Apollo-Soyuz
Pamphlet No. 6:

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# Cosmic Ray Dosage

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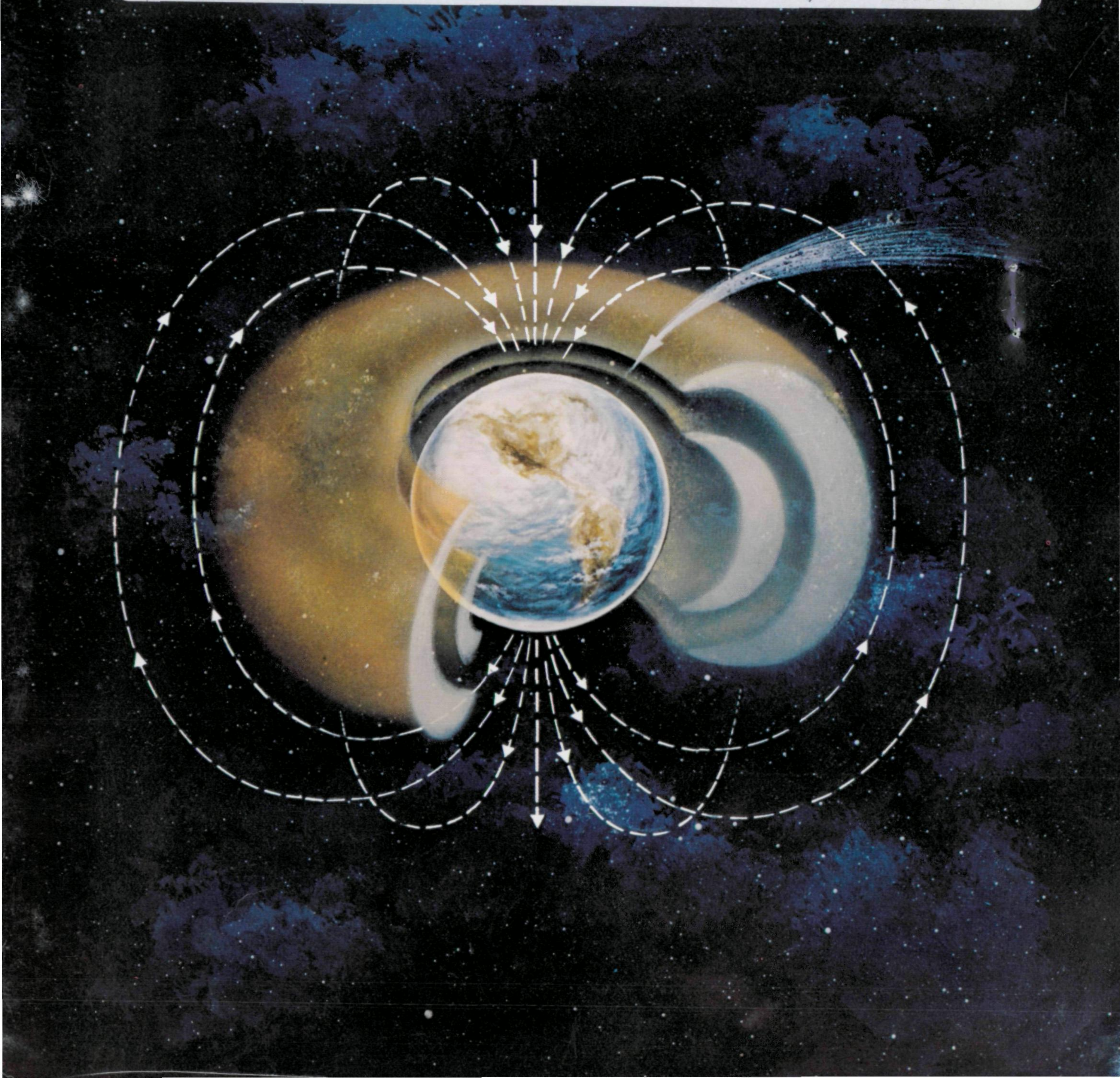

## Apollo-Soyuz Experiments In Space

## 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 Earth's Magnetic Field and Van Allen Belt with Incoming Cosmic Ray

## Apollo-Soyuz Pamphlet No. 6:

# Cosmic Ray Dosage

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

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# 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.

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.

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# 1 Introduction

## The Radiation Hazard in Spacecraft

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.

Planners of the early NASA space missions worried about damage from meteors and the dangers of returning to Earth at high speed through the atmosphere. When these hazards were avoided (by meteor shields and ablative heat shields), the next concern was the effect of weightlessness on astronauts. After the Skylab 3 astronauts spent 84 weightless days in orbit, this anxiety passed.

Recent evidence shows that the ''radiation hazard'' may be of more concern in long spaceflights. ''Radiation'' is used here to mean the bombardment by high-energy particles—cosmic rays in outer space and high-speed protons and electrons in the Van Allen belt about 320 to 32 400 kilometers above the Earth's surface. This radiation is hazardous not only to astronauts and other living organisms in the spacecraft but also to electronic equipment and instruments.

Two Apollo-Soyuz Test Project experiments are described in this pamphlet. Experiment MA-106, Quantitative Observations of Light Flash Sensations (flashes seen by ''blindfolded'' astronauts), was supervised by T. F. Budinger of the Lawrence Berkeley Laboratory at the University of California. He was assisted by 11 Co-Investigators. Experiment MA-107, Biostack III, was a German experiment supervised by Horst Bücker of the Biophysics Space Research Group at the University of Frankfurt. He was assisted by 32 Co-Investigators from West Germany, France, and the United States. Biostack III was the third in a series of experiments to measure the effects of cosmic rays on spores, seeds, and eggs. (Biostack I was carried on Apollo 16 in April 1972 and Biostack II was carried on Apollo 17 in December 1972.)

## A

## Incoming Particles Versus the Earth's Magnetic Field

Cosmic rays are charged particles (ions) moving at high velocity and coming in toward the Earth from all directions. Scientists have found that many of the lower speed cosmic-ray particles come from the Sun. These are called *solar cosmic rays*. They are probably blown out of the Sun by violent explosions. Much slower protons and electrons—the "solar wind"—are streaming continuously out of the Sun in large numbers. The higher energy cosmic rays coming from all other directions probably originate in our Milky Way Galaxy and are called *galactic cosmic rays*. They pass right through spacecraft at a rate of 2 particles/cm$^2$ hr. All these particles are deviated by the Earth's magnetic field: the slow, light ones are deflected more than the fast, heavy, galactic cosmic-ray particles.

The Earth has a magnetic field[1] somewhat like that of a large bar magnet or "magnetic dipole." There is a region around the Earth where a compass needle will point along the *magnetic lines of force*, represented by the dashed lines in Figure 1.1. Of course, there is no bar magnet inside the Earth. The Earth's magnetism is thought to arise from currents in the molten core due to the Earth's rotation (although the magnetic dipole is inclined 13° to the rotation axis). The magnetic field strength is about 500 milligauss ($50 \times 10^{-6}$ tesla) at the surface and the strength rapidly decreases outwardly (in proportion to $1/r^4$, where $r$ is the distance from the Earth's center). Other planets also have magnetic fields, but those of Mercury, Venus, and Mars (and the Moon) are much smaller. Mercury's magnetic field is about 1 percent of the Earth's and the magnetic fields of Venus and Mars are nearly zero. Jupiter and Saturn have much stronger magnetic fields (4000 milligauss, or $400 \times 10^{-6}$ tesla, at the surface), probably because they are rotating faster than the Earth.

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[1] Project Physics, Secs. 14.2, 14.13; PSSC, Secs. 22-1, 22-3; and ESCP, Secs. 3-11 to 3-13. (Throughout this pamphlet, references will be given to key topics covered in these three standard textbooks: "Project Physics," second edition, Holt, Rinehart and Winston, 1975; "Physical Science Study Committee" (PSSC), fourth edition, D.C. Heath, 1976; and "Investigating the Earth" (ESCP), Houghton Mifflin Company, 1973.)

The direction of travel of a charged particle (ion) is changed by the magnetic field.[2] The cosmic ray in the upper right of Figure 1.1 thus is deflected downward. Such deflections of cosmic rays produce the ''latitude effect'': cosmic rays are more intense at high latitudes (north and south) than near the Equator.

Deflections of slower moving ions—the protons and electrons in the solar wind—are larger, and the Earth's magnetic field has ''captured'' many of them in the Van Allen belt[3] (named after physicist James Van Allen of the University of Iowa, who discovered it from measurements on the Explorer 1 satellite in 1958). The cutaway view of Figure 1.1 shows the doughnut-shaped regions where protons and electrons are oscillating north and south along the magnetic lines of force (dashed lines). These charged particles spiral around the lines of force at speeds of several kilometers per second and are reflected back where the lines of force get close together near the magnetic poles. There are no sharp boundaries to the regions where protons and electrons are oscillating, but the whole Van Allen belt is between 320 and 32 400 kilometers altitude and extends all around the Earth. The peak intensity of protons occurs at about 3000 kilometers altitude, where the protons have energies of more than 10 megaelectronvolts and a flux of more than 10 000/cm$^2$ sec. Because of the intensity of this ''radiation'' in the Van Allen belt, this region of space is by far the most hazardous to living organisms (and to sensitive instruments) in spacecraft. (The NASA Pioneer 10 mission found the similar radiation belt of Jupiter to be several thousand times more intense.)

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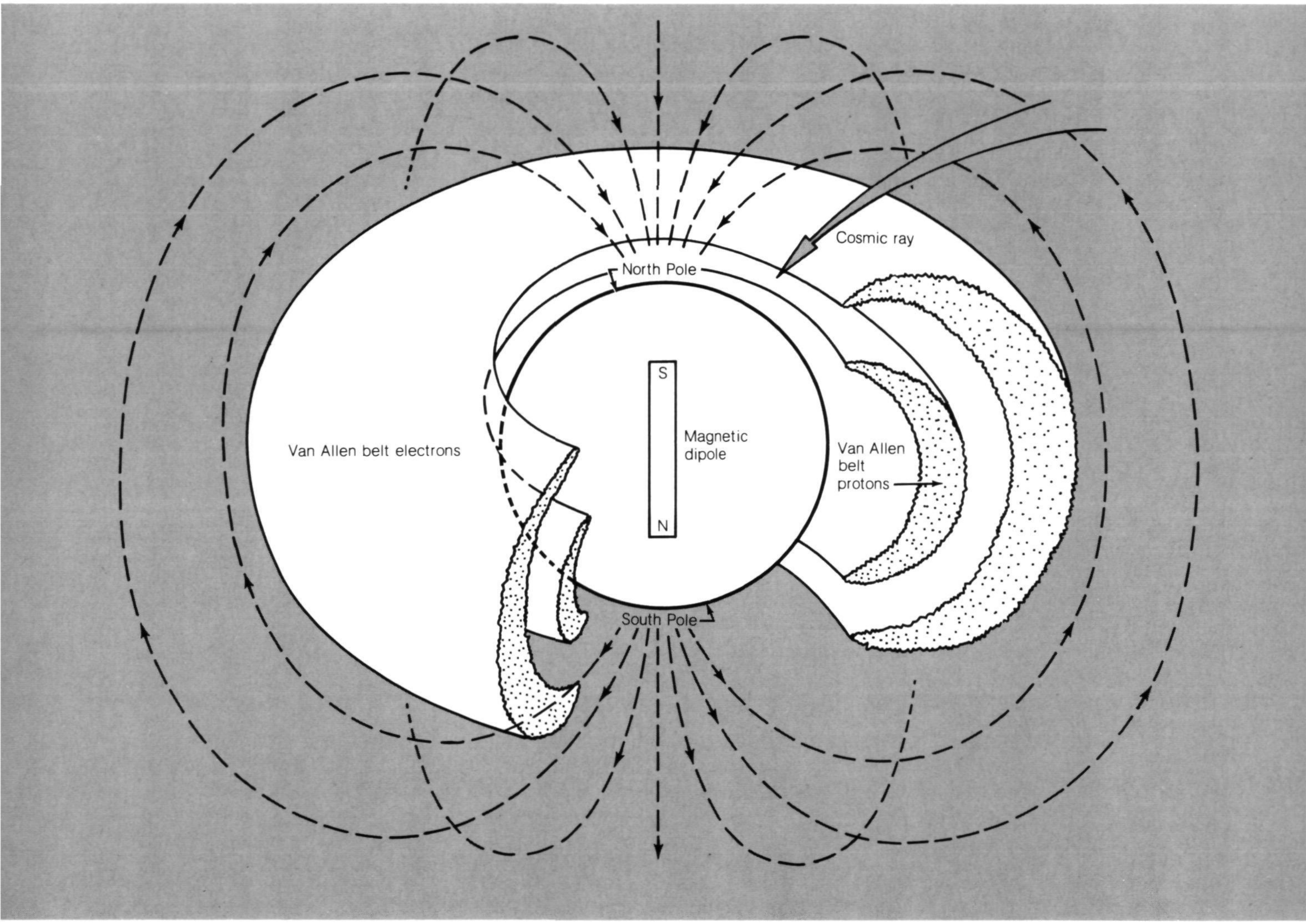
[2] Project Physics, Sec. 14.13; PSSC, Secs. 22-4, 22-6.

[3] Project Physics, Secs. 14.2; PSSC, Secs. 22-1, 22-3.

**Figure 1.1** Schematic diagram of the magnetic field of the Earth and the Van Allen belt. The dashed lines are magnetic lines of force.



The Earth's magnetic field is not as simple as the diagram in Figure 1.1 would suggest. Its outer regions are affected by the solar wind, and the ''magnetosphere''—the region of the upper atmosphere that is dominated by the Earth's magnetic field—has a ''shock front'' facing into the wind (more or less toward the Sun) and a ''tail'' stretching downwind. More important for Earth satellites such as Apollo-Soyuz, the Earth's magnetic field has a ''dent'' over the Atlantic Ocean just east of Brazil that causes the Van Allen belt to bulge downward toward the Earth's surface in a region called the South Atlantic Anomaly. This irregularity in the magnetic field produces a region of very intense radiation in the lower part of the Van Allen belt there (about 1000 times more intense than in nearby space). NASA scientists have learned that some instruments on spacecraft give erroneous readings while they are in the South Atlantic Anomaly. NASA's Skylab, at a 444-kilometer altitude, went through it regularly. Apollo-Soyuz was below it at an altitude of 222 kilometers, where the radiation dose was almost 10 times less than at the Skylab altitude.

## B Radiation Effects on Instruments

Photographic film in cameras, most of the electronic equipment in spacecraft, and sensitive instruments designed to detect x-rays or far-ultraviolet light are affected by Van Allen belt radiation and cosmic rays. The detectors themselves may give false counts because a fast proton or cosmic ray is recorded. (This problem is avoided by using ''anticoincidence counters''—see Pamphlets II and III.) Photographic film is fogged by the radiation, and electronic parts, such as semiconductors or discharge tubes, may give unwanted pulses of current (false counts) when cosmic rays or high-speed protons pass through them. Long exposure can permanently damage some electronic parts and can also fog photographic film so that it is unusable. This can be partly prevented by *shielding*. On the long Skylab missions, film was kept in a cabinet that had thick metal sides, like a bank vault. On most space instruments, the electronics are shielded by metal containers. The spacecraft hull also provides some shielding for everything inside. This shielding can be effective against Van Allen belt electrons and most of the medium-speed protons. However, most of the cosmic rays penetrate a few centimeters of metal, and the few that are absorbed create ''secondaries''—often high-energy gamma rays. This makes the exposure of astronauts and other living organisms near metals in a spacecraft very complicated.

## C Biological Effects

When ''radiation'' (high-energy protons and cosmic rays as well as gamma rays or x-rays) is absorbed in living cells, it ionizes atoms or molecules in the cell and may disorganize or kill the cell. The loss of a few cells in a large organism such as a human usually doesn't matter. Long exposure may do harm, however, and for that reason x-ray technicians and astronauts usually wear photographic badges that show how much exposure they have accumulated. The overall biological damage is measured in ''rads.'' One rad (*r*adiation *a*bsorbed *d*ose) is equivalent to $10^{-5}$ joules of energy absorbed *per gram of tissue*. For humans, the lethal dose is about 400 rads. Hospital x-ray photographs give less than 0.01 rad, and astronauts on long space missions have so far accumulated only 3 or 4 rads, which has no significant effect. However, on future missions of much longer duration, cosmic-ray dosage may be a serious matter.

The biological damage by a single cosmic-ray particle is measured by its ''linear-energy transfer'' (LET), which is the cosmic-ray energy absorbed per micrometer of cells or living tissues penetrated. The LET is larger for higher energy, highly charged particles. In space, the important cosmic rays are the heavy ones—the nuclei of carbon, nitrogen, and oxygen (atoms of atomic weight $A$ stripped of all $Z$ electrons)—that have kinetic energies $E$ of many millions of electronvolts (see Pamphlet II). These rays have an LET of 10 keV/$\mu$m or larger (LET is proportional to $Z^2E/A$).

One unexpected biological effect of cosmic rays was the occurrence of ''light flashes,'' first reported by Astronaut Edwin ''Buzz'' Aldrin on the Apollo 11 mission to the Moon in July 1969. He reported seeing the flashes with his eyes closed. Other astronauts reported the flashes, and they were counted and timed on later Apollo and Skylab missions. As noted in Section 2, several complicated explanations have been proposed by biologists and physicists. (Actually, C. A. Tobias of the Lawrence Berkeley Laboratory had predicted in 1954 that cosmic rays would produce flashes in astronaut's eyes, but few scientists remembered his prediction.)

## D Questions for Discussion

(Cosmic Rays, Magnetic Fields, Shielding)

**1.** If you wanted to describe one cosmic ray completely, what characteristics would you list?

**2.** Why is there no Van Allen belt around the planet Venus?

**3.** Some rocks were magnetized by the Earth's magnetic field as they were formed. Measurements show that the magnetic field has changed in strength and direction during the past 500 million years. What could cause this?

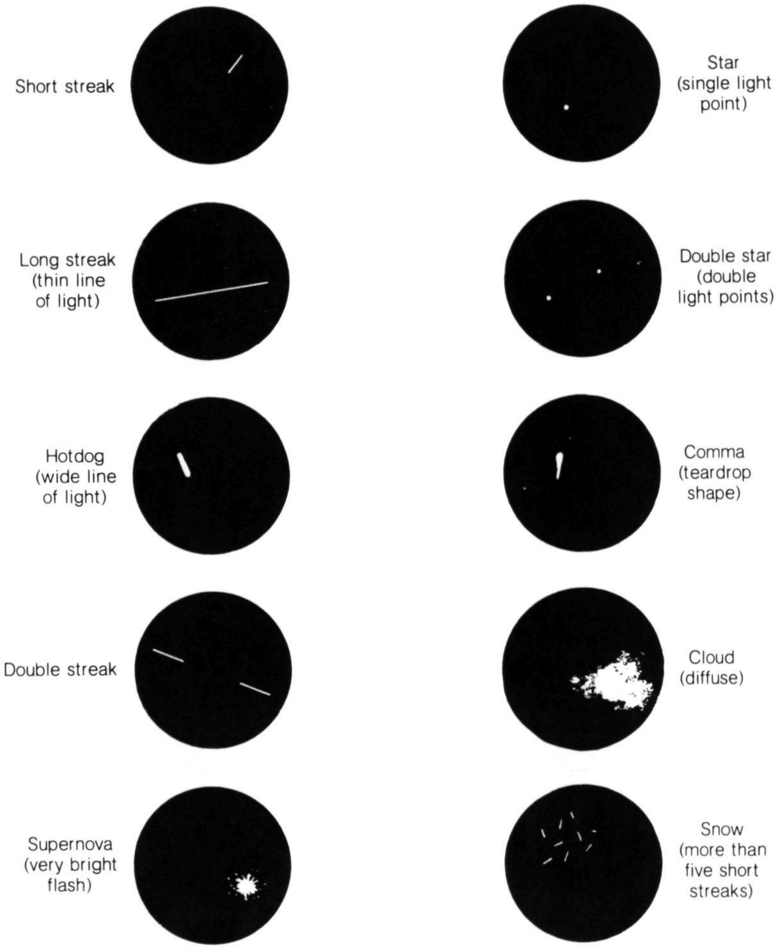
**4.** If the Earth's atmosphere were much higher, what would happen to the Van Allen belt?

**5.** Which would shield photographic film in a spacecraft better: a 1-centimeter thickness of aluminum or a 1-centimeter thickness of lead?

**6.** A 2000-megaelectronvolt cosmic ray has an LET of 10 keV/$\mu$m. If this ray were to pass through your head, how much energy would remain in the cosmic ray?

# 2 Light Flashes in the Eyes of Astronauts

The flashes of light, as reported by the astronauts, have various shapes (Fig. 2.1). The variety of shapes complicates their explanation. The simplest idea is that a cosmic ray passes through the eye's ''detector'' (the retina) and ionizes a few atoms or molecules, which results in a signal in the optic nerve. The signal is interpreted by the brain as a ''single star'' (upper right in Fig. 2.1), or perhaps a ''comma.'' The ''diffuse-cloud'' flashes, however, would seem to be something different.



**Shapes and sizes of light flashes noted in space and in cyclotron experiments.** **Figure 2.1**

One theory proposed by G. G. Fazio, a Harvard astronomer, is that the diffuse-cloud flash is "Cerenkov radiation" produced in the astronaut's eyeball. Cerenkov radiation is a "shock wave" of light emitted when a particle traveling near the speed of light *c* ($3 \times 10^8$ m/sec) enters a substance in which the speed of light is *slower* than the speed of the particle. (In glass, or plastic, or the human eyeball, light travels about 40-percent slower than *c*.) For the vitreous humor in the human eye, Cerenkov radiation would be produced whenever a 5000-megaelectronvolt cosmic ray passed into it. The resulting flash should fill the entire eyeball. It would be out of focus because the vitreous humor is located between the lens and the retina. Such out-of-focus flashes could account for the reported "diffuse clouds."

A third explanation of the flashes, proposed by T. F. Budinger of the Lawrence Berkeley Laboratory, involves a nuclear reaction between high-energy protons and the nuclei of atoms in the retina (carbon, nitrogen, and oxygen). Such nuclear collisions produce high-speed alpha particles (helium nuclei) at the rate of one $He^{++}$ for each 250 000 protons entering the eye. Budinger's calculations show that when Skylab passed through the South Atlantic Anomaly, the intensity of high-energy protons inside the spacecraft would produce eight alpha particles per minute in the two eyes of an astronaut, just as reported (Sec. 2B). These alpha particles have mass and energy high enough to produce stars and streaks (Fig. 2.1), whereas the Van Allen belt protons themselves pass through the eyes unnoticed.

In summary, there are probably at least three causes of light flashes in astronauts' eyes: (1) ionization in the retina by high-mass cosmic rays; (2) Cerenkov radiation in the eyeball by high-mass, very high energy cosmic rays; and (3) ionization in the retina by alpha particles produced by nuclear collisions with high-energy Van Allen belt protons.

## A Laboratory Experiments With Flashes in the Eyes

T. F. Budinger, the Principal Investigator for Experiment MA-106, and C. A. Tobias, the Co-Investigator, conducted a series of experiments using high-energy ions from a cyclotron at Berkeley. They knew exactly which ions were in these artificial cosmic rays and exactly how much energy they had in a narrow beam. Several Berkeley physicists volunteered as subjects. Each was blindfolded for 15 minutes or more (to adapt his eyes to darkness) and then given a few short bursts of high-energy ions through the eyes and head at specific places. Budinger found that firing the ions through the brain or optic nerve did *not* produce flashes but that firing them through the eye did. The speed (energy) of the ions was not high enough to produce Cerenkov radiation; therefore, Budinger and Tobias concluded that ionization in the retina was the main cause of the light flashes in the eyes of the astronauts.

## B Counts of Flashes in Spacecraft

The explanation of the light flashes and their different shapes is still unclear. Budinger thinks that some of the flashes may come from light emitted by atoms near the retina that have been excited by the passing cosmic ray, as well as from ionization in the retina. In Earth-orbiting spacecraft such as Skylab, where Astronaut Bill Pogue saw about 8 flashes per minute while passing through the South Atlantic Anomaly, there are obviously many different kinds of ions (protons and heavy nuclei) passing through the eye. On Apollo flights to the Moon, far from Earth, there should be mostly heavy nuclei, and the Apollo astronauts averaged 2 flashes per minute.

Apollo-Soyuz was in a much lower orbit than Skylab and passed underneath the South Atlantic Anomaly. It was expected that careful counting would show the cosmic-ray latitude effect as the spacecraft moved from the Equator to 51.8° N and then to 51.8° S latitude.

## C Experiment MA-106

The MA-106 scientists wanted timed counts and descriptions of the flashes and separate measurements of the cosmic-ray intensity near each astronaut's head. They wanted to check the astronaut's adaptation to darkness by measuring the faintest light that he could see just before the counting started. All this was accomplished with the equipment shown in Figure 2.2. Two astronauts were fitted with light-tight masks, each with a microphone in front of the mouth and a small, controllable light (''diode'') in front of one eye. The two men were placed so that their heads were beside two cosmic-ray detector boxes, and they held pushbuttons to press each time that they saw a flash. The third astronaut operated the light controls and a tape recorder that recorded each astronaut's pushbutton count and his verbal description of the flash and the counts of cosmic rays from the two detector boxes. In effect, men's eyes were calibrated as cosmic-ray detectors!

In each detector box, there were two kinds of cosmic-ray detectors. One was provided by the German Co-Investigators, who had invented it at the Nuclear Physics Institute in Frankfurt. It uses small wafers of silver chloride (AgCl) crystals doped with cadmium (Cd). Each AgCl(Cd) wafer was 1 by 2 by 0.3 centimeters. Cosmic rays have been found to leave ''latent tracks'' in AgCl(Cd) that can be developed like photographic film. However, the undeveloped tracks disappear in a few minutes unless they are ''frozen in'' by

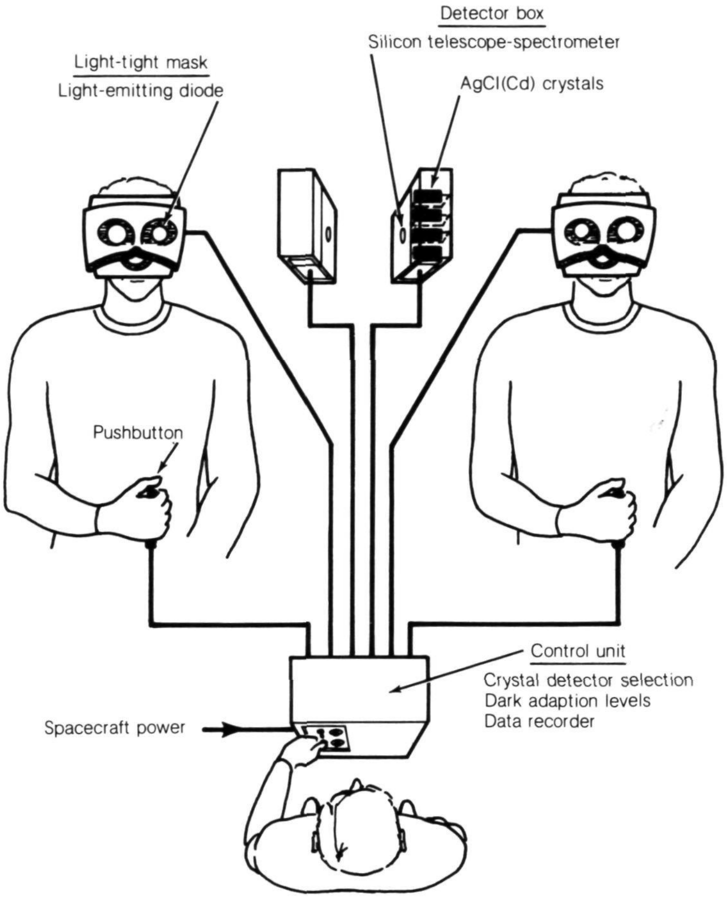
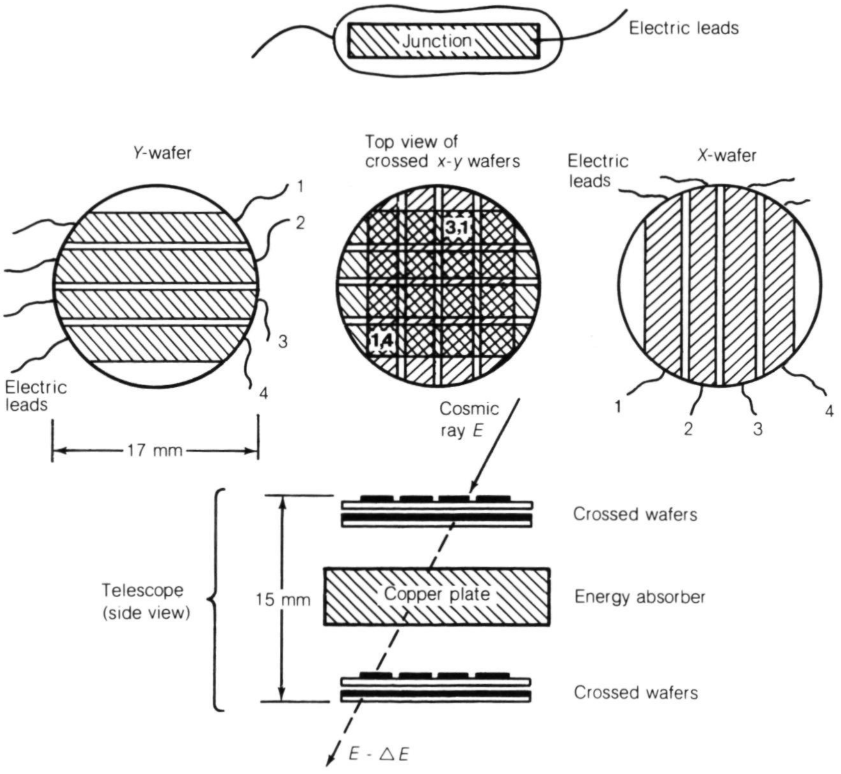


**Figure 2.2** **Experiment MA-106 layout.**

shining light on the crystal. Then, when the crystal is developed, the tracks made while the light was on (and no others) will show as black lines. The thickness and graininess of the lines show roughly the ion type and speed or energy.

The AgCl(Cd) wafers were put in four small boxes, one on each side of a small electric lamp in each box. One lamp was turned on while Apollo-Soyuz was at 50° N latitude, a second one while the spacecraft was near the Equator, a third one near the South Atlantic Anomaly, and the last one over the Pacific Ocean, all during one orbit while the astronauts were counting flashes. After Apollo-Soyuz splashed down, the crystals (still in their light-tight boxes) were sent to Frankfurt for development and analysis.

The second detector was a cosmic-ray telescope developed by the Principal Investigator and Co-Investigators at the University of California at Berkeley. This detector depends on the effect of a cosmic ray passing through a silicon solid-state junction. The effect is a pulse (count) in the electric current flowing through the junction. Budinger made a strip-shaped junction (top of Fig. 2.3) that detected a cosmic ray anywhere in its 17-millimeter length and 3-millimeter width. He put four of these detector strips on each of four 0.3-millimeter-thick silicon wafers. He used two of these wafers crossed at a 90° angle, as shown in Figure 2.3, to measure *x* and *y* where the cosmic ray entered the top of the telescope. That is, if he got a pulse on the $x = 3$ strip and a pulse on the $y = 1$ strip, the cosmic ray entered somewhere in the square patch labeled 3,1.



**Cosmic-ray telescope for Experiment MA-106.** **Figure 2.3**

At the bottom of the telescope, 15 millimeters below, was another pair of $x$-$y$ wafers, and a cosmic ray is shown going through $x = 1$, $y = 4$ there. Between the two pairs of wafers was a 5-millimeter slab of copper that reduced the cosmic-ray kinetic energy $E$ by an amount $\Delta E$ that depends on the cosmic-ray charge $Z$ and its energy $1/2\,Av^2$, where $A$ is the ion mass in atomic units and $v$ is the velocity. Therefore, the pulse sizes (larger from the top crossed wafers and smaller from the lower crossed wafers) gave an estimate of the *kind* of cosmic ray that passed, as well as its direction. The smallest detectable pulse (giving a count) corresponded to an LET of 10 keV/$\mu$m (such as nitrogen nuclei with 4000 megaelectronvolts of energy).

## D

## MA-106 Results

### Light Flashes and Cosmic-Ray Intensity

A plot of Apollo-Soyuz orbit number 111 around the Earth from 15:00 to 16:35 GMT on July 22, 1975, is shown in Figure 2.4. Each of the 82 flashes reported by the two blindfolded astronauts is plotted by one of the five symbols listed on the left. There are 42 star flashes, 1 supernova, 26 streaks or "hotdogs," and 13 commas. Note that there were few flashes reported near the South Atlantic Anomaly (SAA) or anywhere near the Equator. Most of the

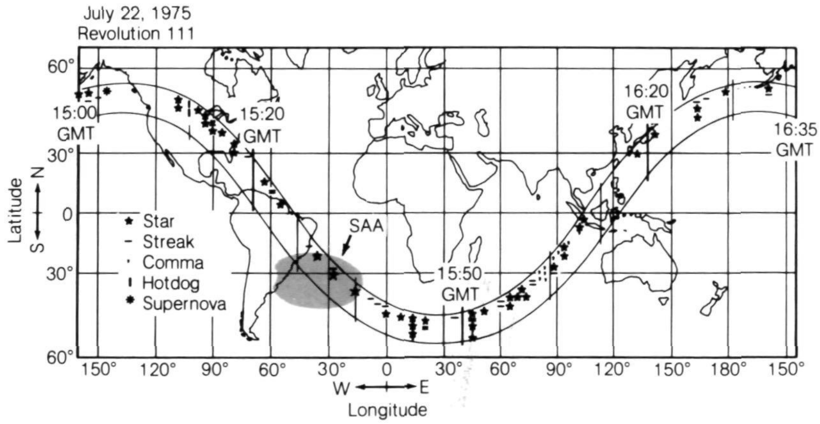
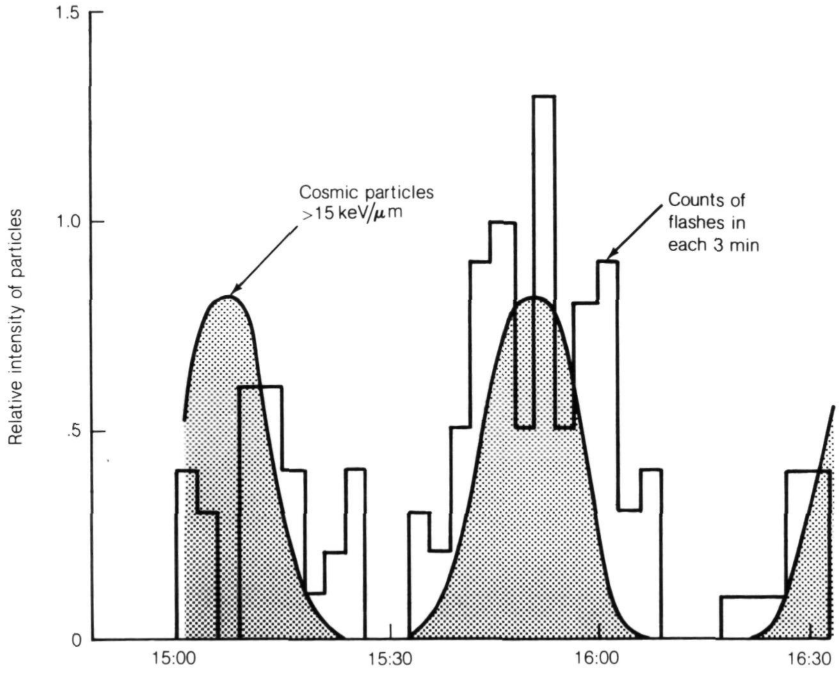


**Figure 2.4** **Orbit track and locations of reported light flashes in Experiment MA-106.**

flashes were seen between 30° and 50° N latitude and between 30° and 50° S latitude. Apollo-Soyuz at 222 kilometers altitude was clearly below the South Atlantic Anomaly, and the cosmic rays that cause flashes are more frequent far from the Equator, as expected from the latitude effect. Figure 2.5 shows a plot of the measured intensity of cosmic rays with LET larger than 15 keV/$\mu$m compared to the numbers of flashes reported by the astronauts in each 3-minute segment of the 90-minute duration of the experiment. The two peaks are the high latitudes of Apollo-Soyuz at 15:06 and 15:52 GMT. The match is fairly good and shows that the light flashes are caused by the high-energy cosmic rays that are deflected in toward the north and south magnetic poles of the Earth.



**Cosmic-ray intensity compared with astronaut's counts of flashes on Apollo-Soyuz orbit 111.** **Figure 2.5**

## E Questions for Discussion

(Flashes, Cosmic Rays)

**7.** If the astronauts had started counting flashes without waiting for their eyes to become adapted to the darkness, what errors might have been made in their reports?

**8.** While Apollo-Soyuz was between 30° and 51.8° latitude (north or south), the astronauts reported 34 stars, 1 supernova, 7 commas, and 21 streaks in about 63 minutes. While between 30° N and 30° S latitude, they reported 8 stars, 6 commas, and 5 streaks in about 30 minutes. On the way to the Moon, far from Earth, Apollo astronauts counted 2 or 3 flashes per minute. What can be concluded about cosmic rays and flashes from these numbers?

**9.** The cosmic-ray telescope detected rays that passed through both pairs of crossed wafers. What cosmic rays did it miss?

**10.** If the number of flashes per minute had been much higher, what kind of error might have been made in the astronauts' reports?

**11.** The artificial cosmic rays used in the laboratory so far to produce light flashes are not of high enough energy and mass to produce Cerenkov radiation. If higher energies and mass are used someday, what results would you expect?

# 3 Cosmic-Ray Effects on Bacterial Spores, Seeds, and Eggs

Small organisms can be carried aboard spacecraft in large numbers, and the effects of cosmic rays on them can be measured statistically. Furthermore, it is possible to count the actual number of cosmic-ray ''hits,'' rather than just measure the cosmic-ray intensity near an astronaut's head, as was done in the Light Flash Experiment. In the Biostack III Experiment (MA-107), individual cosmic rays were tracked through layers of bacterial spores, small seeds, and eggs interleaved with layers of AgCl-crystal wafers, special plastic, and special photographic film that registered where each cosmic-ray particle passed.

The objective of Experiment MA-107 was to determine the damage caused by cosmic-ray hits on these small living organisms, especially the changes (mutations) in the organisms as they grew in the laboratory after the mission. From these studies, we hope to learn what damage cosmic rays may do to men and women on long spaceflights. The Principal Investigator, Horst Bücker, had 32 Co-Investigators who were experts in various biological fields—spores, bacteria multiplication, mutations, development of seeds, growth of plants, and development of eggs and insects—as well as experts on cosmic rays.

## A HZE Particles

The most damaging cosmic-ray particles are those with high electric charge (high $Z$, the atomic number) and high kinetic energy $E$. When such *H*igh-*Z*, High-*E* (HZE) particles pass through a substance, they leave a large amount of energy along their track—energy that ionizes the atoms and disrupts molecules. In some plastics, the material along the track is so changed that it can be ''etched'' out by sodium hydroxide (NaOH, a strong alkali), leaving a thin tube along the track. The HZE tracks can also be seen on ''nuclear track emulsion'' (a special photographic film) after it is developed. (The silver chloride, AgCl, is broken into silver (Ag) and chlorine (Cl) along the track, and the silver particles show black on the developed film.) The emulsion is spread thickly (0.6 millimeter) on the film, and physicists can see the HZE tracks in a microscope as little black lines at various angles through the emulsion. As noted in Section 2C, large crystals of AgCl(Cd) also record HZE tracks while they are illuminated with yellow light.

The MA-107 scientists used all these methods to record HZE tracks through a sealed stack of 277 wafers about 10 centimeters in diameter (Fig. 3.1). The height of the stack was 12.5 centimeters, and the sheets of spores, seeds, and eggs were interleaved with cellulose nitrate plastic (CN), polycarbonate plastic (Lexan), and nuclear-track photographic film. Figure 3.2 shows a small part of the stack in Container A. Each of the two layers labeled PVA has

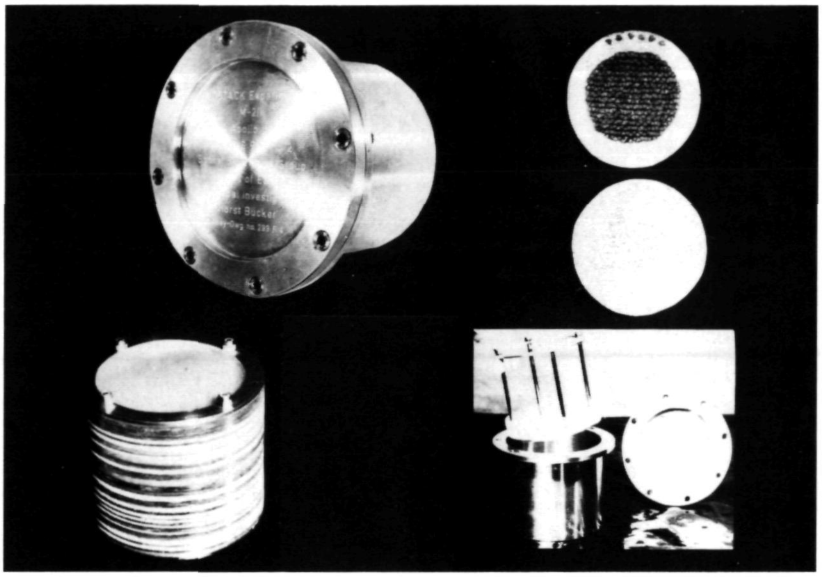


Figure 3.1 **Biostack III Container A and Container B for Experiment MA-107.**

a single layer of seeds embedded in polyvinyl alcohol (a kind of glue). The etched tracks in the CN sheets showed the path of an HZE particle through the stack. The HZE particle often passed through one or more spores, seeds, or eggs, as shown in Figure 3.2. The size of the etched tracks on CN and Lexan showed the energy and approximate Z (ion charge). The photographic emulsion detected lower energy tracks, and the AgCl(Cd) crystals in Container B recorded the lowest energy cosmic rays (1 keV/$\mu$m LET). The crystals showed that 1500 cosmic rays passed through each square centimeter of the Apollo spacecraft during the 217 hours that it was in orbit.

However, of these 1500 cosmic rays/cm$^2$, only 1 percent were HZE particles (with Z greater than 6) that produced wide tracks in the CN etched with NaOH. It is this 1 percent that is expected to cause damage, rather than either the lower energy protons ($Z = 1$) or the alpha particles ($Z = 2$). From the different numbers of tracks in the crystals, photographic film, and etched plastic, Bücker and his Co-Investigators were able to estimate the spectrum of the cosmic-ray energies plotted in Figure 3.3. They also counted "disintegration stars" like the one shown in Figure 3.4, where an atomic nucleus exploded (upon capturing a pion), resulting in many short tracks (100 to 200 micrometers) going in all directions. There were about 3500 of these stars per

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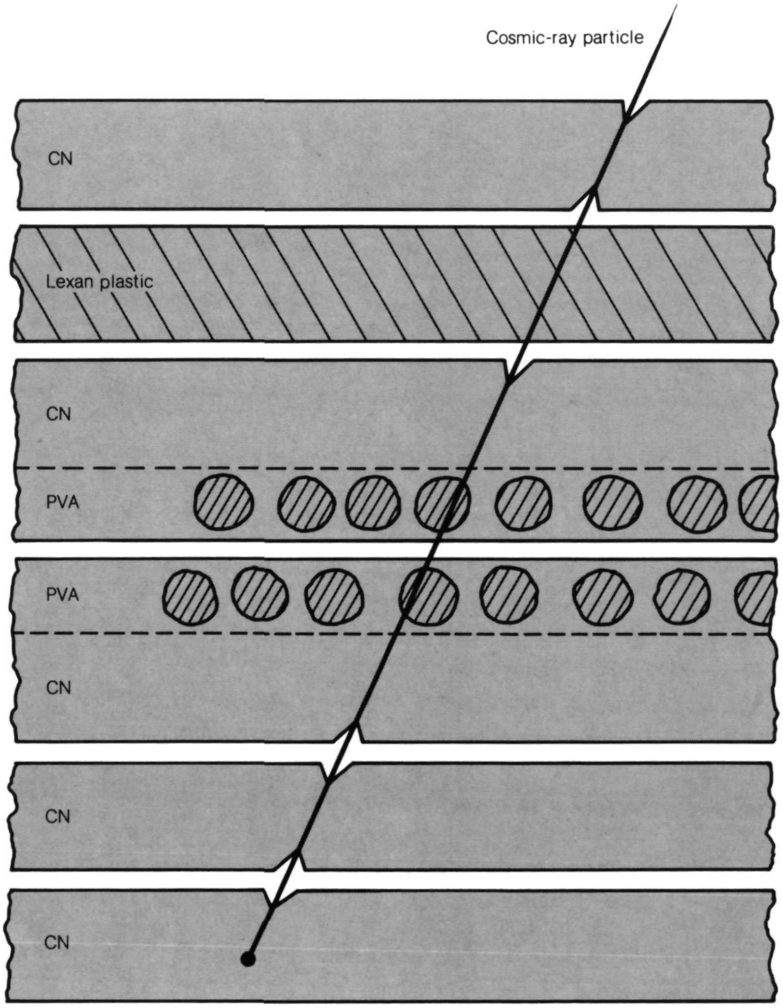
cubic centimeter of photographic emulsion, and presumably about the same number (undetected) per cubic centimeter of spores, seeds, and eggs. Because these disintegration stars release nuclear energy, they are thought to damage living organisms like HZE particles do.



**Part of Biostack III Container A with cosmic-ray track.** **Figure 3.2**

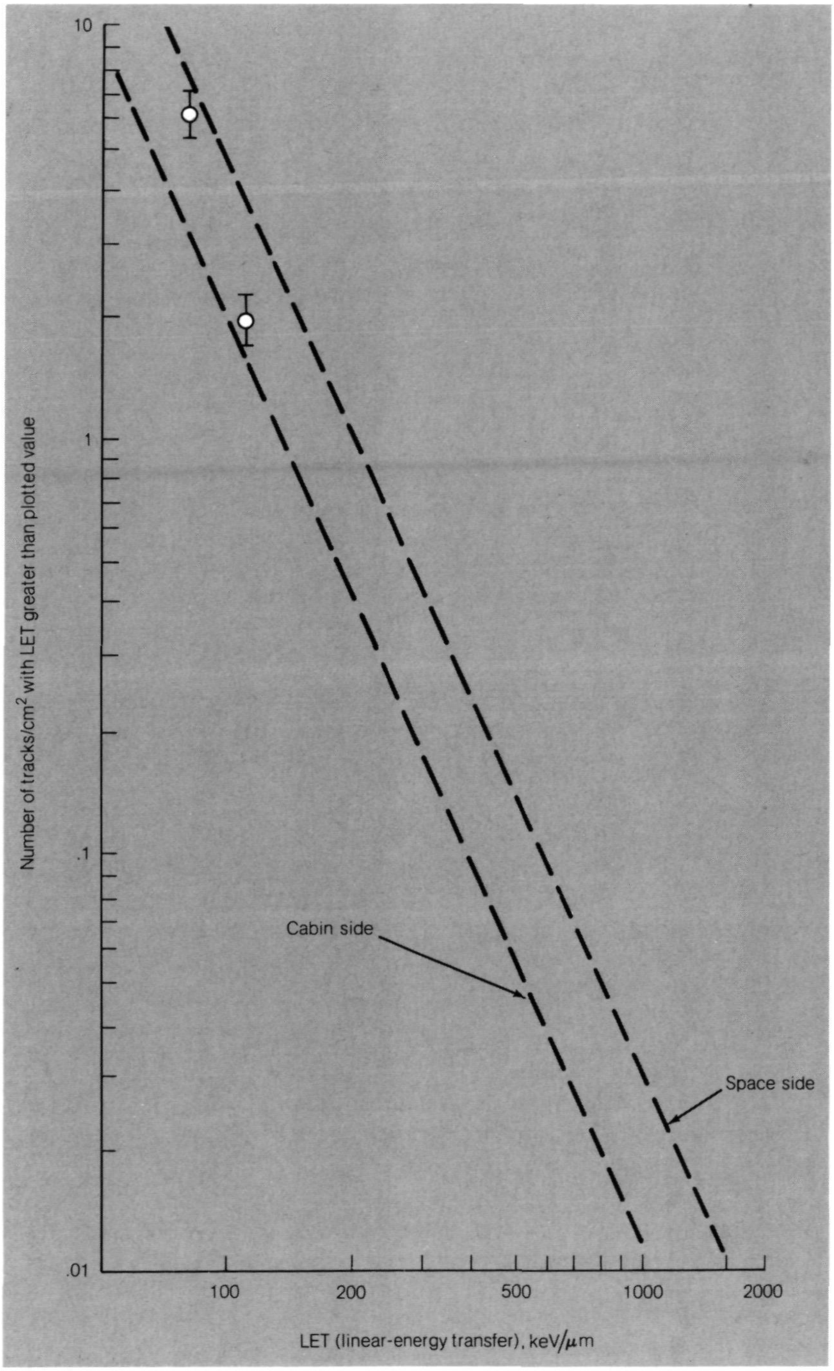
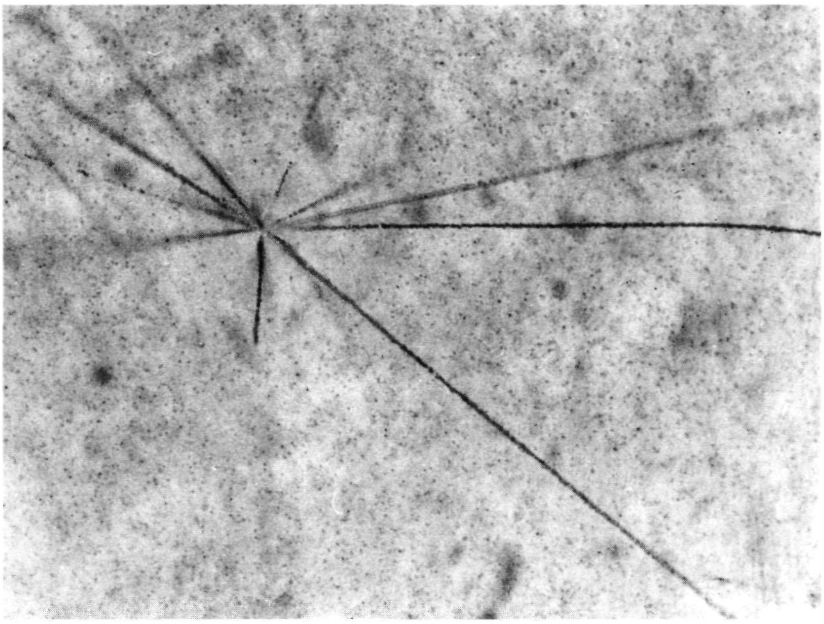


**Figure 3.3** **Cosmic-ray energy spectrum for MA-107 Container A.**



**Disintegration-star tracks magnified 500 times.** **Figure 3.4**

## B Mapping the HZE Hits

The Frankfurt scientists built a very accurate ''micromanipulator'' with which they could pick up spores of 1-micrometer size and place droplets of NaOH on a partly etched cosmic-ray track with a precision of 0.1 micrometer. They had microscopes arranged to measure $x$ and $y$ coordinates on the plastic sheets and films to an accuracy of 0.1 micrometer.

The principle of mapping the HZE tracks through several sheets of plastic and two layers of seeds is shown in Figure 3.2. Because the NaOH used to etch the HZE tracks in the plastic would kill the seeds, the seed layers were sealed between two plastic sheets while the sheets were etched in NaOH for 18 hours. This etching process started a small conical hole in the plastic surface wherever an HZE particle had passed through. With the micromanipulator, the scientists then put droplets of NaOH into the hole to make it deeper and deeper, until it almost reached the seed on the other side of the plastic (Fig. 3.5). This process was repeated for about 3000 tracks on 35 sheets and enabled the scientists to identify 186 seeds and 409 eggs hit by HZE particles. The spores were so small that when the scientists measured the distance from the center of the spore to the nearest HZE track, they found more than 400 spores within 10 micrometers of a track; 22 of them were within 1 micrometer.

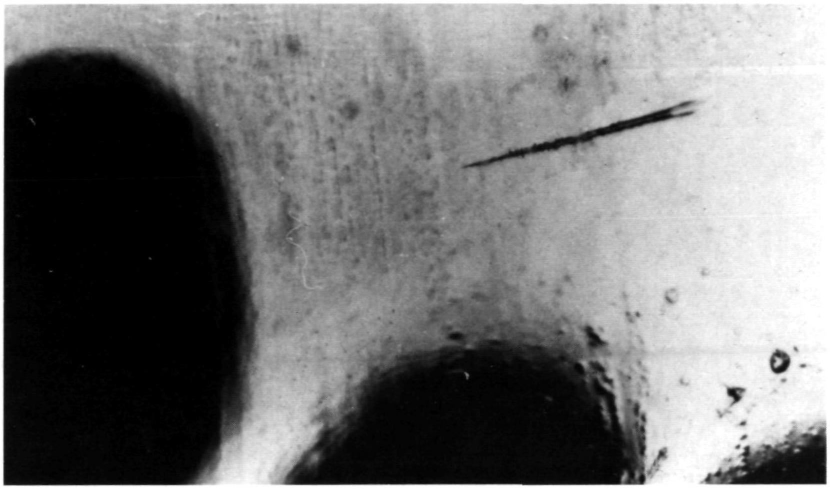


**Figure 3.5** **Etch cone of an HZE-particle track in CN, covered with *Arabidopsis thaliana* seeds in polyvinyl alcohol (PVA).**

## C MA-107 Results on Biological Damage From HZE Hits

After a spore, seed, or egg was identified as having been "hit," it was carefully removed with the micromanipulator. The spores were placed in a known place ($x$ and $y$ measured) on a nutrient jelly. Some of the seeds were planted, and all the eggs were incubated to hatch. Two control groups—one of spores, seeds, and eggs from Biostack III that were *not* near an HZE track and one that remained in Frankfurt during the flight—were handled in the same way.

The MA-107 scientists were aware that factors other than the HZE hits might affect the spores, seeds, and eggs. For instance, they might have become disrupted by one or more of the disintegration stars (Fig. 3.4), or have been hit by low-energy cosmic rays, or have been affected by weightlessness (Pamphlets I and VII) for 9 days in Apollo-Soyuz. There was also the chance that the HZE hit did not pass through a vital part of the spore, seed, or egg. Like many biological experiments, this experiment had to be *statistical,* combining the effects observed on many individuals to give the *probability* of damage from an HZE hit. This is why such a large number of small organisms (about 5 × $10^9$ spores, 23 000 seeds, and 30 000 eggs) were carried on Apollo-Soyuz.

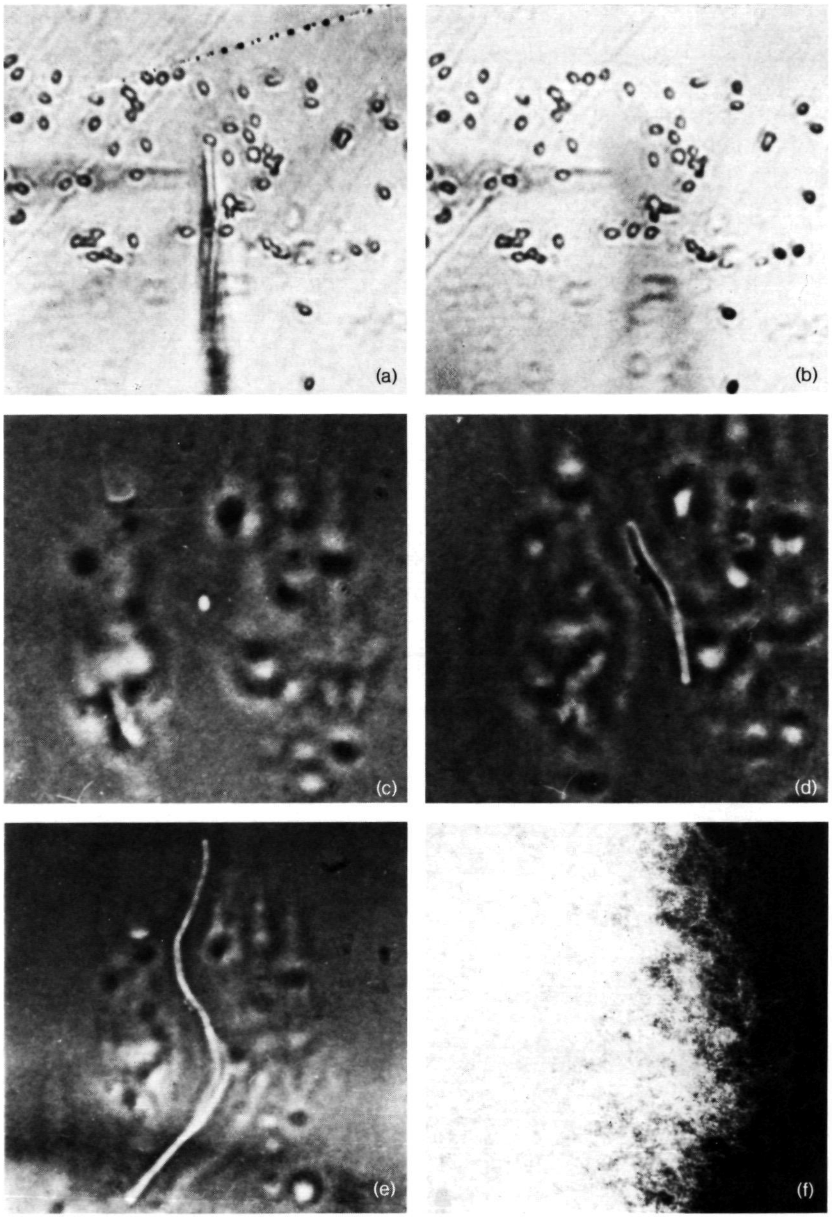


**Figure 3.6**

**Manipulation and growth of a single *Bacillus subtilis* spore. The spore to be removed is shown at the end of the needle in (a); the spore has been removed in (b). Increasing incubation times to 250 minutes are shown in (c), (d), and (e). and the colony after 24 hours is shown in (f).**

The spores were single-cell "eggs" of *Bacillus subtilis* bacteria. When "planted" in warm nutrient jelly, they normally produce a colony of bacteria that multiply rapidly after a few hours (Fig. 3.6). The fraction of spores that formed colonies is plotted in Figure 3.7 against the distance from an HZE track. Only 68 percent of the 22 spores that were less than 1 micrometer from an HZE track were able to form colonies, whereas 89 to 90 percent of the 50 spores in the control groups formed colonies. The fact that 50 spores carried on Apollo-Soyuz (but located more than 50 micrometers from any HZE track) performed just like 50 spores in the ground-control group shows that no other factor affected them.

Ninety seeds of the *Zea mays* plant were hit by HZE particles, and 17 of these were planted immediately. (The others were grown later.) Fifteen

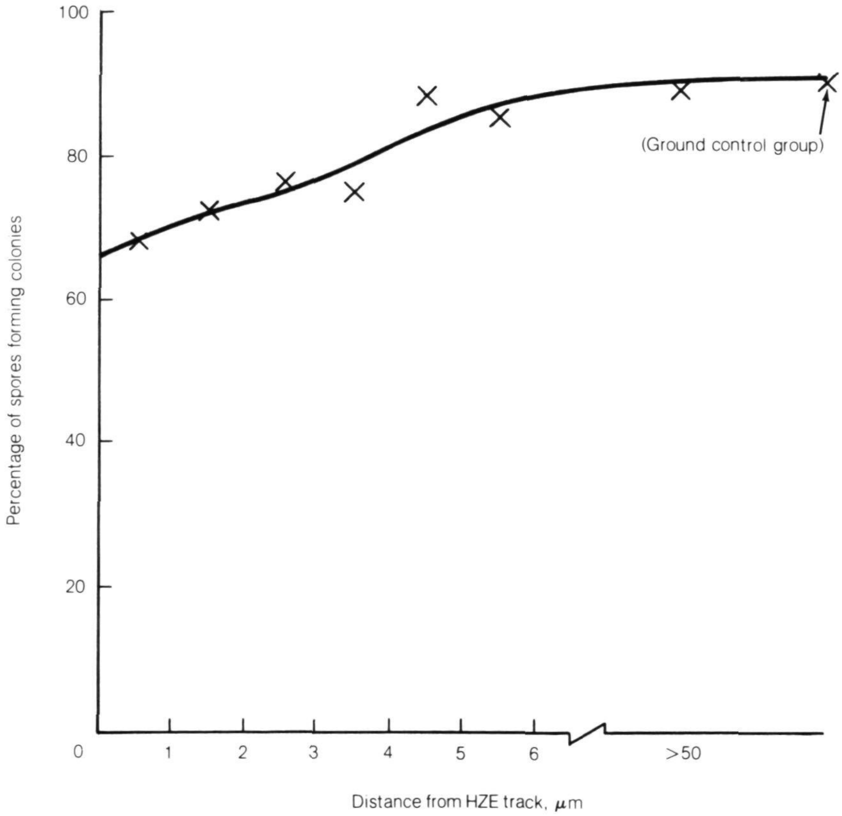
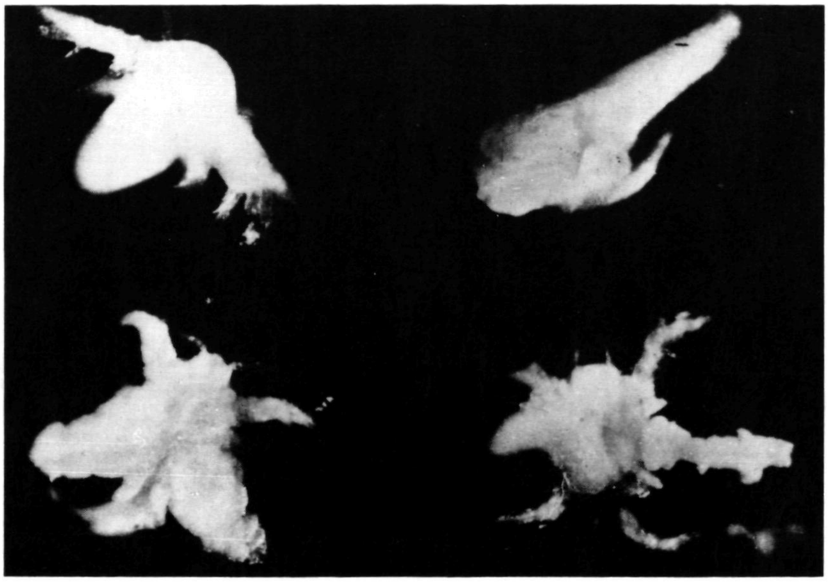


**Figure 3.7** **Percentage of spores forming colonies.**

plants sprouted, but five of them had smaller leaves than the 64 control plants. Eighteen seeds of another plant *(Arabidopsis thaliana)* were hit, but these young plants showed no significant differences from the control plants.

Most of the eggs hit by HZE particles later showed serious damage. The number that hatched was lower than in the control groups, and some of the larvae were deformed (Fig. 3.8). By careful observation and microscopic dissection, the MA-107 scientists hope to learn what parts of the eggs were vulnerable to HZE hits.

Much more research is needed before these studies can be applied to the question of how HZE particles and other radiation in spacecraft may injure men and women over long periods of time. It is worth noting that the eggs and spores carried on Apollo-Soyuz in Biostack III are known to be *more* resistant to x-rays than man is. The lethal dose (a dose that kills 50 percent of the organisms in question) is 400 rads for humans, about 1000 rads for the eggs, and about 100 000 rads for the spores. Assuming that the damage by HZE cosmic rays is similar to the damage by x-rays, men and women should be more vulnerable to cosmic rays than the small organisms carried on Apollo-Soyuz.



**Malformations of *Artemia salina* induced by HZE particles that penetrated their eggs.** **Figure 3.8**

## D Questions for Discussion

(Cosmic Rays)

**12.** Why should high-$Z$ particles make larger tracks and cause more biological damage than protons of the same kinetic energy?

**13.** Are HZE cosmic rays expected to show the same latitude effect as lower energy cosmic rays?

**14.** At any one moment, did cosmic rays come in on Apollo-Soyuz equally from all sides?

**15.** Can you tell which way the HZE particle moved along the track in Figure 3.5?

# Appendix A

## Discussion Topics (Answers to Questions)

**1.** (Sec. 1D) A cosmic ray would be completely described by its speed (usually given as kinetic energy $E$), ion charge $Z$ (positive), mass $A$ in atomic mass units, and direction of motion (two angles needed). Note that because the ions are completely stripped of electrons, the atomic number $Z$ specifies $A$ (because $A$ is approximately $2Z$ for most elements).

**2.** (Sec. 1D) Venus has no magnetic field and therefore no Van Allen belt.

**3.** (Sec. 1D) Changes in the Earth's magnetic field detected by comparing the magnetism of old (dated) rocks with the present field direction could be due to two causes: (a) the currents in the Earth's core changed, thereby changing the magnetic dipole, or (b) continental drift (see Pamphlet V) moved the rocks from where they were formed to a different place.

**4.** (Sec. 1D) If the Earth's atmosphere were drawn on Figure 1.1, it would extend only 1 millimeter or so above the circle representing the Earth. The electrons and protons of the Van Allen belt are reflected back in the polar regions much higher than this. However, if the atmosphere were 10 times thicker, it would interfere with the north-south oscillations of the electrons and protons at each end. The electrons and protons would be absorbed and the Van Allen belt would be eliminated.

**5.** (Sec. 1D) Lead has higher density (11.3 gm/cm$^3$) than aluminum (2.7 gm/cm$^3$); therefore, a lead shield of 1-centimeter thickness has much more mass. It is the mass per unit area that absorbs cosmic rays and x-rays, so 1 centimeter of lead is the better shield. (The production of secondary gamma rays in both shields—more in lead—makes an accurate answer more complex than this.) Living tissues have a density near 1 gm/cm$^3$.

**6.** (Sec. 1D) Your head is about 16 centimeters or 160 000 micrometers thick. The 2000-megaelectronvolt cosmic ray would therefore lose $1.6 \times 10^6$ kiloelectronvolts or 1600 megaelectronvolts and come out with only 400 megaelectronvolts of energy.

**7.** (Sec. 2E) If the astronauts had counted flashes before their eyes had adapted to darkness, they might have missed some of the smaller, fainter flashes at the beginning of the experiment. The Principal Investigator wanted the same eye sensitivity to flashes throughout the experiment.

**8.** (Sec. 2E) At high latitudes, the astronauts counted 63 flashes in 63 minutes; near the Equator, they counted only 19 flashes in 30 minutes, which is equivalent to 40 flashes in 63 minutes. The higher rate at high latitude shows that the intensity of cosmic rays there more nearly resembles the intensity of cosmic rays far from the Earth where the rate was 2 or 3 flashes per minute. (Note that the Earth cuts the cosmic-ray intensity in half for a low-orbiting spacecraft because it shields one side. On the way to the Moon, Apollo had no such Earth shield.) The ratio of streaks to stars and commas was 21 to 42 for high latitudes and 5 to 14 near the Equator. These ratios may show some differences in the kinds of cosmic rays coming in to polar and equatorial regions. (There is also some question about the relative sensitivity of different astronauts' eyes to flashes, but the individual reports are not available.)

**9.** (Sec. 2E) Figure 2.3 shows that the "field of view" (Pamphlets II and III) of the MA-106 cosmic-ray telescope was about 77°. That is, there is a cone in which all the rays were counted: 12 millimeters wide at the top, coming to a point at the center, and 12 millimeters wide at the bottom, 15 millimeters below. The angle $\theta$ of this cone is half the field of view, and $\tan \theta = 6/7.5 = 0.80$, and $\theta = 38.7°$. The telescope missed all the rays coming in from the sides (and a few between the junction strips).

**10.** (Sec. 2E) If the flash rate were much higher, an astronaut might see two or three flashes almost at once and think that he saw only one. Then he would report fewer than the actual number of flashes.

**11.** (Sec. 2E) If 5000-megaelectronvolt neon ions are someday fired into human eyes, they should produce Cerenkov radiation in the eyeball. These would be seen as "diffuse clouds" (Fig. 2.1).

**12.** (Sec. 3D) The larger electric charge on a high-$Z$ ion produces strong electric forces that extend farther out on all sides than do those from a proton ($Z = 1$). The ionization along the high-$Z$ ion path thus extends farther out in plastic or living tissue and affects a larger volume along its track.

**13.** (Sec. 3D) The "bending" of a cosmic ray by the Earth's magnetic field in Figure 1.1 is caused by a force perpendicular to both the field and the particle's velocity vector $\mathbf{v}$. This force is proportional to the ion's charge $Z$ and speed $v$, but the acceleration is inversely proportional to its mass $A$, which is much larger for high $Z$. Therefore, HZE particles are deflected less because of large $A$ and also because the acceleration produces less bending at higher speed. (The radius of curvature is proportional to $Av/Z$.) The latitude effect will thus be smaller for HZE cosmic rays.

**14.** (Sec. 3D) The Earth is an effective shield, so there were never any cosmic rays coming up from Earth toward Apollo-Soyuz.

**15.** (Sec. 3D) Unless the track ends, there is no way to tell which way the cosmic ray was moving. (However, it is more likely that the ray came from the bottom end of Biostack III, which faced the Apollo cabin wall, unless Apollo was rolled so that the wall faced Earth.)

# 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 = $3.9 \times 10^{-5}$ 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 = $2.20 \times 10^{-6}$ lb = $3.5 \times 10^{-5}$ oz |
| Time | second | sec | 1 yr = $3.156 \times 10^7$ sec<br>1 day = $8.64 \times 10^4$ 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 | $N/m^2$ | $1\ N/m^2 = 1.45 \times 10^{-4}\ lb/in^2$ |
| Energy | joule | J | $1\ J = 0.239$ calorie |
| Photon energy | electronvolt | eV | $1\ eV = 1.60 \times 10^{-19}\ J$; $1\ J = 10^7$ erg |
| Power | watt | W | $1\ W = 1\ J/sec$ |
| Atomic mass | atomic mass unit | amu | $1\ amu = 1.66 \times 10^{-27}\ kg$ |

### 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 | $1\ g = 9.8\ m/sec^2$ |

## 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.

**AgCl(Cd) crystal** silver chloride with a small amount of cadmium added; used to record cosmic-ray tracks. (Secs. *2C,* 3, 3A; Fig. 2.2)

**alpha particle** a helium atom ($Z = 2$) with two electrons removed; the helium nucleus. (Secs. 2, 3A)

**Cerenkov radiation** the visible light emitted by a particle traveling near the speed of light when it enters a substance where the velocity of light is less than the particle's speed. (Secs. *2,* 2A, 2E; App. A, no. 11)

**CN (cellulose nitrate)** a plastic in which HZE tracks can be etched with NaOH. (Sec. 3A; Figs. 3.2, 3.5)

**Co-Investigator** a scientist working with the Principal Investigator on a NASA experiment.

**control group** a group of individuals (spores, seeds, eggs, people) with the same characteristics as the experimental group and treated the same way except for the one factor (such as exposure to cosmic rays) that is being tested by the experiment. (Sec. 3C; Fig. 3.7)

**cosmic ray** an extremely high speed ion; a stripped atomic nucleus. Solar cosmic rays are blown out of the Sun; galactic cosmic rays arrive from all directions. (Secs. 1, *1A,* 1B to 3E; App. A, nos. *1,*5, 6, 8, 9, 13 to 15; Figs. 1.1, *2.3,* 2.5, 3.2, 3.3) See *HZE, ion, radiation, track;* also see Pamphlets II and III.

**count** one pulse of current or voltage from a detector, indicating the passage of a photon or particle through the detector. (Secs. 1B, 2C) See *telescope.* Light flashes were counted by astronauts for Experiment MA-106. (Secs. 1C, 2B, 2C; App. A, nos. 7, 8, 10; Fig. 2.5)

**cyclotron** a machine that produces very high speed (high-energy) ions by whirling them around in a magnetic field. (Sec. 2A; Fig. 2.1)

**disintegration star** several particle tracks, from 100 to 200 micrometers long, starting from one point, showing the explosion of an atomic nucleus. (Secs. *3A,* 3C; Fig. *3.4*)

**electronvolt (eV)** a unit of energy equal to the kinetic energy of an electron accelerated from rest by 1 volt: 1000 electronvolts = 1 kiloelectronvolt; 1000 kiloelectronvolts = 1 megaelectronvolt or $1.6 \times 10^{-13}$ joule.

**emulsion** the sensitive layer on photographic film. Some emulsions are specially manufactured to detect tracks of ions. (Sec. 3A)

**etch** to dissolve a plastic where a cosmic ray has changed the composition of the plastic along its track. The etching of CN and Lexan plastic is done with NaOH. (Secs. 3A, 3B; Fig. 3.5)

**gamma rays** very high energy photons of wavelength shorter than x-rays and energy higher than x-rays (higher than about 100 kiloelectronvolts). Gamma rays are produced by nuclear reactions and other processes in distant regions of space. (Secs. 1B, 1C; App. A, no. 5) See Pamphlet II.

**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 space missions to avoid confusion with other time zones. See Pamphlet I.

**HZE particles** cosmic rays with high atomic number $Z$ and high kinetic energy $E$; atomic nuclei of atomic number $Z$ greater than 6 and energy $E$ greater than 100 megaelectronvolts. (Secs. *3A,* 3B, 3C; App. A, no. 13; Figs. 3.5, 3.7, 3.8)

**ion** an atom with one or more electrons removed or, more rarely, added. Cosmic-ray ions have all electrons removed and ionize other atoms as they pass them at high speed. (Secs. 1A, 1C, 2 to 2C, 3A; App. A, nos. 1, 11 to 13)

**junction** the interface between two solid materials. A silicon solid-state junction passes a pulse of current when a cosmic ray passes through. (Sec. *2C;* App. A, no. 9; Fig. *2.3*)

**kiloelectronvolt (keV)** See *electronvolt.*

**latitude effect** the decrease of cosmic-ray intensity on Earth from high latitudes to the Equator. (Secs. *1A,* 2B, 2D; App. A, nos. 8, 13)

**LET (linear-energy transfer)** the energy lost from a cosmic ray per micrometer along its track as it passes through living tissue. It is also called "stopping power." (Secs. *1C,* 1D, 2C, 2D, 3A; Fig. 3.3)

**Lexan** polycarbonate plastic in which HZE tracks can be etched with NaOH. (Sec. 3A; Fig. 3.2)

**MA-106** the Light Flash Experiment on the Apollo-Soyuz mission. (Secs. 1, 2A, *2C,* 2D; App. A, no. 9; Figs. 2.2 to 2.5)

**MA-107** the Biostack III Experiment. (Secs. 1, *3*, 3A to 3C; Figs. 3.1 to 3.3)

**magnetic dipole** a bar magnet with a north pole at one end and a south pole at the other. Electric current in a coil of wire produces a similar magnetic dipole. (Sec. 1A; App. A, no. 3; Fig. *1.1*)

**magnetic field** the strength of the magnetic force on a unit magnetic pole in a region of space affected by magnets or electric currents. (Secs. 1A, 1D; App. A, nos. 2, 3, 13; Fig. *1.1*)

**magnetic lines of force** theoretical lines giving the direction of the force on a test magnetic pole at any place in a magnetic field. (Sec. 1A; Fig. *1.1*)

**magnetosphere** a region around the Earth which the solar wind cannot penetrate because of the Earth's magnetic field. (Sec. 1A)

**megaelectronvolt (MeV)** See *electronvolt.*

**micrometer ($\mu$m)** one-millionth of a meter, formerly called a micron.

**Milky Way Galaxy** a disk-shaped group of more than 100 billion stars, including our Sun. (Sec. 1A) See Pamphlet II.

**mutation** a change in the DNA (deoxyribonucleic acid) "code," usually caused by a cosmic ray passing through the nucleus of a cell that controls development. The developed organism, a mutant, differs from others in its species. (Sec. 3)

**NaOH** sodium hydroxide, a strong chemical used to etch CN and Lexan plastic so that cosmic-ray tracks through the plastic will show. (Secs. 3A, 3B)

**nutrient jelly** a culture medium made of agar, sugar, water, and other materials needed as food by growing bacteria. (Sec. 3C)

**orbit** the path followed by a satellite around an astronomical body such as the Earth or Moon. The orbit number was used on Apollo-Soyuz to identify the time. (Secs. 2C, 2D; Figs. *2.4*, 2.5)

**pion** an unstable nuclear particle (meson) of mass between the electron and the proton that can cause an atomic nucleus to explode. (Sec. 3A)

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

**proton** a positively charged atomic particle, the nucleus of the hydrogen atom. Ionized hydrogen is made up of separated protons and electrons. (Secs. 1 to 1C, 2, 2B, 3A, 3D; App. A, nos. 4, 12; Fig. 1.1)

**PVA (polyvinyl alcohol)** an inert glue used to hold small spores, seeds, and eggs to a plastic sheet in the Biostack III Experiment. (Sec. 3A; Figs. *3.2*, 3.5)

**rad (*r*adiation *a*bsorbed *d*ose)** a unit of radiation damage to living organisms; equal to $10^{-5}$ joule absorbed per gram of tissue. (Secs. *1C*, 3C)

**radiation** a term used loosely to include cosmic-ray particles and high-energy protons, as well as penetrating electromagnetic waves (x-rays and gamma rays). (Secs. *1*, 1A, *1B*, 1C, 3C)

**retina** the region at the back of the eyeball, formed of nerve ends sensitive to light. Light is focused there by the lens at the front of the eye. (Secs. 2 to 2B)

**shield** an absorbing material that prevents the passage of radiation or reduces its intensity. (Secs. 1, 1B; App. A, nos. *5*, 8, 14)

**Skylab** a very large space workshop that NASA put into orbit on May 14, 1973. It was visited by three astronaut crews who worked on scientific experiments in space for a total of 172 days. (Secs. 1 to 1C, 2, 2B)

**solar wind** a stream of ionized gas, mostly protons and electrons, blown out of the Sun at high speed (20 km/sec) on all sides. (Sec. 1A)

**South Atlantic Anomaly (SAA)** an irregularity in the Earth's magnetic field, east of Brazil, where the radiation in the Van Allen belt is very intense. (Secs. *1A*, 2, 2B to 2D; Fig. 2.4)

**spore** a small seed-germ that can grow into a microbe or a plant such as a fern. Spores of bacteria (about 1 micrometer in size) were used in Experiment MA-107. (Secs. 1, 3 to 3B, *3C;* Figs. *3.6,* 3.7)

**telescope** an instrument for measuring the direction of incoming rays. (Secs. 2C, 2E; App. A, no. 9; Fig. *2.3*)

**track** the path of a cosmic ray through a substance that is changed by the passage of a high-speed ion. Photographic emulsion must be developed and CN and Lexan plastic etched to show the tracks. ''Latent tracks'' in AgCl(Cd) crystals disappear unless the crystals are illuminated by yellow light. (Secs. *2C,* 3A, 3B, 3D; App. A, no. 15; Figs. *3.2*, 3.3, 3.4, *3.5*, 3.7)

**ultraviolet** invisible light of wavelengths less than 4000 angstroms (400 nanometers), shorter than those of visible light. (Sec. 1B)

**Van Allen belt** a doughnut-shaped region around the Earth from about 320 to 32 400 kilometers (200 to 20 000 miles) above the magnetic equator, where high-speed protons and electrons oscillate north-south in the Earth's magnetic field. (Secs. 1, 1A, 1B, 1D, 2; App. A, nos. 2, 4; Fig. *1.1*)

**weightlessness** the condition of free fall or zero-g in which objects in an orbiting spacecraft are weightless. (Secs. 1, 3C)

**x-rays** electromagnetic radiation of very short wavelength (about 0.1 to 100 angstroms, or 0.01 to 10 nanometers) and high photon energy (about 100 electronvolts to 100 kiloelectronvolts). (Secs. 1B, 1C, 3C; App. A, no. 5) See Pamphlet II.

**Z** atomic number, or the number of electrons in an atom. Cosmic rays are atoms with all electrons removed; that is, ions of charge $Z$. (Secs. 1C, 2C, 3A, 3D; App. A, nos. 1, 12, 13)

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