3.5(b) well. Figure 3.6 shows the apparently changing shape of the Sun in the last 15 seconds before sunset. (The Sun set much more quickly as seen from Apollo than as seen from the ground because the spacecraft had a "day" of only 93 minutes instead of our 24 hours.)

The Sun's changing brightness was measured for 1.5 minutes before sunset with the MA-007 photometer shown in Figure 3.7. This instrument was aimed at the Sun through a window in the Apollo Command Module (CM) cabin. It was a pinhole camera with a filtered phototube that recorded the intensity of 8400-angstrom light from a 10° field of view. The Sun is only 0.5° in diameter, so the spacecraft did not have to be pointed very accurately. The astronauts could check the pointing by the shadow of a pin on a white circle (top of Fig. 3.7).

The photometer's 1.5-minute record of changing Sun brightness was radioed to the ground and later converted to curves of aerosol density versus altitude. The curve for sunset over Kansas City is shown in Figure 3.2, where the dashed line shows the balloon measurements. The agreement is good from 17 to 23 kilometers altitude. The MA-007 Experiment shows more aerosols at higher altitudes.

One of the Soviet experiments on Apollo-Soyuz was very similar to the MA-007 photography. As mentioned in Pamphlet I, the cosmonauts performed six experiments on their own in addition to the five joint experiments. One of the joint experiments was the Artificial Solar Eclipse (MA-148; see Pamphlet III) for which Apollo blocked (eclipsed) the Sun as seen from Soyuz. The cosmonauts later used the camera from that experiment to photograph the setting Sun and the stars seen near the Sun. By measuring the Sun's shape and the distances between the stars in the sky, the refraction at different altitudes was obtained. In this way, the air density at various altitudes was determined. The U.S.S.R. has not yet released the results of these experiments. In another experiment, the cosmonauts continued photography after sunset to measure the zodiacal light (Pamphlet III), and they photographed the horizon in other directions to detect "airglow." (You can see the airglow as a blue haze above the horizon at the top of Figure 2.1 and on the photograph on the cover.)

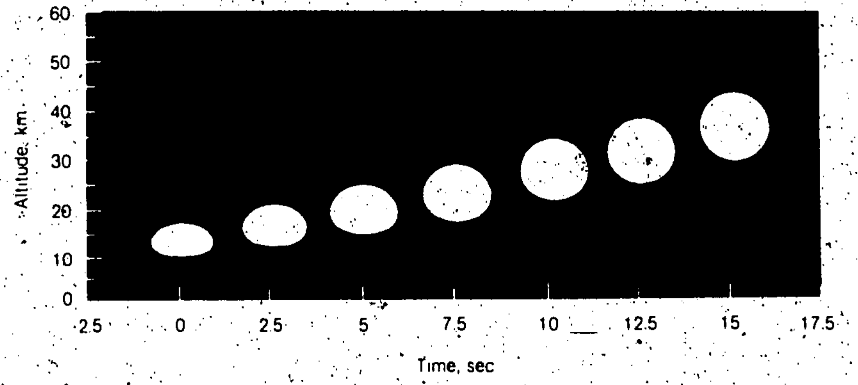
Images of the Sun. **Figure 3.5**



**(a) Photograph of the Sun near the horizon.**

**(b) Contours of image brightness in (a).**

**(c) Expected shape of the Sun's image due to refraction.**



**The shape of the setting Sun appears to change because of refraction by the atmosphere.** **Figure 3.6**

**Figure 3.7** The photometer used for making stratospheric aerosol measurements for Experiment MA-007.

## D Results of MA-007 Measurements

The Stratospheric Aerosol Measurement Experiment on Apollo-Soyuz showed that a fairly simple 7-kilogram instrument (the photometer shown in Fig. 3.7) can check high-altitude aerosol densities in short observation times before sunset and after sunrise on Earth-orbiting spacecraft. In addition to the sunset over Kansas City, one other sunset off the coast of New Jersey and two sunrises, one northwest of Australia and the other over the Indian Ocean, were observed. The two sunrise observations showed 30-percent fewer high-altitude aerosols in the Southern Hemisphere than in the Northern Hemisphere.

Why should aerosol densities be so different in the two hemispheres? Scientists attribute the difference to a volcano that erupted in Guatemala during October 1974, 9 months before the Apollo-Soyuz mission. During the northern winter, there is a general northward movement of the atmosphere which, in this case, carried the volcanic dust and droplets at least 2400 kilometers (1500 miles) north to Missouri and New Jersey. Later, during the southern winter (northern summer), the aerosols probably moved southward.

Combining the balloon data on droplet or particle size, the lidar data on the color of backscattered light, and the Apollo MA-007 data on altitude gives an estimated 1.43 for the index of refraction of the aerosol droplets. (This refraction is not in the atmosphere but in the droplet.) The MA-007 scientists note that this somewhat uncertain number is consistent with the droplets being sulfuric acid (75-percent $H_2SO_4$ and 25-percent $H_2O$), which possibly resulted from the release of hydrogen sulfide ($H_2S$) and sulfur dioxide ($SO_2$) from the volcano and the subsequent combining of these compounds with oxygen and water in the atmosphere.

## E Questions for Discussion

(Climate, Radar, Optics)

7. If the aerosol particles in the entire atmosphere were increased by a factor of 10, how would you expect the climate on Earth to be affected?

8. In order to plot the number of aerosol particles per cubic centimeter versus the altitude in kilometers, what do you need to know in addition to the balloon-borne dust-particle counts?

9. With its 30-nanosecond pulses, how accurate can the lidar measurement of aerosol *altitude* be?

10. In the atmosphere, different wavelengths are refracted by different amounts (Fig. 3.4). How would this change photographs of the setting Sun in *white* light (such as Fig. 3.5(a))?

11. How large was the image of the Sun on the original 70-millimeter film in the Hasselblad camera with the 250-millimeter lens?

12. Two successive sunsets from Apollo-Soyuz were 93 minutes apart in time. If the first was over Kansas City (95° W longitude), at what longitude would you expect the second?

# 4 Oxygen and Nitrogen in the Outer Atmosphere

At 222 kilometers altitude, Apollo and Soyuz were almost outside the Earth's atmosphere. There is a very low density gas there, mostly hydrogen, helium, oxygen, and nitrogen. To verify their theoretical "models" of the atmosphere (how it becomes less dense with altitude), scientists need measured densities. These measurements were provided by Apollo-Soyuz Experiment MA-059, Ultraviolet Absorption.

## A Layers in the Atmosphere

The results of many years of exploring the atmosphere are shown in Figure 4.1. The heavy line is a plot of temperature (bottom scale) versus altitude (left scale). The scale on the right gives the gas pressure in millibars (mbar), starting at 1000 millibars, which is equal to 1 atmosphere or 100 kN/m$^2$ at the Earth's surface. The terms in the figure are used by scientists to describe the layers of the atmosphere, which can be thought of as "onionskins," each completely enclosing the one below. In some parts of the world, such as the polar regions, the lower layers of the atmosphere are less dense. The temperature curve in Figure 4.1 is a rough average near the Earth's surface where the "troposphere" is changing all the time because of weather (winds, rain, clouds, and storms).

At about 15 kilometers altitude, the atmosphere "calms down," and the layers above are more stable and predictable. Above this "tropopause," the temperature starts to rise because much of the Sun's radiation is absorbed in the layers between 20 and 60 kilometers altitude. In these layers, the composition of the air is changed, as the absorbed sunlight breaks up oxygen molecules ($O_2$) into oxygen atoms (O). Some of the atoms combine with $O_2$ molecules to form ozone ($O_3$), which peaks near the top of the ozone layer shown in Figure 4.1. There is only a very small amount of ozone in that layer (about 13 millionths of all the other gases in the ozone layer), but it absorbs *all* the Sun's ultraviolet light of wavelength shorter than 3000 angstroms (300 nanometers).

In the ionosphere, pressure and density are so low that much of the gas remains ionized. (Atoms or molecules lose an electron after absorbing ultraviolet sunlight.) The ionosphere was first detected more than 50 years ago with early radar sets that "bounced" radio waves off the ions. Scientists calculated the height of the ionosphere by knowing the speed of the radio waves and measuring the time for the echo to return. Later, they found that there are ionized layers at different heights, and they lettered them D, E, and F.

Above the "stratopause," the temperature starts dropping because the gas pressure and density are so low that very little sunlight is absorbed to heat the

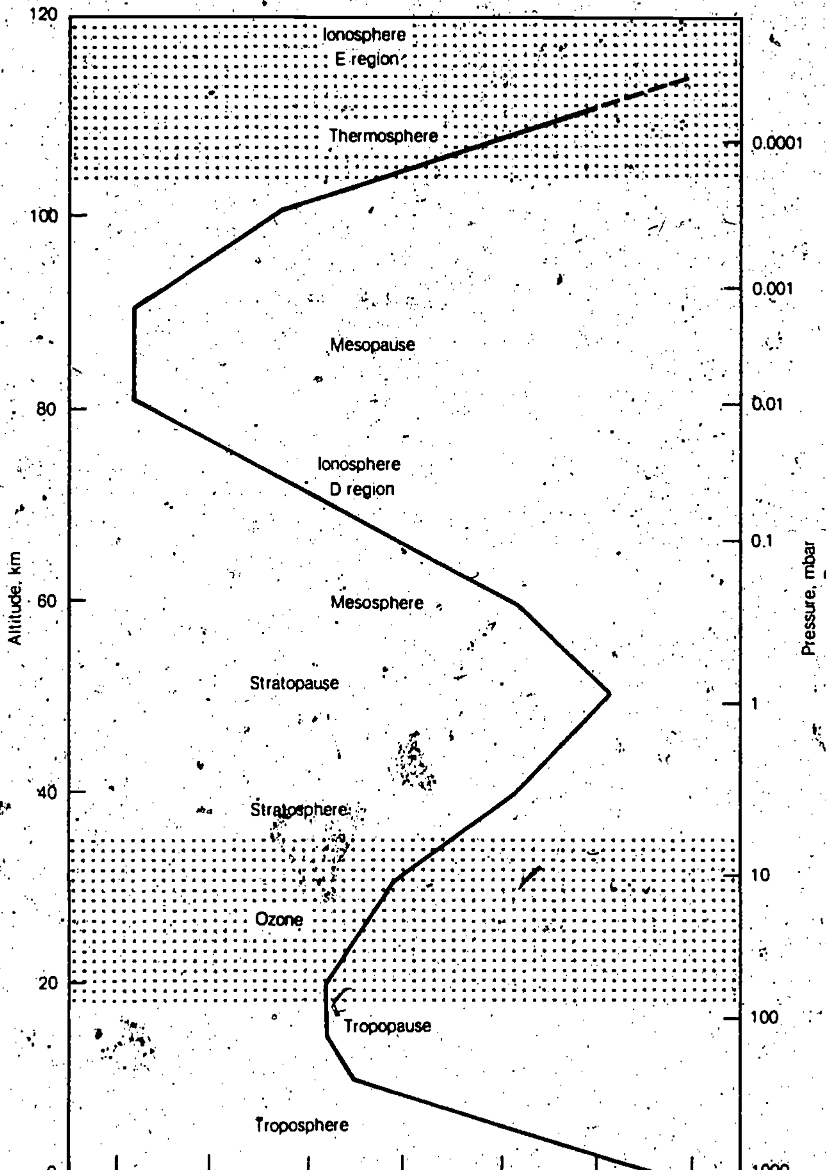


**Figure 4.1** Temperature and pressure versus altitude in the atmosphere and the names of the various layers of the atmosphere.

gas. However, the temperature starts rising again above the "mesopause" at about 90 kilometers altitude. This outer, very low density layer is called the thermosphere because it is very hot, as measured by the average velocities of atoms and molecules. At the altitude of Apollo-Soyuz (222 kilometers), the gas temperature is about 780 K (507° C). Information about the ionosphere above 120 kilometers comes mostly from spacecraft and rocket measurements. The pressure and the density keep falling, which causes the temperature to rise, and the composition changes (relatively more hydrogen and helium—see Pamphlet III). The outermost layer, called the geocorona, is mostly hydrogen and extends outward 50 000 kilometers, where it merges with the very low density hydrogen and helium between the planets. In the low-density regions, information about composition can be obtained by observing the light emitted or absorbed by the gas, as revealed by absorption and emission lines in the spectrum.

## B Spectrum Lines of Atomic Oxygen and Nitrogen

Gases can emit various colors of light, and this property is used in neon signs for advertising. Pure neon radiates a characteristic red light when excited by a discharge in a sealed glass tube, and other gases at low pressure emit other colors. A spectroscope shows "emission lines" in the spectrum (see Pamphlets II and III); that is, the intensity is strong in a number of narrow bands of wavelength (color), and the pattern of bright lines is characteristic of the emitting gas. When light from a distant source passes through the same gas, most of the same wavelengths are absorbed by the gas, leaving gaps, or "absorption lines," in the same pattern.[3] The more gas there is along the line of sight, the darker the absorption lines. Scientists measure these lines with a spectrometer, which separates the different wavelengths $\lambda$ and measures the intensity $I_\lambda$ at each wavelength. Astronomers use the measured wavelengths of spectrum lines to identify gases in interstellar space and to estimate the amount of each gas in terms of the numbers of atoms or molecules along the line of sight.

---

[3] Project Physics, Secs. 19.1, 19.7, 19.8; PSSC, Secs. 26-2 to 26-5.

The spectrum lines[4] (both emission and absorption) were explained by quantum theory in terms of electrons in orbit around the nucleus of an atom. Each orbit has a different energy. According to quantum theory, only certain specific orbits are "permitted," with energies $E_1$, $E_2$, $E_3$, and so on. These "energy levels" are different for each kind of atom. The spectrum lines come from "electron jumps" between energy levels, downward for emission lines and upward for absorption lines. In a downward jump, the atom emits a photon. If the electron jumps from $E_2$ to $E_1$, the photon has energy $E_2 - E_1 = hf = hc/\lambda$, where $h$ is the Planck constant, $f$ is the photon frequency, and $c$ is the velocity of light. So, all the jumps from $E_2$ to $E_1$ give photons of the same wavelength $\lambda$. Different kinds of atoms have different $E_1$, $E_2$, $E_3$, and so on and thus emit photons of different wavelengths. This pattern of wavelengths in the spectrum is often called the "fingerprint of the atom" because it is unique to one kind of atom.

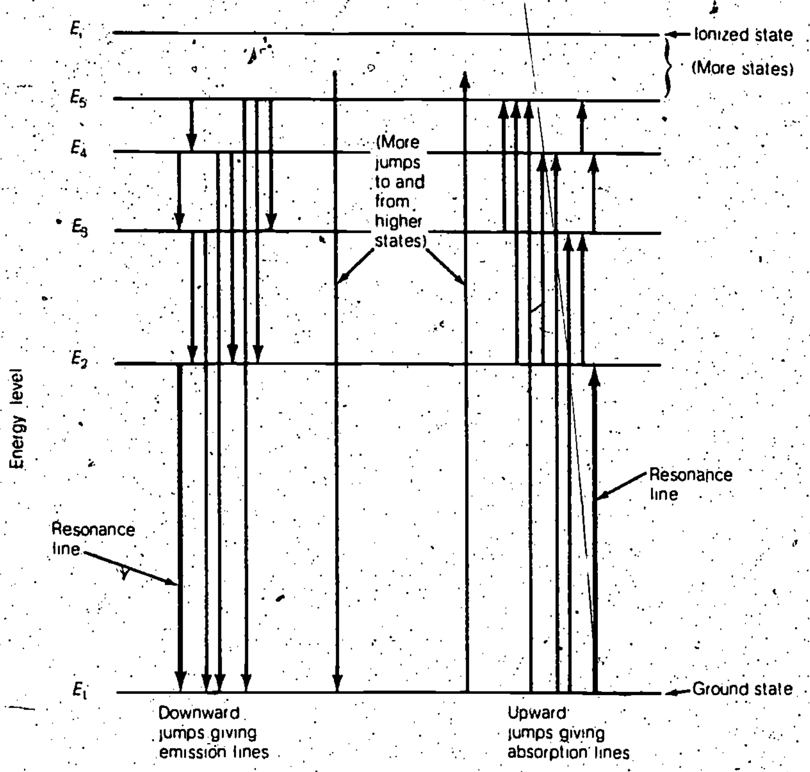
The pattern of absorption lines is the same "fingerprint" because that one kind of atom absorbs photons of energy $E_2 - E_1$ when it jumps from $E_1$ to $E_2$ and photons of energy $E_3 - E_1$ when it jumps from $E_1$ to $E_3$. These are the *same* energy differences—photon wavelengths—as for the emission lines. Thus, the fingerprint of the atom is the same in absorption lines as in emission lines, with a few exceptions as noted below. Figure 4.2 is a diagram of energy levels with the downward (emission) and upward (absorption) jumps marked with arrows. For most atoms, the energy levels must be arranged in columns (not shown in Fig. 4.2), and there are "selection rules" about which jumps are most probable between levels in the various columns.

The lowest energy level, $E_1$, is called the "ground state," and each atom prefers to be in that state. If an atom absorbs a photon or is joggled into a higher energy level by high temperature or by collision, it can emit a photon and return to $E_1$ almost instantaneously. In the cold dark of interstellar space, most atoms are in the $E_1$ level, so the jump from $E_1$ to $E_2$ (which occurs when a photon is absorbed, thereby removing it from the light beam) gives a strong absorption line, called the *resonance line* for that atom. The same wavelength will be emitted later because the atom "prefers" to be in the lowest energy ground state. This reemission or "resonance scattering" does not "fill in" the absorption line because the emitted photons go off in all different directions, not just along the light beam from which photons were first absorbed.

In the laboratory, physicists have measured the probabilities for absorption or emission of a photon by each kind of atom and the probability for each energy jump. If 100 atoms are in the level $E_3$ in Figure 4.2, the physicists

---

[4] PSSC, Secs. 34-2, 34-3.



**Schematic diagram of energy levels in one kind of atom and jumps giving spectrum lines. (The larger jumps correspond to shorter wavelengths.)** **Figure 4.2**

know that 20 of them will jump to $E_2$ and 80 to $E_1$, in less than a microsecond. If 100 atoms are in level $E_1$ with many photons passing them (in strong sunlight, for instance), 70 will jump to $E_2$, 20 to $E_3$, 5 to $E_4$, and 5 to other higher levels. (These numbers are cited for illustration only. In actuality, there are many billions of atoms, and the jump probability is not an even percentage like 80 percent. The point is that these probability numbers are *known* for most kinds of atoms and the resonance lines are the most probable lines for each kind of atom.) Therefore, one can calculate from the intensity of the $E_2 - E_1$ emission-line strength how many atoms in the line of sight were in the $E_2$ level. The $E_1 - E_2$ absorption line will give the number of atoms in the line of sight that were in the $E_1$ ground state.

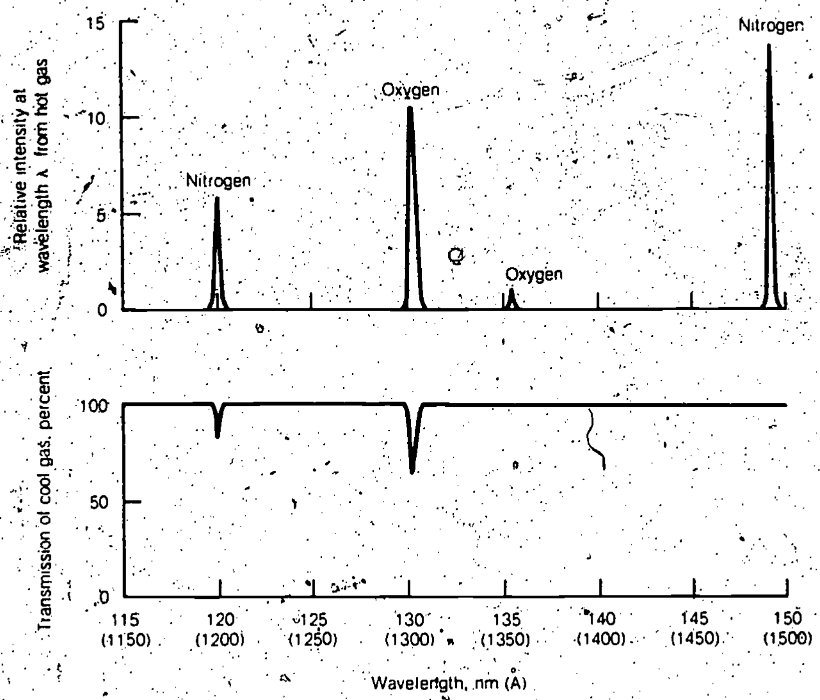
A complete and accurate diagram of energy levels for an atom like oxygen is more complicated than the one shown in Figure 4.2. Some 80 years ago, physicists found that some energy jumps did not take place, and they called these jumps "forbidden transitions." When the energy levels were plotted in separate columns, it was possible to make "selection rules" stating which transitions were "permitted" and which were "forbidden," all keyed to a set of three quantum numbers associated with each energy level. Then astronomers found some of the "forbidden lines" in the spectra of nebulae—vast clouds of low-density, glowing gas between the stars. They are still called "forbidden lines," although the quantum theory now shows that a "forbidden jump" from level $E_f$ to $E_1$ is not really impossible but just very improbable. The atom waits for a second or two in level $E_f$ before jumping to $E_1$. Under most conditions, the atom is bombarded many millions of times during a second and gets joggled out of $E_f$ before the forbidden jump can take place. That is why 19th-century physicists never observed forbidden lines in their laboratories.

In very low density gas near the top of the Earth's atmosphere and in nebulae between the stars, an atom may not be jostled out of level $E_f$ before jumping to $E_1$ and emitting the forbidden line. The aurora (northern lights) and nebulae mostly glow in forbidden lines of oxygen. The atoms of oxygen are raised to the energy level $E_f$ by solar-wind bombardment, and the oxygen ions ($O^{++}$) in nebulae get to their energy level $E_f$ by similar electron bombardment. The absorption of a forbidden line is possible but very improbable, so we do not expect forbidden absorption lines.

A resonance line of atomic oxygen at a wavelength of 1304 angstroms (130.4 nanometers) and a forbidden line of oxygen at 1356 angstroms (135.6 nanometers) are shown in Figure 4.3. Both lines are produced by a high-voltage radiofrequency oxygen lamp. However, when light passes through atomic-oxygen gas, only the 1304-angstrom line is absorbed. The same is true for nitrogen with the resonance line at 1200 angstroms (120 nanometers) and the forbidden line at 1493 angstroms (149.3 nanometers) (Fig. 4.3). A nitrogen lamp produces both lines but only the 1200-angstrom line is absorbed by nitrogen atoms. These wavelengths are short; they are in the far-ultraviolet part of the electromagnetic spectrum (see Pamphlets II and III).

## C Absorption by Oxygen and Nitrogen at 222 Kilometers Altitude

T. M. Donahue and his team planned the MA-059 Experiment to measure the absorption of 1304-angstrom light by oxygen atoms and 1200-angstrom light by nitrogen atoms between the Apollo and the Soyuz spacecraft. The basic idea was to shine light from an oxygen lamp and a nitrogen lamp toward



**Emission-line spectrum (top) and absorption lines (bottom).** **Figure 4.3**

Soyuz, where a mirror would reflect the light back. On Apollo, the intensity of the 1304-angstrom line was measured and compared with the source. The difference, after correction for mirror reflectivity, shows how much light was absorbed by oxygen atoms between Apollo and Soyuz. The same is true for the 1200-angstrom line of nitrogen. The mirror on Soyuz was a set of seven retroreflectors ("cat's-eyes"), each 3.3 centimeters wide. (These "cat's-eyes" are better than a plane mirror because they reflect light back in exactly the same direction from which it came.)

Light from the oxygen and nitrogen lamps was pointed at Soyuz as shown in Figure 4.4. Each lamp faced a concave mirror that reflected a parallel beam toward Soyuz. Part of the reflected beam returned between the two concave mirrors and was focused on the slit of a spectrometer at the left. All the MA-059 equipment was mounted on the side of the Docking Module (DM) facing away from the Apollo CM, and Apollo had to be pointed so that the

46

oxygen and nitrogen beams of light hit the retroreflector on Soyuz. This was done by placing a bright white (visible) light in a position similar to that of the oxygen lamp but above the plane of Figure 4.4. The astronauts could look out a window in the CM, past the DM, and see whether the bright white light was on the Soyuz retroreflector. If it was not, they corrected the CM-DM direction with the reaction-control jets.

The spectrometer (off the left side of Fig. 4.4) was designed to scan the four emission lines at 1200, 1304, 1356, and 1493 angstroms every 12 seconds. The intensities $I_\lambda$ were radioed to the Mission Control Center at the

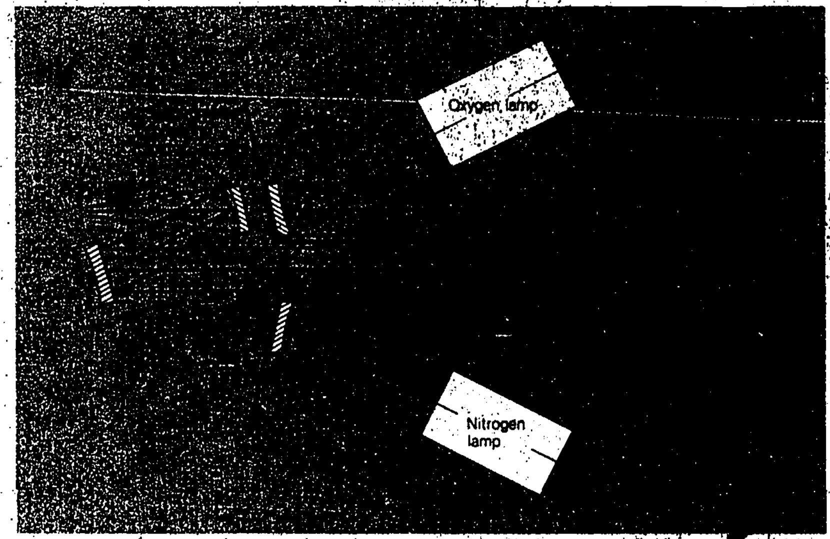


**Figure 4.4** Schematic diagram of MA-059 lamps and mirrors

NASA Lyndon B. Johnson Space Center (JSC) in Houston, [illegible]. Because the forbidden lines at 1356 and 1493 angstroms were not absorbed, their intensities checked the reflectivity of the retroreflector, which was normally about 0.8 percent.

One problem was Doppler shift (see Pamphlet IV). The Apollo and Soyuz spacecraft were moving at an orbital speed $v$ of 7.4 km/sec through the oxygen and nitrogen atoms. If the line of sight was along the velocity vector, the oxygen and nitrogen absorption would be shifted by $\Delta\lambda = \lambda v/c$, which would prevent oxygen and nitrogen absorption of the emission lines in the light from the oxygen and nitrogen lamps. Therefore, it was planned to move Apollo so that the beam of light to Soyuz was across (perpendicular to) the velocity vector. The easiest way to do this was to swing Apollo around the side of Soyuz, as shown in Figures 4.5 and 4.6. This was done three times: once at 150 meters separation, once at 500 meters separation, and once at 1000 meters separation. The idea was that the maximum absorption of the 1304- and 1200-angstrom lines would occur when the Apollo-Soyuz line of sight was at a 90° angle to the velocity vector v. At this angle, the reflected beam at 500 meters separation was expected to be reduced by 41 percent because of oxygen absorption and by 20 percent because of nitrogen absorption, assuming the densities $2 \times 10^9$ oxygen atoms/cm$^3$ and $2 \times 10^7$ nitrogen atoms/cm$^3$. If the absorptions were found to be more, then the densities would be higher.

Another problem was the *emission* of the resonance lines at 1304 and 1200 angstroms by oxygen and nitrogen atoms in the beam. This emission would fill in the absorption lines a little—a few percent if the Soyuz mirror (retroreflector) reflectivity was about 1 percent. If the Soyuz mirror were to get dirty (as it did, in fact), the direct emission-line intensity would be higher, compared to the absorption line in the beam reflected from a dirty mirror.

D

## MA-059 Oxygen and Nitrogen Density Measurements

On July 16, 1975, 27 hours after the Apollo-Soyuz mission started, the MA-059 equipment on Apollo was tested while the outside door (off the right side of Fig. 4.4) was closed. The door had small mirrors on the inside that reflected parts of the lamp beams back into the spectrometer. Scans showed that emission lines were of the correct intensity. After Apollo and Soyuz undocked (separated) on July 19, Apollo moved 18 meters ahead of Soyuz, and the cosmonauts uncovered (by remote control) the Soyuz retroreflectors. There were three retroreflectors—one facing up, one sideward, and one toward the back—and the astronauts in Apollo could see all three covers open.

During the next spacecraft night, the astronauts moved Apollo around the south side of Soyuz and spent 10 minutes in the 33° arc, 150 meters from Soyuz, as shown in Figure 4.5. The MA-059 lamps were on and the spectrometer was scanning, but the intensities of the 1200-, 1356-, and 1493-angstrom lines were all zero. The spectrometer was working satisfactorily; it detected the 1304-angstrom airglow emission of oxygen and checked out on

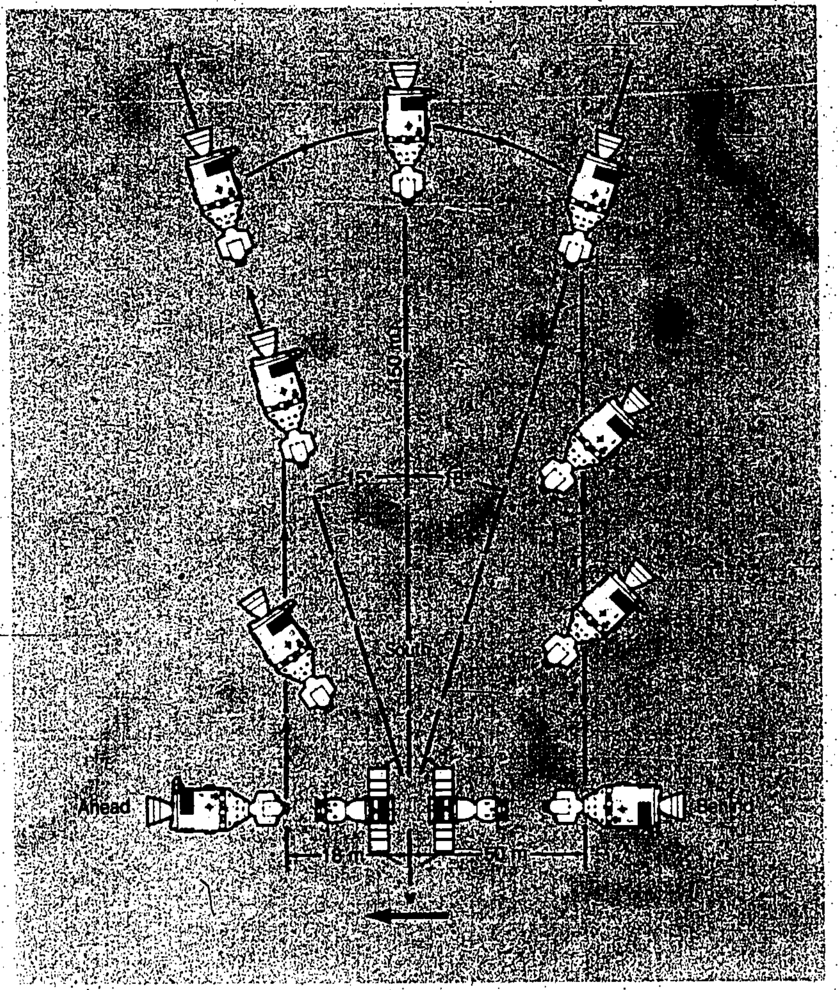


**Figure 4.5** Illustration of the MA-059 150-meter data take. The symbol v represents the velocity vector.

all four lamp emission lines after the door was closed. The scientists at the Mission Control Center at JSC in Houston thus concluded that the sideward retroreflector on Soyuz was too dirty to reflect far-ultraviolet light. (Dirt could have gotten on the retroreflector during launch or could have come from a nearby oil leak.) The scientists asked the cosmonauts to swing Soyuz

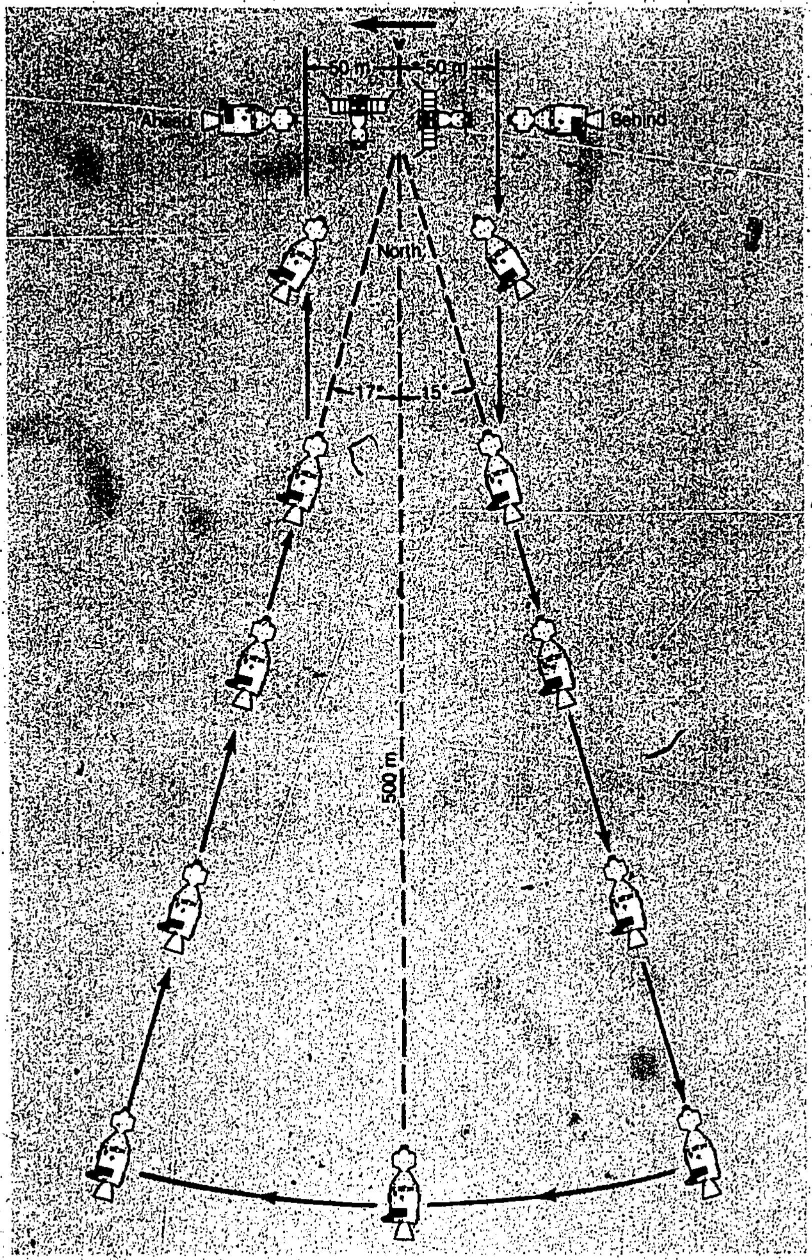


Illustration of the MA-059 500-meter data take; v is the velocity vector. Figure 4.6

around to use the aft retroreflector on the second try.

During the next spacecraft night, Apollo moved 500 meters north of Soyuz along the 32° arc shown in Figure 4.6, and this time the spectrometer scans showed all four emission lines during the 10 minutes that Apollo moved along that arc. However, after about 3 minutes, the intensities all dropped by a factor of 5, which indicated that the aft Soyuz retroreflector had just been dirtied. (Some oil probably leaked from Soyuz and spread across the face of the retroreflector.) When the MA-059 door was closed, the spectrometer scans were normal again.

The following spacecraft night, Apollo moved 800 meters above Soyuz and along the 30° arc to 1300 meters above (Fig. 4.7). From these larger distances, and in bright moonlight, the astronauts had difficulty keeping Apollo aimed at the Soyuz retroreflector, so only a few good spectrometer scans were made. Also, the calibration check with the MA-059 door closed showed that the lamp beam was low by a factor of 4.

Apollo left the vicinity of Soyuz and made a slow roll with the MA-059 Experiment still on. During this roll, the MA-059 beam was facing 90° from Apollo's orbital velocity vector v, but at first the beam was on the forward side (Fig. 4.8(a)), where the oxygen and nitrogen atoms were hitting the spacecraft at 7.4 km/sec. Later the beam was moved around to the back side (Fig. 4.8(b)). As expected, the emission lines (1304 and 1200 angstroms) were more intense on the front side. The gas density was about 10 times higher on the "ram side" than in the "wake" of the DM.

After correcting as best they could for the changing reflectivity and beam strength, the MA-059 scientists collected all the measurements of absorption at 500 meters separation and the emission-line intensities that had been measured at varying times. They concluded that the density at 222 kilometers altitude is $1.5 \times 10^8$ oxygen atoms/cm$^3$ with an error of ±20 percent and $8.6 \times 10^6$ nitrogen atoms/cm$^3$ with an error of ±25 percent. These densities are consistent with measurements made at 340 kilometers altitude by the NASA unmanned Atmosphere Explorer satellite.

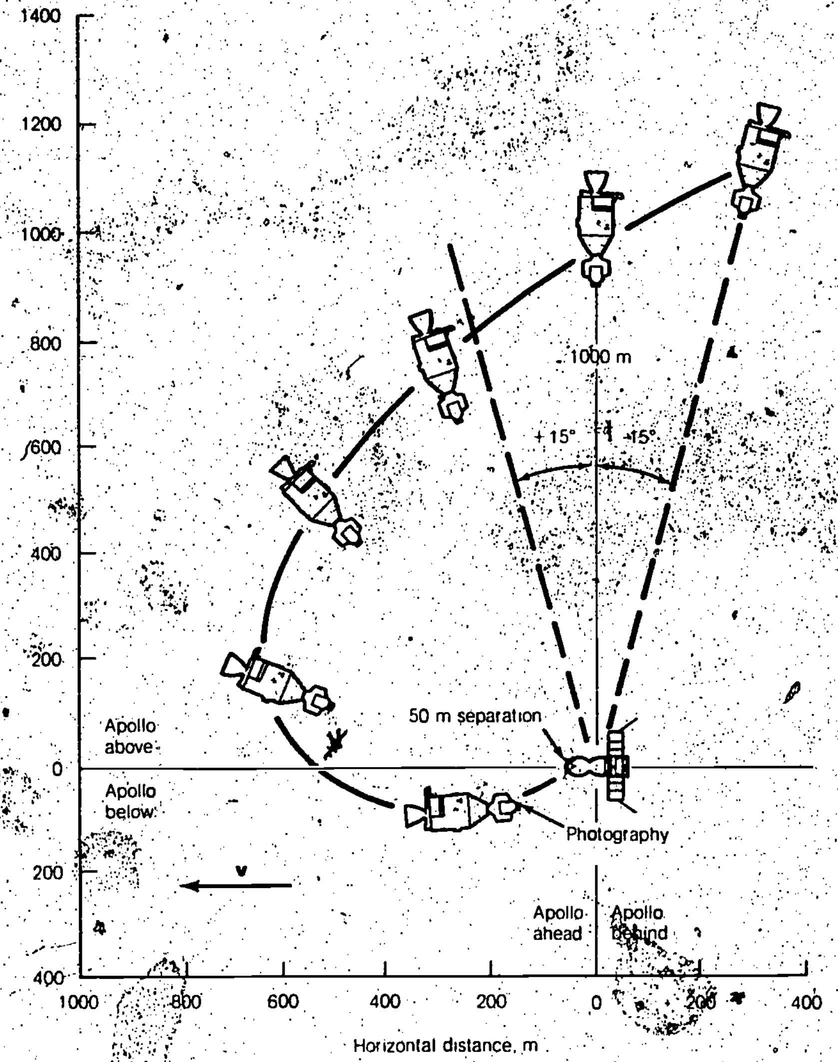


Illustration of the MA-059 1000-meter data take; v is the velocity vector. Figure 4.7

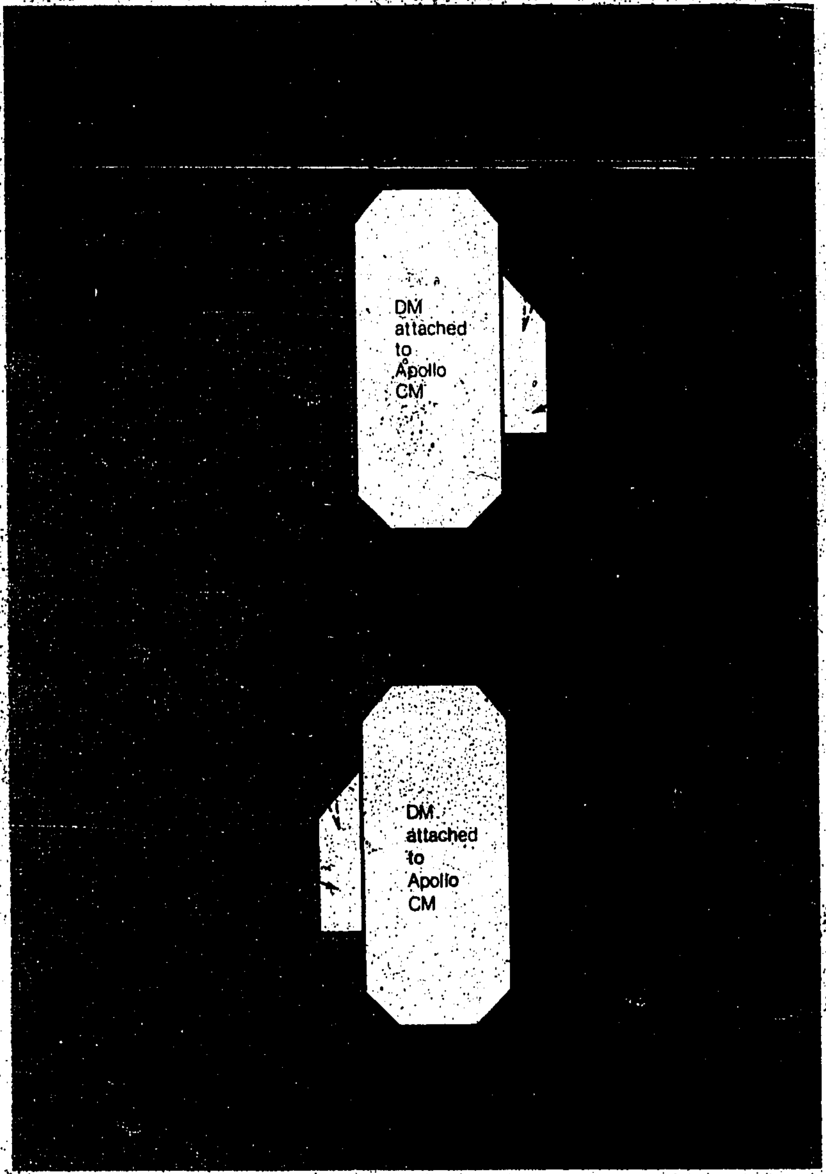


Figure 4.8 Location of MA-059 Experiment relative to the Apollo velocity vector. The dashed lines show the direction of the beam of light.

## E Questions for Discussion

(Atmosphere, Spectrum)

**13.** By what processes are gases in the lowest layer of the atmosphere (Fig. 4.1) heated? Why are troposphere temperatures near the Equator higher than troposphere temperatures near the poles?

**14.** If the gas temperature is more than 773 K (500° C) at 222 kilometers altitude, why weren't the Apollo and Soyuz spacecraft unbearably hot?

**15.** If a radio pulse is reflected from the mesosphere (Fig. 4.1), what is the echo delay?

**16.** If an atom has just six energy levels ($E_1$, $E_2$, $E_3$, $E_4$, $E_5$, and $E_6$) and all jumps are allowed, how many spectrum lines can the atom absorb and reemit?

**17.** The oxygen lamp used in the MA-059 Experiment produced many weaker emission lines at longer wavelengths (off the right side of Fig. 4.3). Why wasn't one of these lines used to measure oxygen-atom density instead of the 1304-angstrom line?

**18.** The MA-059 Experiment used three different separations of Apollo and Soyuz: 150, 500, and 1000 meters. What advantage comes with larger separation? What disadvantages would you expect?

**19.** How could the dirty-retroreflector problem be avoided?

# Appendix A

## Discussion Topics (Answers to Questions)

1. (Sec. 2E) The river separation $x$ is the small side of a triangle 220 kilometers long. This triangle is similar to the line separation of 0.03 millimeter on a paper 10 centimeters away. So, $x$/220 kilometers = 0.03 millimeter/10 centimeters = sin 0.017°, and $x$ = 66 meters. The monocular was "×16 power," which enlarges angles 16 times. So the 66-meter river separation just perceptible to the naked eye was reduced to 66/16 = 4.1 meters perceptible with the monocular.

2. (Sec. 2E) The 38° field of view of the camera corresponds to 144 kilometers on the ground. (From the center to the edge is 19°, and 222 sin 19° equals 72 kilometers; thus, edge-to-edge is 144 kilometers.) To obtain a 60-percent overlap, you would want photographs that were 40 percent of 144 or 57.5 kilometers apart. The time for Apollo-Soyuz to move 57.5 kilometers is 57.5/7.4 = 7.8 seconds. If the 60-millimeter lens were used, the field of view on the ground would be (100/60)144 = 240 kilometers, and the interval would be 13 seconds.

3. (Sec. 2E) The Hasselblad with the 250-millimeter lens gives the largest scale (Fig. 2.3) and therefore the best resolution.

4. (Sec. 2E) "The one thing I noticed was that . . . line on the left up near the end . . . makes a bend to the left and follows a new tectonic line or fault which goes along parallel to the Turkish coast. In other words, the one on the left, number 1, goes up . . . and then makes a left turn and parallels the Turkish coast. [Number] two seems to be obscured and it just ends in a lot of jumbled country . . . and it seems to end right in this jumbled area. [Number] three, I could trace clear up to a river which—I'll have to see a map later. But I could trace the faults out, going rather eastward. You could see them through the valley silt, clear up to a river which must be inland in either Syria or Turkey. So the overall pattern of these is a fan; [number] three going almost eastward, and [number] one bending finally to the north, and [number] two going to the northeast." (Verbal comments made during the mission by Astronaut Vance D. Brand.) Other reports referred to colors on the color wheel.

5. (Sec. 2E) In Figure 2.9, there is a sharp division between red sand and yellow sand to the left of the center. The ground-truth teams should measure the surface color on either side of this line and also analyze the sand for evidence of its age. An accurate survey of the latitude and longitude of at least two points along the red-yellow division is needed to pinpoint map coordinates in Figure 2.9.

6. (Sec. 2E) The distance (roughly along the Equator) from the eastern tip

of South America to the "dent" in West Africa (near the Congo River) where it came from is about 5000 kilometers. At 2 cm/yr, this continental drift would take $5 \times 10^8$ centimeters/ (2 cm/yr) = $2.5 \times 10^8$ years, or 250 million years.

**7.** (Sec. 3E) Aerosols at high altitude scatter sunlight and reduce the amount reaching the Earth's surface. Therefore, a higher aerosol count would decrease the surface temperature.

**8.** (Sec. 3E) In addition to the dust-particle counts per second, yo[illegible]ed to know the *volume* of air pumped through the dust-particle counter each second. You also need the conversion from measured outside air pressure to altitude.

**9.** (Sec. 3E) The time up and back can be measured with an error of 30 nanoseconds, so the time up to the aerosol is in error by only 15 nanoseconds. The speed of light $c$ is $3 \times 10^8$ m/sec; therefore, in $15 \times 10^{-9}$ seconds, light moves $(15 \times 10^{-9})(3 \times 10^8) \doteq 5 \times 10^{-1}$ or 0.5 meter. The error in altitude thus is 50 centimeters.

**10.** (Sec. 3E) Blue light is refracted more than red light, with other colors in between (see Pamphlet II). White-light photographs of the setting Sun would be blue on top and red on the bottom. A star would show a small spectrum from blue on top through green, yellow, and orange to red on the bottom.

**11.** (Sec. 3E) The Sun as seen from the Earth or from Apollo is 0.5° in diameter. In the triangle from lens to film, the size of the Sun's image is equal to 250 millimeters $\sin 0.5° =$ (250 millimeters) (0.0087) $\doteq$ 2.2 millimeters in diameter.

**12.** (Sec, 3E) In 93 minutes, the Earth rotates eastward (93 minutes/24 hours) $360° \doteq 23°$. So the second sunset would be 23° farther west at 95° W + 23° = 118° W (west of Mexico).

**13.** (Sec. 4E). In the troposphere, just above the Earth's surface, the air is heated by the *surface*, which derives its heat from the Sun's light and from infrared radiation that penetrates the atmosphere. The surface passes heat to the air directly by *conduction* and by *radiation* in long-wave infrared rays. Hot air rising from near the surface carries heat to higher altitudes by *convection*. Near the Equator, sunlight strikes the Earth's surface almost perpendicular to the surface, which gives the surface more heat per unit area than at higher latitudes.

**14.** (Sec. 4E). The high temperature of a very low density gas is misleading. Because the number of atoms, ions, and molecules in 1 cubic meter is low, the total energy per cubic meter is low also, and the thermal energy received by Apollo-Soyuz was therefore very small. The spacecraft lost energy and was cooled by radiation. The spacecraft temperature was controlled by the balance between incoming solar radiation and outgoing spacecraft radiation. The incoming solar radiation was reduced by reflective "radiation shields" of metal-covered plastic sheets.

**15.** (Sec. 4E) The mesosphere is at 90 kilometers altitude (Fig. 4.1), so the distance up and back is 180 kilometers. The round-trip radio pulse time is 180 kilometers/$c$ = 180 kilometers/(3 × $10^8$ m/sec) = 6 × $10^{-4}$ seconds, or an 0.0006-second echo delay.

**16.** (Sec. 4E) "Jumps" or "transitions" are possible between each pair of the six levels. An upward jump absorbs the same spectrum line as the downward jump emits between any two energy levels. Therefore, there are five downward jumps to $E_1$, four to $E_2$, three to $E_3$, two to $E_4$, and one to $E_5$ for a total of 15 spectrum lines. Real atoms have many more levels and spectrum lines than this simplified example.

**17.** (Sec. 4E) The weaker lines at longer wavelengths would be less efficient detectors of oxygen atoms; that is, there would be less intensity absorbed per atom in the beam between Apollo and Soyuz. Because the objective was to measure the number of oxygen atoms, the strongest ("resonance") line at 1304 angstroms was best.

**18.** (Sec. 4E) With larger separation, there were more oxygen and nitrogen atoms in the beam between Apollo and Soyuz, and the absorption could be measured more accurately. This advantage was offset by the difficulty of aiming the lamp beam to hit the 10-centimeter retroreflector on Soyuz when it was 1000 meters away.

**19.** (Sec. 4E) Preventing oil leaks and other contamination around Soyuz is the obvious way to keep the retroreflector clean. Another solution would be to eliminate the retroreflector and put the lamps on one spacecraft and the spectrometer on the other.

# Appendix B

## SI Units

## Powers of 10

### International System (SI) Units

Names, symbols, and conversion factors of SI units used in these pamphlets:

| Quantity | Name of unit | Symbol | Conversion factor |
|---|---|---|---|
| Distance | meter | m | 1 km = 0.621 mile<br>1 m = 3.28 ft<br>1 cm = 0.394 in.<br>1 mm = 0.039 in.<br>1 $\mu$m = 3.9 × $10^{-5}$ in. = $10^4$ Å<br>1 nm = 10 Å |
| Mass | kilogram | kg | 1 tonne = 1.102 tons<br>1 kg = 2.20 lb<br>1 gm = 0.0022 lb = 0.035 oz<br>1 mg = 2.20 × $10^{-6}$ lb = 3.5 × $10^{-5}$ oz |
| Time | second | sec | 1 yr = 3.156 × $10^7$ sec<br>1 day = 8.64 × $10^4$ sec<br>1 hr = 3600 sec |
| Temperature | kelvin | K | 273 K = 0° C = 32° F<br>373 K = 100° C = 212° F |
| Area | square meter | $m^2$ | 1 $m^2$ = $10^4$ $cm^2$ = 10.8 $ft^2$ |
| Volume | cubic meter | $m^3$ | 1 $m^3$ = $10^6$ $cm^3$ = 35 $ft^3$ |
| Frequency | hertz | Hz | 1 Hz = 1 cycle/sec<br>1 kHz = 1000 cycles/sec<br>1 MHz = $10^6$ cycles/sec |
| Density | kilogram per cubic meter | $kg/m^3$ | 1 $kg/m^3$ = 0.001 $gm/cm^3$<br>1 $gm/cm^3$ = density of water |
| Speed, velocity | meter per second | m/sec | 1 m/sec = 3.28 ft/sec<br>1 km/sec = 2240 mi/hr |
| Force | newton | N | 1 N = $10^5$ dynes = 0.224 lbf |

| Quantity | Name of unit | Symbol | Conversion factor |
|---|---|---|---|
| Pressure | newton per square meter | N/m² | 1 N/m² = 1.45 × 10⁻⁴ lb/in² |
| Energy | joule | J | 1 J = 0.239 calorie |
| Photon energy | electronvolt | eV | 1 eV = 1.60 × 10⁻¹⁹ J; 1 J = 10⁷ erg |
| Power | watt | W | 1 W = 1 J/sec |
| Atomic mass | atomic mass unit | amu | 1 amu = 1.66 × 10⁻²⁷ kg |

## Customary Units Used With the SI Units

| Quantity | Name of unit | Symbol | Conversion factor |
|---|---|---|---|
| Wavelength of light | angstrom | Å | 1 Å = 0.1 nm = 10⁻¹⁰ m |
| Acceleration of gravity | g | g | 1 g = 9.8 m/sec² |

### Unit Prefixes

| Prefix | Abbreviation | Factor by which unit is multiplied |
|---|---|---|
| tera | T | $10^{12}$ |
| giga | G | $10^{9}$ |
| mega | M | $10^{6}$ |
| kilo | k | $10^{3}$ |
| hecto | h | $10^{2}$ |
| centi | c | $10^{-2}$ |
| milli | m | $10^{-3}$ |
| micro | $\mu$ | $10^{-6}$ |
| nano | n | $10^{-9}$ |
| pico | p | $10^{-12}$ |

### Powers of 10

| Increasing | Decreasing |
|---|---|
| $10^2 = 100$ | $10^{-2} = 1/100 = 0.01$ |
| $10^3 = 1\,000$ | $10^{-3} = 1/1000 = 0.001$ |
| $10^4 = 10\,000$, etc. | $10^{-4} = 1/10\,000 = 0.000\,1$, etc. |
| Examples: | Example: |
| $2 \times 10^6 = 2\,000\,000$ | $5.67 \times 10^{-5} = 0.000\,056\,7$ |
| $2 \times 10^{30} = 2$ followed by 30 zeros | |

# Appendix C

## Glossary

References to sections, Appendix A (answers to questions), and figures are included in the entries. Those in *italic* type are the most helpful.

**absorption line** a gap or dip in a spectrum, caused by the absorption of specific wavelengths by a gas between a light source and the observer. (Secs. 4A to 4C; App. A, nos. 16, 18; Figs. *4.2*, 4.3)

**aerosol** very small particles of dust or droplets of liquid suspended in the Earth's atmosphere. (Secs. 1, *3*, 3A to 3D; App. A, nos. 7 to 9; Figs. *3.2*, 3.3, 3.7)

**altitude** distance above the Earth's surface. (Secs. 3 to 3C; 4, 4A; App. A, nos. 8, 9, 15; Figs. 3.2, 3.6, *4.1*)

**angstrom (Å)** a unit of wavelength used by physicists for more than 80 years; 1 angstrom = $10^{-10}$ meter or 0.1 nanometer.

**Apollo-Soyuz** a joint U.S.-U.S.S.R. mission from July 15 to July 24, 1975. Apollo, the three-man U.S. spacecraft, consisted of the Command Module (CM) connected to the Service Module (SM) and the Docking Module (DM). For 2 days, the DM was attached to Soyuz, the two-man Soviet spacecraft. The two spacecraft were in a circular orbit inclined 51.8° to the Equator, with a 93-minute period, 222 kilometers above the Earth's surface. See *groundtrack*, *orbit*, and Pamphlet I.

***c*** the velocity of light and all other electromagnetic waves in a vacuum, $3 \times 10^8$ m/sec. (Sec. 4B; App. A, nos. 9, 15)

**climate** the weather conditions of a region (temperature, humidity, cloudiness, rainfall, snowfall, sunshine, and winds) throughout the year, averaged over several years. (Sec. 3; App. A, no. 7)

**color wheel** a device for describing visual color by number. (Sec. 2B)

**concave mirror** an optical component that acts like a lens, forming images or giving parallel rays from a point source of light at its focus. (Sec. 4C)

**continental drift** the very slow motion of continents and the sea floors adjacent to them (plates). (Secs. 2, 2D, 2E; App. A, no. *6*)

**contour** a line connecting points of equal value, such as altitude on a map or brightness on a photograph. (Sec. 3C; Fig. 3.5(b))

**count** one pulse of current or voltage from a detector, indicating the passage of a photon or particle through the detector. (Secs. 3, 3A; App. A, nos. 7, 8; Fig. 3.1)

**Docking Module (DM)** a special component added to the Apollo spacecraft so that it could be joined with Soyuz. (Sec. 4C; Fig. 4.8) See Pamphlet I.

**Doppler shift** the change of frequency $f$ and wavelength $\lambda$ in the spectrum of a source approaching an observer (blue shift) or receding from him (red shift). The change in wavelength is $\Delta\lambda = \lambda v/c$, where $v$ is the velocity of approach or recession. (Sec. 4C) See Pamphlet IV.

**emission line** a small band of wavelengths emitted by a low-density gas when it glows. The pattern of several emission lines is characteristic of the gas and is the same as the absorption lines absorbed by that gas from light passing through it. (Secs. 4A, *4B*, 4C to 4E; App. A, nos. 16, 17; Figs. *4.2*, *4.3*)

**energy level** a specific internal energy that one kind of atom can have. The quantum theory explains and predicts discrete (separate) energy levels for each kind of atom. (Sec. *4B*; App. A, no. 16; Fig. *4.2*)

**fault** a crack in the Earth's crust where surface rocks have slipped up, down, or sideward. (Sec. *2B*; App. A, no. 4; Fig. 2.6)

**field of view** the angular area covered by a camera or other type of detector. (Secs. 2A, 2E, 3C; App. A, no. 2; Fig. 2.*3*)

**film** a plastic strip coated with light-sensitive emulsion on one side, used to record focused images in a camera. After development, black-and-white film shows a negative image (blackened where light struck it). Color film, after processing, shows the colors of light that struck it. Red and infrared film record longer wavelengths of light than does ordinary film. (Secs. 2A, 3C; App. A, no. 11)

**focal length** the distance from a lens to its focused image of an object very far away. (Sec. *2A*; Fig. 2.3)

**forbidden line** a spectrum line that can be emitted by a low-density gas but not absorbed by it. (Secs. *4B*, 4C) See *emission line*, *energy level*, *spectrum*.

**Greenwich mean time (GMT)** the time of an event, from 0 at midnight to 12 hours at noon to 24 hours at midnight, as measured at 0° longitude (Greenwich, near London, England); used on the Apollo-Soyuz mission and other space missions to avoid confusion with other time zones. See Pamphlet I.

**groundtrack** the path followed by a spacecraft over the Earth's surface. (Secs. 2, 2A; Fig. 2.*5*)

**ground truth** measurements made from the ground to confirm or calibrate measurements made from a spacecraft in orbit. (Sec. 2C; App. A, no. 5; Figs. 2.*4*, 3.1)

**infrared** invisible electromagnetic radiation with wavelengths from 0.7 to 1000 micrometers; longer than visible wavelengths. (Sec. 3C; App. A, no. 13; Fig. 2.2)

**ion** an atom with one or more electrons removed or, more rarely, added. (Sec. 4A; Fig. 4.2)

**laser** (from *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation) a light source emitting only one wavelength of coherent light (all in the same phase of the wave cycle). A pulsed laser emits short flashes of very high intensity. (Secs. 3, 3B)

**lens** a set of pieces of glass or quartz accurately shaped to focus light from a distant object to form an image of that object. (Secs. 2A, 3C; App. A, nos. 2, 3, 11; Figs. 2.2, *2.3*, 3.1)

**lidar** a pulsed *li*ght *d*etection *a*nd *r*anging instrument similar to radar (*ra*dio *d*etection *a*nd *r*anging). Lidar was used to measure the altitude of aerosols and the droplet characteristics. (Secs. *3B*, 3D; App. A, no. 9; Fig. *3.3*)

**MA-007** the Stratospheric Aerosol Measurement Experiment on the Apollo-Soyuz mission. (Secs. 1, *3*, 3A, 3B, *3C*, 3D; Figs. 3.2, *3.4*, 3.7)

**MA-059** the Ultraviolet Absorption Experiment. (Secs. 1, 4, *4C*, 4D, 4E; App. A, nos. 17, 18; Figs. 4.4 to 4.8)

**MA-136** the Earth Observations and Photography Experiment. (Secs. 1, 2, *2A*, 2C, 2D; Figs. *2.4*, *2.5*)

**MA-148** the Artificial Solar Eclipse Experiment. (Sec. 3C) See Pamphlet III.

**millibar (mbar)** a unit of pressure equal to 100 N/m$^2$, used for measuring atmospheric pressure. (Sec. *4A*; Fig. 4.1)

**monocular** a small telescope, like binoculars but for one eye only. (Sec. 2B; App. A, no. 1)

**orbit** the path followed by a satellite around an astronomical body, such as the Earth or the Moon. The orbit number was used on Apollo-Soyuz to identify the time. (Sec. 2; Fig. 3.4)

**ozone ($O_3$)** a somewhat unstable molecule formed in the Earth's atmosphere from atomic and molecular oxygen at altitudes from 19 to 35 kilometers. (Sec. 4A; Fig. *4.1*)

**photometer** an instrument that uses electrical voltage to measure the intensity (brightness) of light. (Secs. *3C*, 3D; Fig. *3.7*) There are several types; a *photomultiplier* amplifies the electron current. (Sec. 3A; Fig. 3.1)

**photon** a quantum of light—the smallest separable amount of energy in a beam of light. Photon energy is proportional to frequency and inversely proportional to wavelength. (Sec. 4B)

**plates** the six continental masses and the sea floors adjacent to them on Earth; *subplates* are segments of these plates. *Plate tectonics* is a study of the motion of plates and subplates. (Sec. 2D)

**Principal Investigator** the individual responsible for a space experiment and for reporting the results.

**radar** (*ra*dio *d*etection *a*nd *r*anging) a transmitter that sends a radio pulse toward an object and measures the time interval until the reflected (echo) pulse comes back. The time interval gives the range (distance) of the object. (Secs. 3B, 4A; App. A, no. 15)

**reaction-control jets** small propulsion units on a spacecraft used to rotate or accelerate it in a specific direction. (Sec. 4C) See Pamphlet I.

**reflectivity** the ratio of the reflected intensity to the intensity falling on a mirror or retroreflector. (Secs. 4C, 4D)

**refraction** the bending of electromagnetic rays such as light or radio waves, where the material they are passing through changes in density, composition, or other properties. (Secs. 2D, *3C*, 3D, 3E; App. A, no. 10; Figs. *3.4*, 3.5(c), 3.6)

**refractive index** the ratio of c (the velocity of light in a vacuum) to the velocity of light through a transparent substance. Each such substance lowers the velocity of light slightly and by a different amount—low-density air has a different refractive index from high-density air and from water, glass, sulfuric acid, etc. (Sec. 3D)

**resonance line** a spectrum line resulting from a jump between the two lowest energy levels in an atom. A resonance line is strongly absorbed and strongly emitted. (Secs. *4B*, 4C; App. A, no. 17; Fig. 4.2)

**retroreflector** three mirrors perpendicular to each other (like the inside corner of a box). These mirrors reflect any entering light ray back on itself. A group of seven such "corner reflectors" made up each retroreflector on Soyuz. (Sec. *4C*, 4D; App. A, nos. 18, 19; Fig. 4.4)

**rift** a crack in the Earth's surface, where one land mass is sliding past another in plate or subplate movement of continental drift. (Secs. 2B, *2D*, Fig. 2.6)

**salinity** the percentage content of salt in seawater. (Secs. 2C, 2D; Figs. 2.7, 2.10)

**scattered light** light striking fine aerosol particles is reflected (scattered) in all directions. Similarly, photons of resonance-line wavelength are absorbed by atoms and reemitted in all directions. (Secs. 3, 3B to 3D, 4B; App. A, no. 7)

**spectrometer** an instrument that spreads light into a spectrum and measures the intensity at different wavelengths. (Secs. 4B, *4C*, 4D; App. A, no. 19; Fig. 4.4)

**spectrum** light spread out into its component wavelengths. The full *electromagnetic spectrum* extends from very short gamma rays and x-rays through visible light to infrared and long radio waves. (App. A, no. 10) *Spectrum lines* are peaks (emission lines) or gaps (absorption lines) in a plot of intensity versus wavelength. See Pamphlet II.

**troposphere** the lowest layer of the atmosphere, just above the Earth's surface, about 10 kilometers thick. (Secs. 4A, 4E; App. A, no. 13; Fig. *4.1*)

**velocity vector v** (of Apollo-Soyuz) the speed and direction of Apollo-Soyuz through the atmospheric gases at 222 kilometers altitude. (Secs. 4C, 4D; Figs. *4.5*, *4.6*, 4.7, 4.8)

**wavelength** (λ) the distance from the crest of one wave to the crest of the next, usually measured in angstroms for light waves. Spectra are usually plotted as intensity versus wavelength. (Secs. 3C, 3E, 4A, 4B, 4E; App. A, no. 17; Figs. *4.2*, 4.3)

# Appendix D

## Further Reading

*ABC's of Space* by Isaac Asimov, Walker and Co. (New York), 1969—an illustrated glossary of spaceflight terms.

*Atoms and Astronomy* by Paul A. Blanchard (Available from the U.S. Government Printing Office, Washington, D.C. 20402), 1976—atomic spectra explained in simple terms.

*Continental Drift: The Evolution of a Concept* by Ursula B. Marvin, Smithsonian Institution Press (Washington, D.C.), 1973—a clear and easily understood account of this newest branch of geology.

*Continents Adrift* (readings from *Scientific American*, with an introduction by J. Tuzo Wilson), W. H. Freeman & Co., Inc. (San Francisco), 1972—an anthology on evidence for and developments of this theory.

*Earth and Space Science* by C. W. Wolfe et al., D. C. Heath and Co. (Boston), 1966—a general reference for topics discussed in this pamphlet.

*Introduction to the Atmosphere* by Herbert Riehl, McGraw-Hill, Inc. (New York), 1972—for students who want to learn about the dynamics of the Earth's atmosphere, particularly in relation to experiments onboard Earth satellites.

*The Language of Space: A Dictionary of Astronautics* by Reginald Turnill, John Day Co., Inc. (New York), 1971—a well-written glossary of 1100 space terms, with a section on "the next 20 years in space."

*Lasers and Light* (readings from *Scientific American*), W. H. Freeman & Co., Inc. (San Francisco), 1969—college-level descriptions of optics, x-rays, radio waves, and lasers.

*Modern Physics* by H. Clarke Metcalfe, John E. Williams, and Joseph F. Castka, Holt, Rinehart and Winston (New York), 1976—see Section 12.9, "Quantum Theory."

*The Origin of the Solar System*, Thornton Page and Lou Williams Page, eds., Macmillan Publishing Co., Inc. (New York), 1966—see Chapter 5, "Earth's Atmosphere Viewed From Below and Above."

*Physics for Society* by W. B. Phillips, Addison-Wesley Publishing Co. (Menlo Park, Calif.), 1971—covers recent advances in technology and space sciences.

*Physics: Foundations and Frontiers* by George Gamow and John N. Cleveland, Prentice-Hall, Inc. (Englewood Cliffs, N.J.), 1976—see Chapter 21, Section 21-9, "Spectroscopes," and Chapter 22, "The Energy Quantum."

*Readings in the Physical Sciences and Technology* (articles from *Scientific American*, with an introduction by Isaac Asimov), W. H. Freeman & Co., Inc. (San Francisco), 1969—contains well-illustrated articles on pertinent subjects.

*Science From Your Airplane Window* by Elizabeth A. Wood, Dover Publications (New York), 1975—discusses locating and observing geologic features from the air.

☆U.S. GOVERNMENT PRINTING OFFICE: 1977 0--243-575