SKYLAB,
Classroom in Space

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Skylab, Classroom in Space

NASA SP-401

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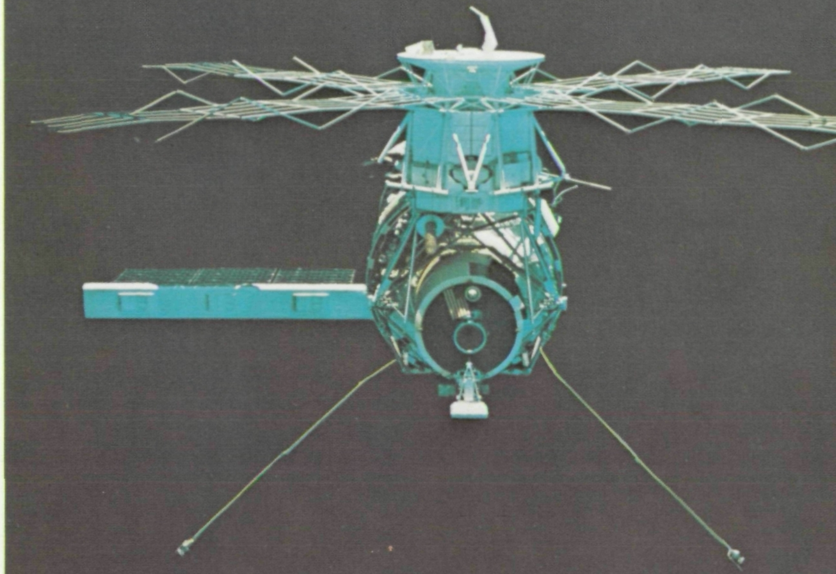
Scientific and Technical Information Office
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.
1977

Classroom in Space

Edited by Lee B. Summerlin

Prepared by
George C. Marshall
Space Flight Center



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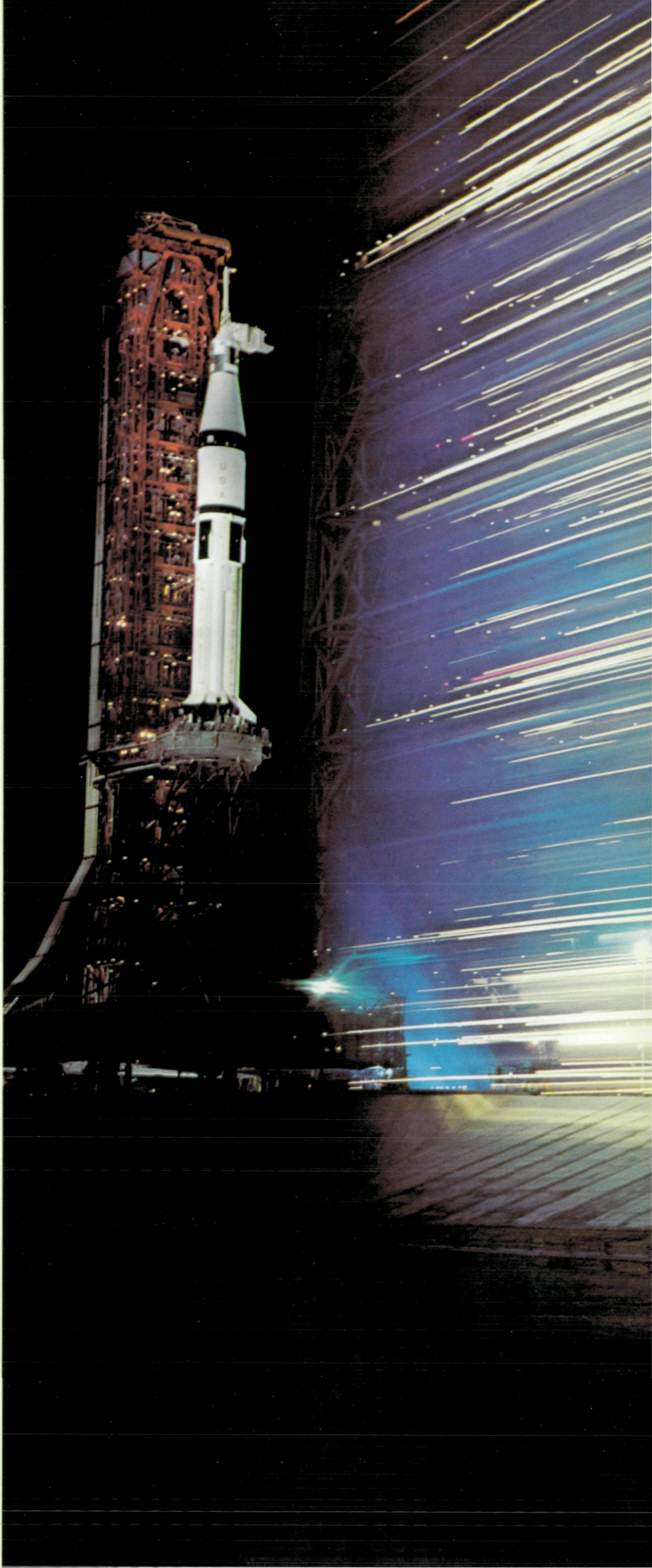
FOREWORD

One of the most challenging projects in our nation's exploration of space was the Skylab program. The very concept of launching and operating a scientific laboratory in space, with teams of scientist-astronauts journeying out to operate it for periods of time, was awe inspiring.

The Skylab program was dedicated to the use of the unique environment and vantage point of space to increase our knowledge and understanding of Earth's importance to man's well-being and man's influence on Earth's ecology. It also represented a major step in manned spaceflight, serving as a bridge between the Apollo flights and the long-duration spaceflights of the future.

To accomplish this mission, Skylab was launched in May 1973, was placed in Earth orbit, and was visited and inhabited by three different crews during an 8-month period. Data were acquired by Skylab primarily through the conduct of experiments in physical science, biomedical science, Earth applications, and space applications. Skylab was a laboratory and workshop with unique features: a constant zero-gravity environment, sustained operation above Earth's atmosphere, and a continuous, broad view of Earth's surface.

One of the innovative features of Skylab was the decision to give talented high school students an opportunity to participate directly in a major national space project. In the Skylab student project, designed and administered by the National Science Teachers Association, the National Aeronautics and Space Administration invited students in U.S. high schools to submit proposals for experiments that could be performed on board Skylab by the astronauts during their tours of duty. The experiments were to be designed to make the best possible use of the Skylab environ-



ment. The purpose of the student project was to encourage interest in science and engineering careers.

The response was overwhelming and gratifying; several thousand entries were received from all over the nation. All entries were thoroughly screened on a regional basis, and the 305 regional winners were then judged again to select the 25 national winners.

This book has been prepared to share this innovation in our nation's space program. It describes the experiments designed by the students and reports what happened to those experiments in the close-packed space laboratory. It also describes the demonstrations performed on Skylab by the astronauts to show the effects of weightlessness.

Plans do not always work out as we hope they will, and there were disappointments. Some of the biological experiments were affected by the severe heat during the time before a shield could be deployed. We are reminded of the scientist's ability to compensate, with spirit and intelligence, for the limitations of the finest equipment. Surely the astronauts' repair of the damaged craft was one of the unforgettable episodes.

Progress is often based on just efforts. Skylab demonstrated that disciplined young people, when given the opportunity, can contribute on an adult level to such enterprises.

This book was not written for the scientist or engineer. Its language is not technical so that many people will be able to appreciate the splendid contribution of some very gifted high school students to one of our nation's most significant space projects. It is our hope that it may inspire other students and teachers to join in future space efforts where similar opportunities are offered.

DOROTHY K. CULBERT
Director, Division of Secondary Education
National Science Teachers Association

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Part I

The Mission

1
Skylab

Shortly after noon on May 14, 1973, America launched Skylab, its first space station, from Kennedy Space Center. For the first time in the dozen years that had elapsed since Astronaut Alan Shepard had briefly arched through the lower fringes of space and 12 men had walked upon the Moon, the nation launched a space station that was designed solely as a laboratory, workshop, and home in the space relatively near Earth.

Skylab was no small spacecraft in which one or two men could perform limited scientific and engineering experiments in cramped quarters as they orbited Earth or journeyed to and from the Moon. It was big enough for three men to live and work in for months on end. Indeed, man and his unique capabilities were uppermost in the minds of Skylab's designers. The crew could move freely within it to undertake complicated experiments. Each of the three astronauts had his own bedroom, but they all had to share a kitchen and bath. Still, Skylab, a three-bedroom home and workshop in orbit 270 miles above Earth, was one of the greatest achievements in manned spaceflight during the decade of the 1970's.

The Genesis of Skylab

The original idea for Skylab was as novel at its inception as it was later to prove complex in execution. The concept, at first, was to have a Saturn IB rocket place its burned-out second stage into orbit about Earth. Once there, it would be visited by crews of astronauts in Apollo spacecraft launched by other Saturn IB rockets. They would dock their Apollo with the orbiting rocket stage, move in, and furnish the spent rocket with equipment and supplies brought with them. Since the rocket stage would have contained liquid oxygen and liquid hydrogen propellants during the flight into orbit, this version of the Skylab was known as the "wet workshop."

Where did the idea originate? Like the appearance of so many concepts in science and technology, tracing the origin of Skylab is impractical and fruitless. Sometimes the same idea appears to various individuals around the world at almost the same time. Calculus, for example, was developed

In 1968, seven new scientist-astronauts inspected a model of the proposed "wet workshop" for Skylab during a visit to the Marshall Space Flight Center. However, none of them were destined to be among the crews who manned Skylab.

independently and almost simultaneously by Newton in England and Leibnitz in Germany in the 17th century. The earliest written ideas for the "wet workshop" appeared in a November 1962 technical report of the Douglas Aircraft Co., which manufactured the second stage (or S-IVB stage) of the Saturn IB rocket booster. However, such a thought had probably occurred much earlier to a number of individuals, even in those early days of manned spaceflight.

Throughout the mid-1960's, the idea was pursued with increasing detail and planning. However, by 1969, the concept was altered; a Saturn V rocket booster, left over from the Apollo program, would launch its third stage into orbit. That stage was the same (S-IVB) as the second stage of the Saturn IB. Thus was born the idea of a "dry workshop." Such a space station would be launched from Earth with all supplies and equipment aboard. Once in orbit, it would be visited by teams of astronauts launched in Apollo spacecraft by Saturn IB rockets to perform scientific and technical experiments. The final concept for Skylab had arrived, and detailed planning and design for America's first space station got under way at the Marshall Space Flight Center in Huntsville, Ala.

Training for their mission, members of the first Skylab crew sample a meal they have prepared in the ward room of the space station. Left to right are Joseph P. Kerwin, Paul J. Weitz, and Charles Conrad, Jr.

Putting on a space suit is not a one-man job. Members of the second Skylab crew assist their commander during a training session. Left to right are Owen K. Garriott, Jack R. Lousma, and Alan L. Bean.

The Astronauts of Skylab

While nine astronauts lived and worked in Skylab during the 171 days of its manned occupancy, an additional six were also involved as backup crewmen to the primary flight crews. Each primary crew had a commander and pilot who were technically educated and qualified jet pilots. Additionally, each crew had a scientist pilot who was also a jet pilot.

The first crew consisted of Commander Charles Conrad, Jr., Pilot Paul J. Weitz, and Scientist Pilot Joseph P. Kerwin. Conrad was a U.S. Navy captain who had become an astronaut in 1962. He had been in space before on the Gemini 5 mission in 1965 and the Gemini 11 flight in 1966. In 1969, he became the third man to walk on the Moon as commander of the Apollo 12 mission. Weitz was a commander in the U.S. Navy, and he became an astronaut in 1966. Kerwin, also a commander in the U.S. Navy, was a doctor of medicine who had been selected as an astronaut in 1965.

The third crew of Skylab is checked aboard their recovery ship in the Pacific Ocean. Left to right are Edward G. Gibson, William R. Pogue, and Gerald P. Carr.

The men of the second Skylab mission were Commander Alan L. Bean, Pilot Jack R. Lousma, and Scientist Pilot Owen K. Garriott. Bean, like his close friend Conrad, was also a captain in the U.S. Navy. He became an astronaut in 1963 and flew in Apollo 12 as the lunar module pilot in 1969. Lousma, a major in the U.S. Marine Corps, joined the astronaut ranks in 1966. Garriott was a civilian with a Ph.D. in electrical engineering who became an astronaut in 1965.

Skylab's third mission was headed by Commander Gerald P. Carr, a lieutenant colonel in the U.S. Marine Corps, who had been appointed an astronaut in 1966. Pilot William R. Pogue, a lieutenant colonel in the U.S. Air Force, had joined the astronauts in 1966. Scientist Pilot Edward G. Gibson, a civilian with a Ph.D. in engineering and physics, had been named as an astronaut in 1965.

Assisting these nine astronauts during their training, and capable of taking over for them in case of emergency, were six other astronauts who formed backup crews. For the first mission, the backup men included Russell L. Schweickart, a civilian, who had joined the astronauts in 1963. "Rusty" had been the lunar module pilot for Apollo 9 in 1969. He was assisted by Bruce McCandless II, a lieutenant commander in the U.S. Navy who had been appointed an astronaut in 1966. The third member of the crew was Story Musgrave, a civilian and a doctor of medicine (with three other college degrees) who had been selected as an astronaut in 1967.

Backup crews for the second and third missions were the same. Vance D. Brand, a civilian, was named as an astronaut in 1966. Don L. Lind, a civilian with a Ph.D. in physics, joined the astronaut corps in 1966. He also had a scientific experiment aboard Skylab. William B. Lenoir, also a civilian, with a Ph.D. in electrical engineering, became an astronaut in 1967.

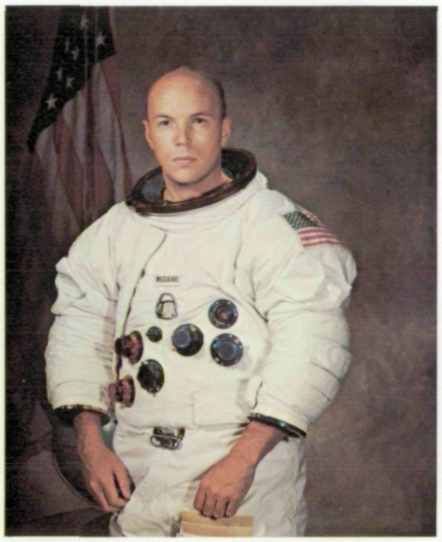
With the exception of Conrad, Bean, and Schweickart, none of the crewmen had flown in space before Skylab.

Getting Skylab Together

Skylab was much more than merely an empty third stage of a Saturn V rocket that had launched the first men to the Moon. The 117-foot-long space station consisted of five major components.

1ST MISSION

Commander Russell L. Schweickart



Scientist Pilot F. Story Musgrave

Pilot Bruce McCandless II

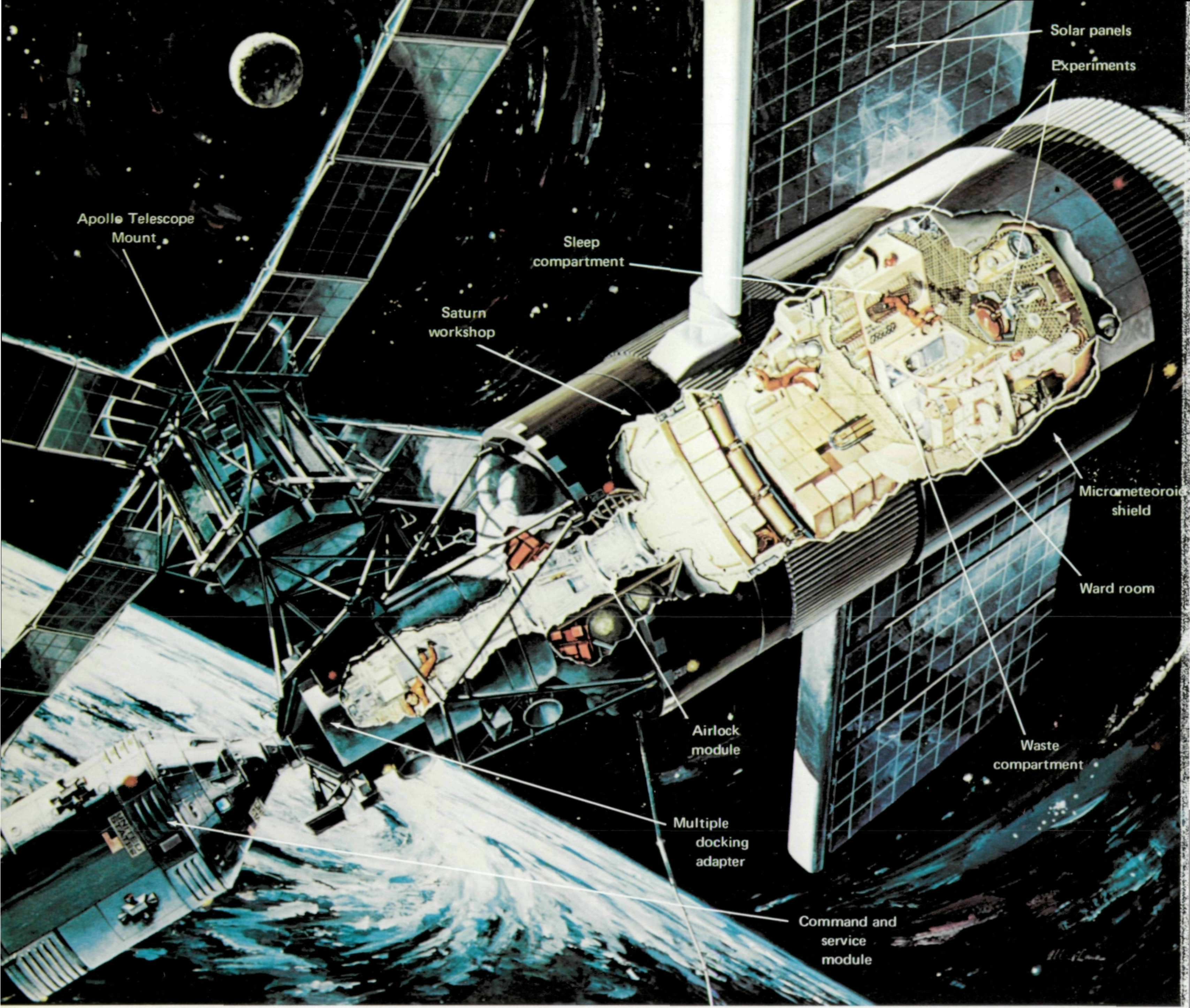
2ND AND 3RD MISSIONS

Commander Vance D. Brand

Scientist Pilot William B. Lenoir

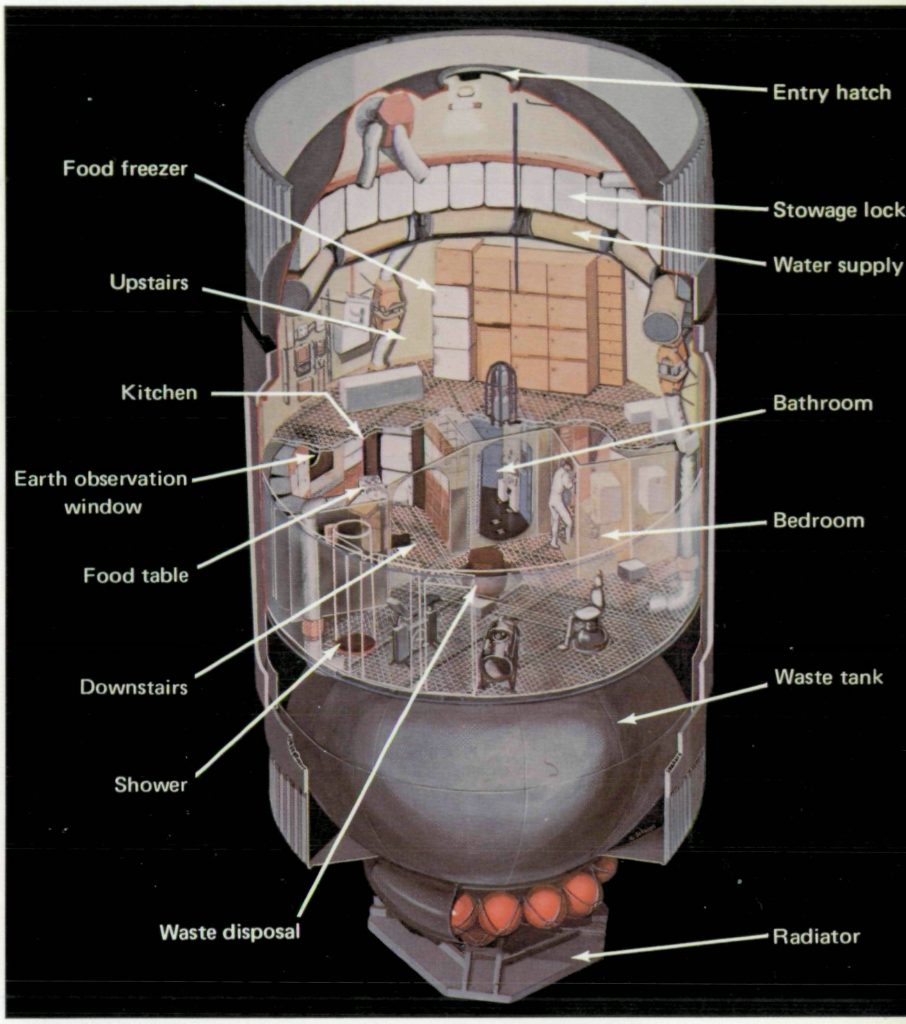
Pilot Don L. Lind

Two additional crews were also trained for the Skylab mission as backups in case something happened to primary crew members.



There is no need for streamlined design above Earth. Skylab consisted of five major components or modules with purely functional design. The crews were ferried to and from it in an Apollo spacecraft.

The empty stage itself was called the orbital workshop and housed most of the scientific, engineering, and biological experiments for the mission. Also, the former S-IVB stage provided the astronauts with their three bedrooms, kitchen, and bath. The orbital workshop was the hydrogen propellant tank portion of the rocket stage, which was divided into an upstairs and downstairs. Most of the astronauts' activities took place downstairs. The upstairs consisted largely of storage bins for various supplies and tanks for water as well as freezers for food, packaged somewhat like TV dinners. Spacesuits for the crew were also stowed there when not needed. With their boots anchored to the floor, the spacesuits stood like headless and handless crucifixes in the zero gravity of Skylab.



Three bedrooms, kitchen, and dinette, with bath. The orbital workshop of Skylab was home, office, and laboratory for its astronauts.

Additionally, two important engineering experiments for the future of manned spaceflight were located upstairs. These were astronaut maneuvering units, rocket-propelled devices designed to permit an astronaut to move about freely outside his spaceship. The upstairs also had two airlocks in the wall through which scientific instruments could be placed into space. The oxygen tank of the S-IVB stage, much smaller than the hydrogen tank and suitably fitted with a special airlock, served as a garbage can for the astronauts.

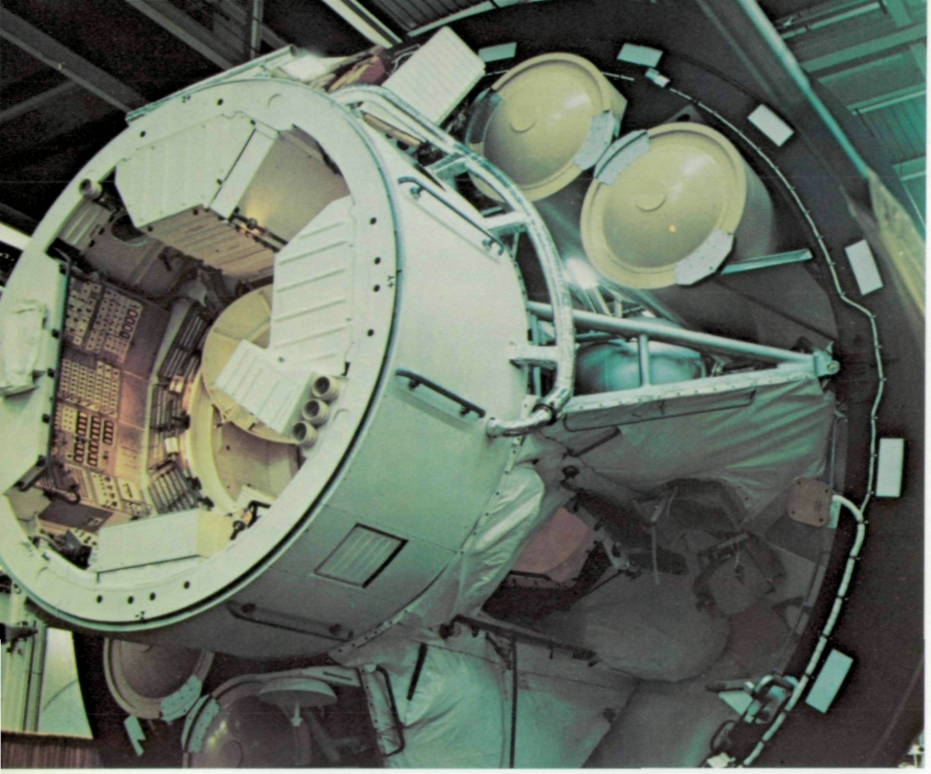
The workshop also had two huge solar panels to supply electric power. These were folded against the outside of the workshop during launch and were designed to spring outward once Skylab was in orbit.

Attached to the forward end of the workshop was the airlock module. As the name implies, this cylindrical compartment permitted the astronauts to leave and reenter the workshop without having to depressurize it. This compartment had a circular hatch, or door, at either end and a rectangular hatch on the side. All could be sealed airtightly against the almost complete vacuum of space. The forward hatch gave entrance and exit to the compartment, while the aft hatch gave entrance and exit to the workshop. The rectangular hatch in the side of the airlock module permitted the astronauts to enter and reenter Skylab. This hatch was the same as that used on the Gemini spacecraft. In 1965, Astronaut Edward White had exited through one like it on Gemini 4 to become the first American to walk in space. The hatch had been well tested and proven in space. It was selected because of the predominant design philosophy of Skylab, which was to use, as much as possible, equipment that had proven itself in the environment of space.

The airlock module had other functions, too. In it were located the controls for the temperature of the Skylab and the purification system of its air. In addition to the space station's electrical control and hazard warning systems, the module also had a Teletype printer, like that used by newspaper wire services and telegraph companies, over which Skylab astronauts received messages from Earth. Much more information could be sent over it than by voice.

Attached to the forward end of the airlock module was the multiple docking module, a cylindrical compartment that permitted the Apollo spacecraft to dock with the Skylab at either of two ports. One of these was on the end, and the other was on the side. The latter was to be used for emergency rescues, which were not required during the mission. While the primary purpose of this module was to allow the astronauts to dock with the Skylab, it had other purposes as well. The major components located in it were the solar observatory control and display console and the electric furnace and vacuum chamber for materials processing experiments. It also provided space for various Earth resources experiments and had a window through which the astronauts could view and photograph Earth.

Attached by a trusswork to the shroud around



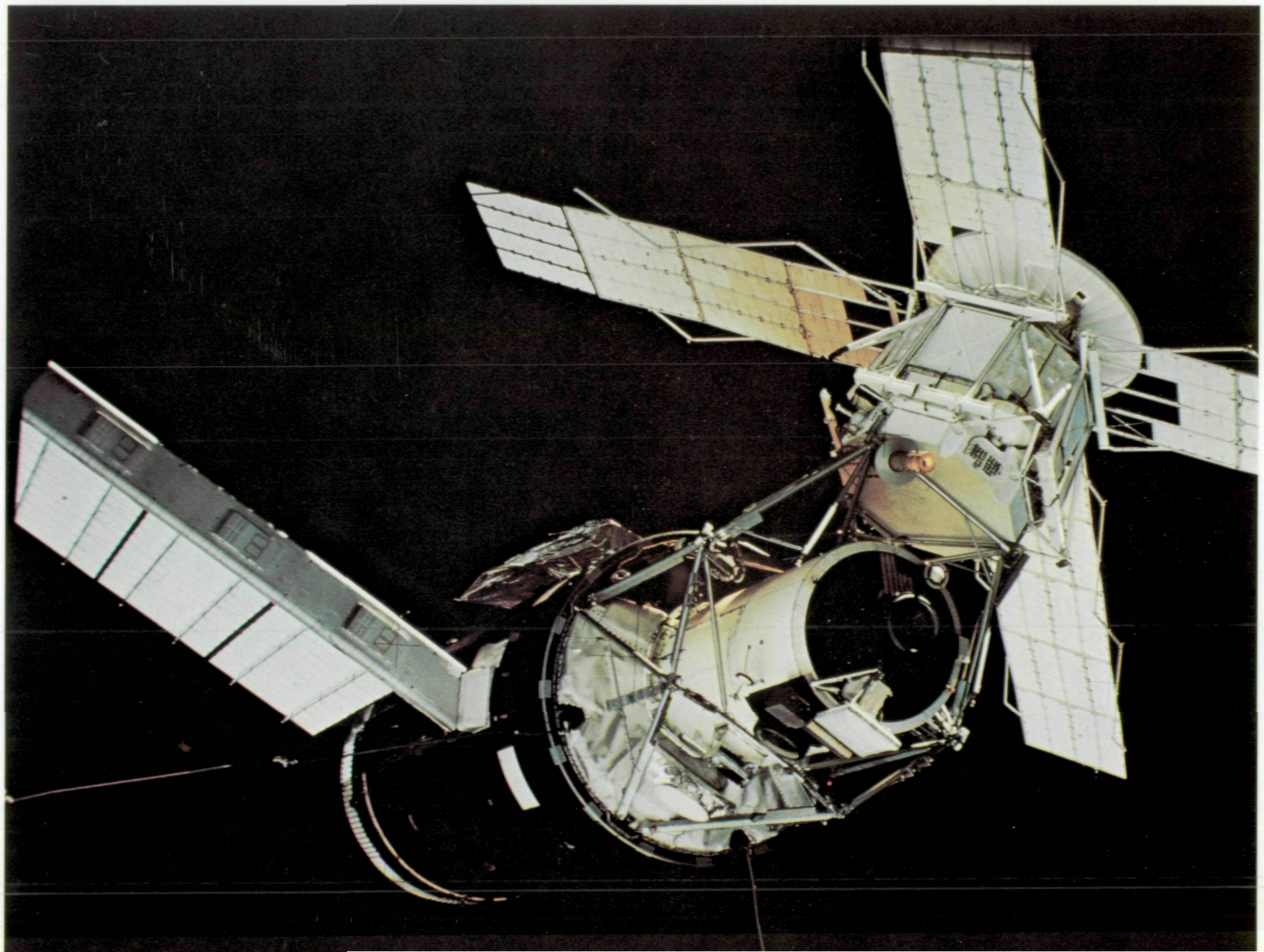
The airlock module, with docking adapter removed, contained controls for the life-support system, a teleprinter, and other controls and stowage areas. The hatch shown open on the lower right was used by the astronauts to enter and leave the space station while it was in orbit.

the upper end of the airlock module was the Apollo Telescope Mount or solar observatory. The mount was fixed to the trusswork in a manner that permitted it to pivot. During flight to orbit, it was stowed over the multiple docking adapter and covered by a large shroud to provide a streamlined cover for it. Once in orbit, the observatory swung 90 degrees to the side so that it could face the Sun.

Basically, the observatory consisted of a canister fitted within a rack that was free to rotate and also to be pointed up and down and from side to side. Attached rigidly to a spar that ran lengthwise through the canister were eight instruments to measure various radiations of the Sun. Film for these instruments was changed by the astronauts, who exited Skylab through the airlock module.

This canister could also be held stationary by an extremely accurate gyroscopic control system. The instruments in the canister could be pointed out at a spot on the Sun and held there for 15 minutes with an error of only 2.5 seconds of arc, which is

Parking places for two Apollo spacecraft were provided by the docking module of Skylab. The circular port on the right end was used as the primary one. The port on the bottom would have been used had a rescue become necessary.



equivalent to pointing a 7-foot-long rod at a certain spot and not having it move in any direction more than 1/1000th of an inch.

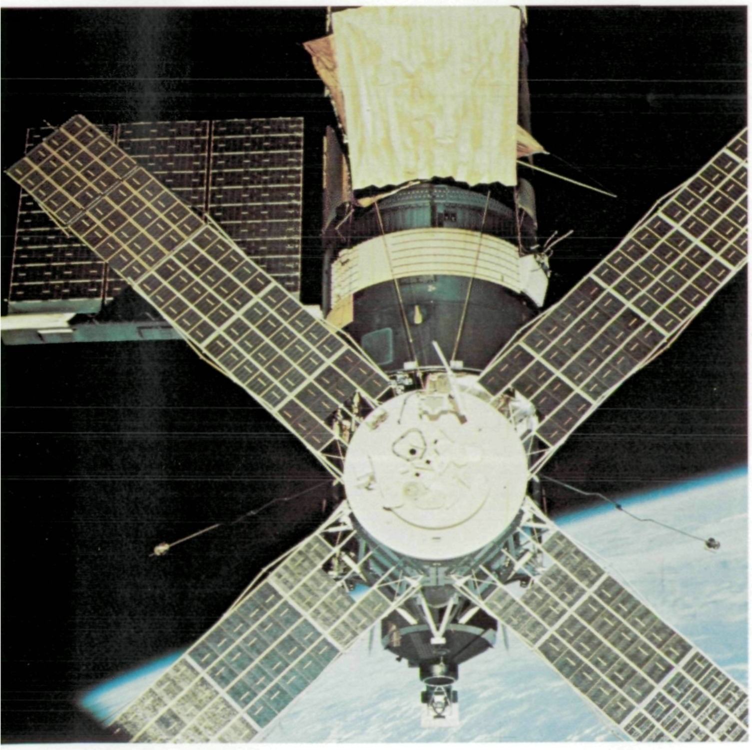
Also an important part of the solar observatory were four large panels containing solar cells. These were folded against the sides of the Mount during launching and unfolded after the Skylab reached orbit. They provided electric power for the instruments in the observatory as well as for other systems of the space station.

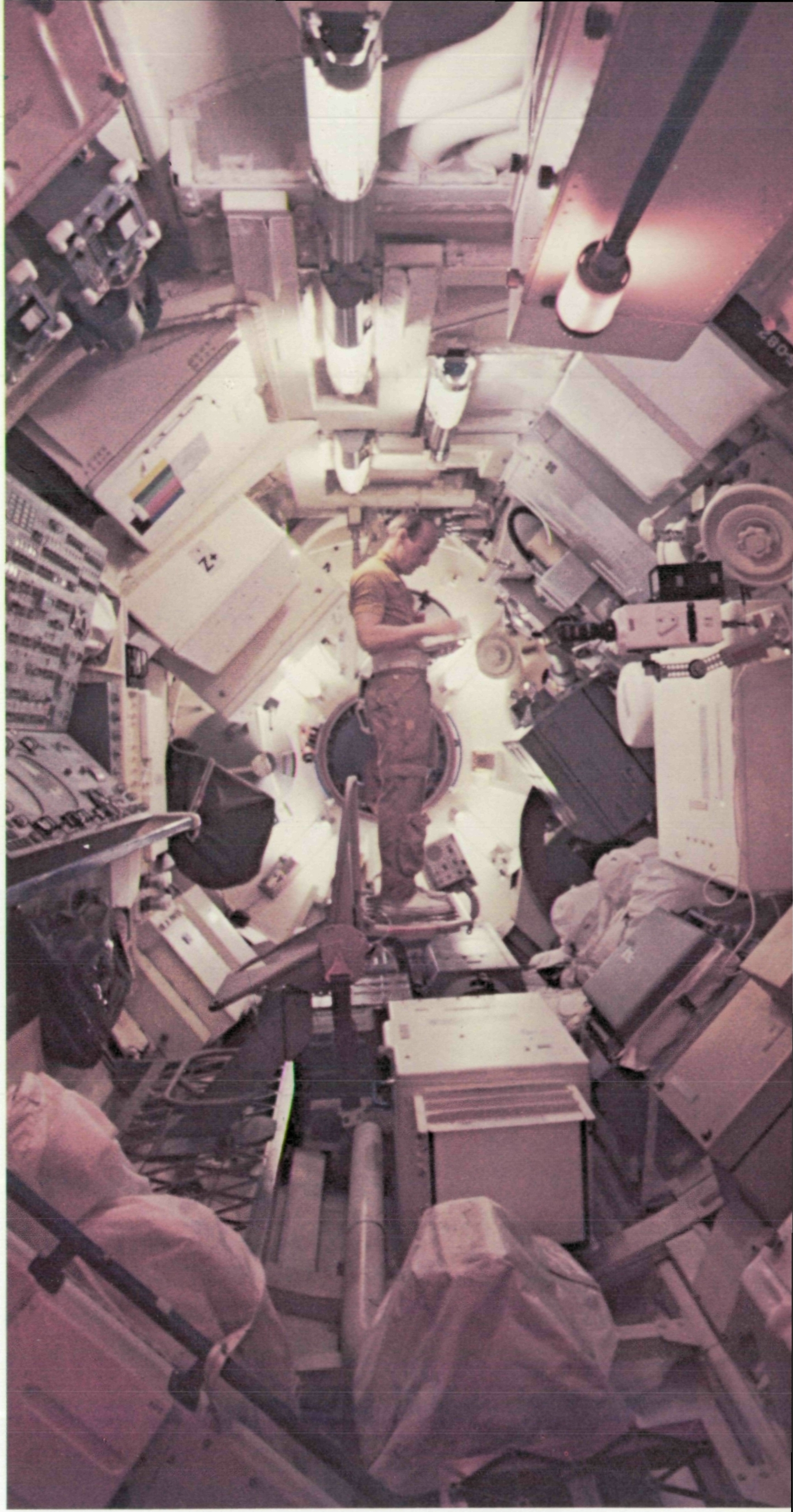
Science and Engineering in the Space Environment

Skylab was designed primarily as a laboratory and workshop to study various aspects of science and engineering technology in the space environment near Earth. Included, too, were important studies of man himself in such an environment.

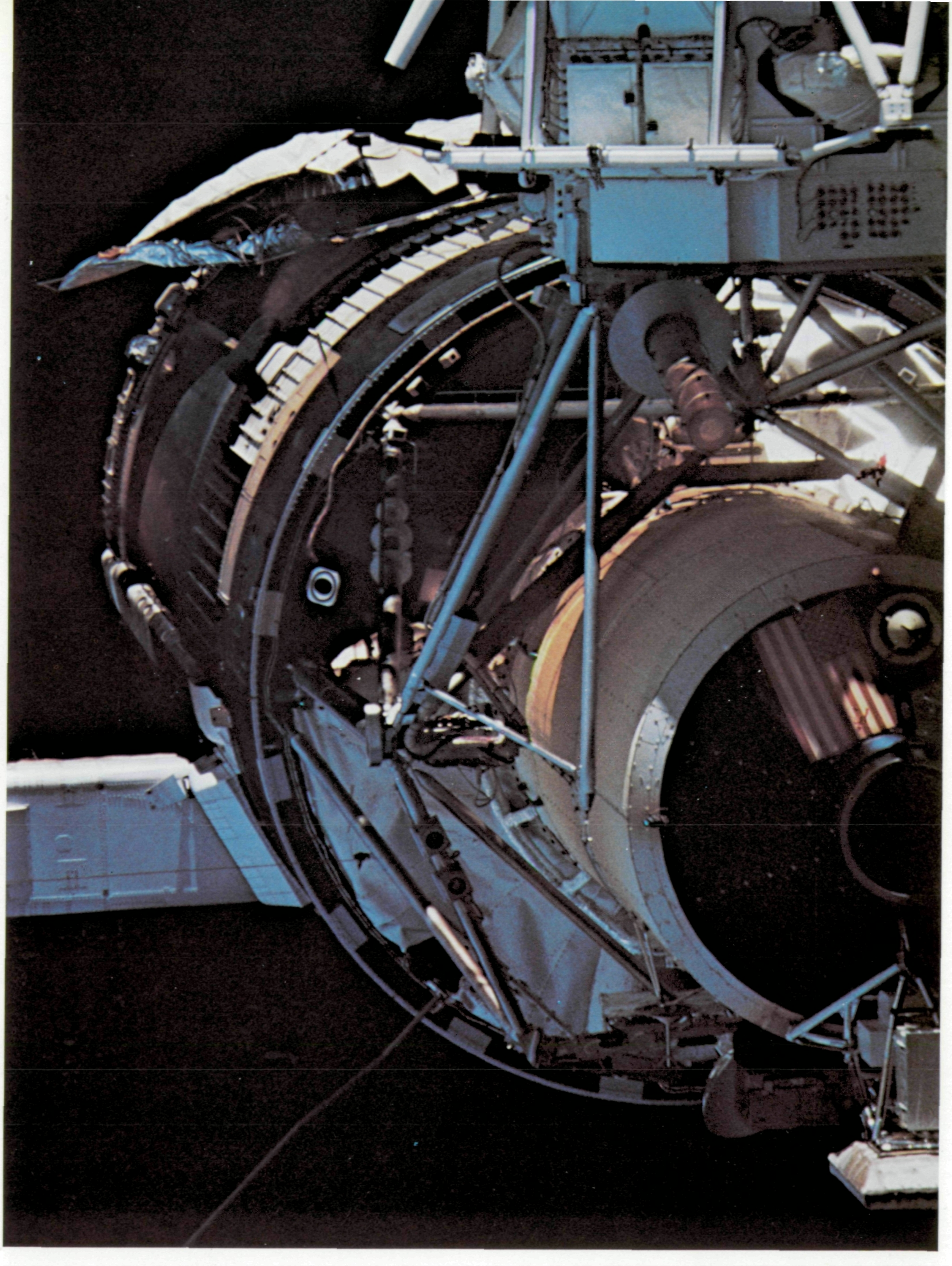
These experiments fell into seven categories: the life sciences, solar physics, Earth observations, astrophysics, materials science and manufacturing,

Facing the Sun were the astronomical instruments of the solar observatory in the center of four solar cell panels that generated electric power for them and other equipment aboard Skylab. The sunshade deployed by the second crew is also visible.





A place for everything and everything in its place . . . the interior of the docking adapter was crowded with equipment and experiments. On the left is the control console for the solar observatory. In the rear, Astronaut Conrad stands before the hatch leading into the airlock module of Skylab.



This side view shows how the solar observatory was attached to the docking module.

engineering and technology, and student experiments.

The life sciences experiments included studies of man and other forms of life from the cellular level to the functional being. Among them were experiments to determine the effect of weightlessness on the inner ear, the loss of minerals from bones, the loss of body weight, and the degradation of the cardiovascular system. Others included studies of sleep patterns and the bioassay of body fluids.

Physics of the Sun were investigated by eight special instruments located within the solar observatory that measured solar radiation in the visible light as well as ultraviolet and X-ray regions of the electromagnetic spectrum.

Earth was observed by six especially designed systems of instruments to help scientists better understand the natural and cultural features that impact its ecology. These cameras and other

One experiment aboard Skylab used a special helmet in which sensors measured the brainwaves of astronauts as they slept. Astronaut Kerwin settles "up" for a good night's sleep, while his brainwaves are transmitted to doctors on Earth.

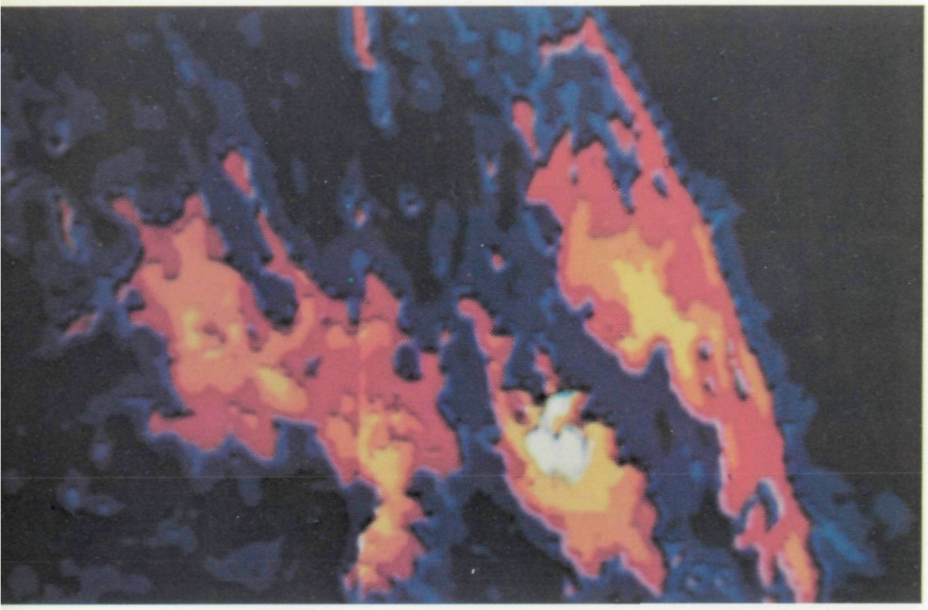
Among the biomedical experiments of Skylab was one that measured the effect of weightlessness on the body's cardiovascular system. Astronaut Kerwin, on the right, a doctor himself, became a part of the experiment with the help of his fellow crewman Astronaut Weitz.

devices gathered data of tremendous importance to agriculture, forestry, oceanography, geology, geography, meteorology, and hydrology.

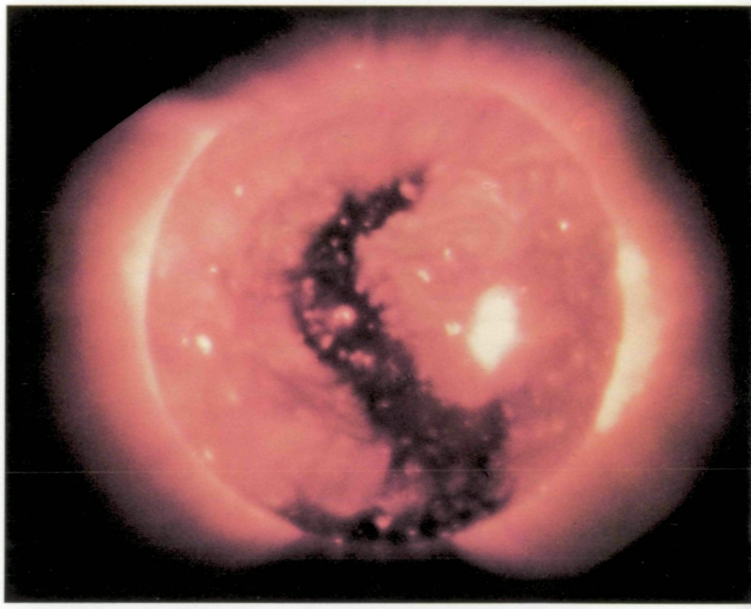
The astrophysical experiments included three instruments for probing into the workings of the atmosphere of Earth and the nature of the interplanetary medium. An additional six others investigated celestial objects beyond the solar system, including Comet Kohoutek.

Eighteen experiments were involved in materials processing and manufacturing. They included such techniques as welding in zero gravity, forming almost perfect spheres of metals, and growing extremely pure crystals for electronic components such as transistors.

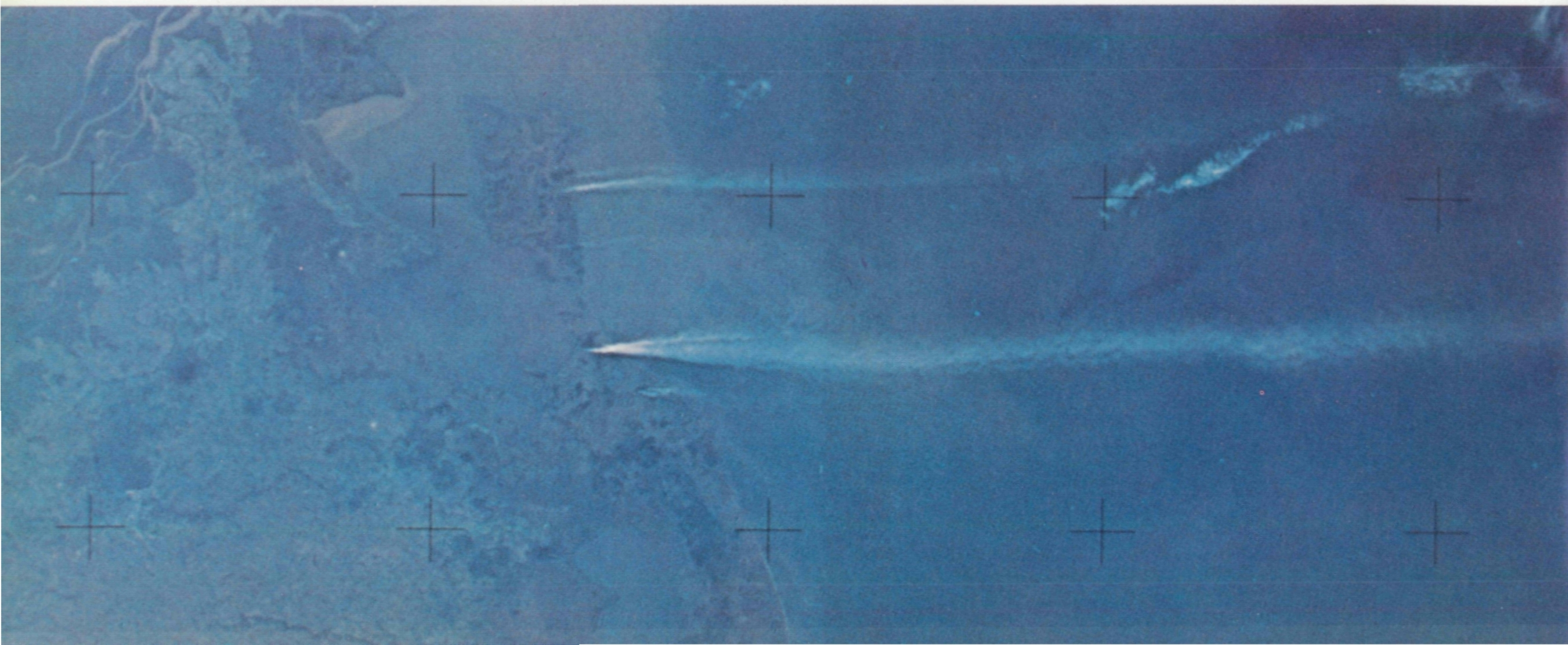
The engineering and technological experiments numbered a dozen. Several studied the interaction between man and his space station in the zero-gravity environment, while others investigated the environment of Skylab itself, both natural and



A special instrument called the spectroheliometer scanned the Sun and recorded its ultraviolet radiation.

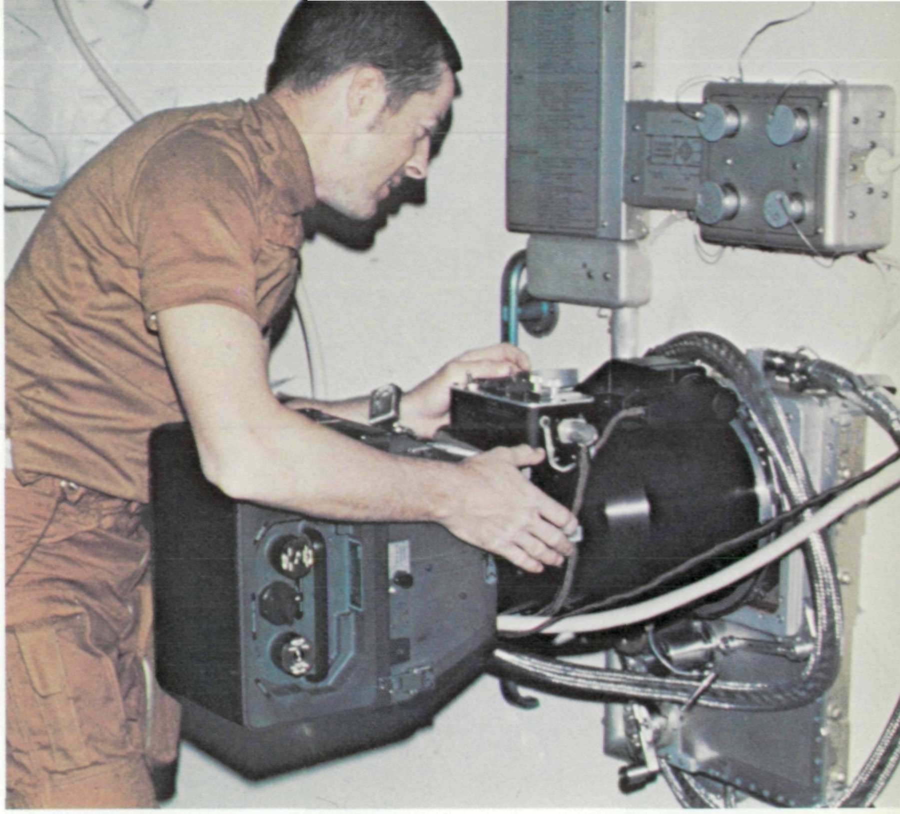


Among many images of the Sun made by Skylab's solar observatory was this one showing its X-ray corona.



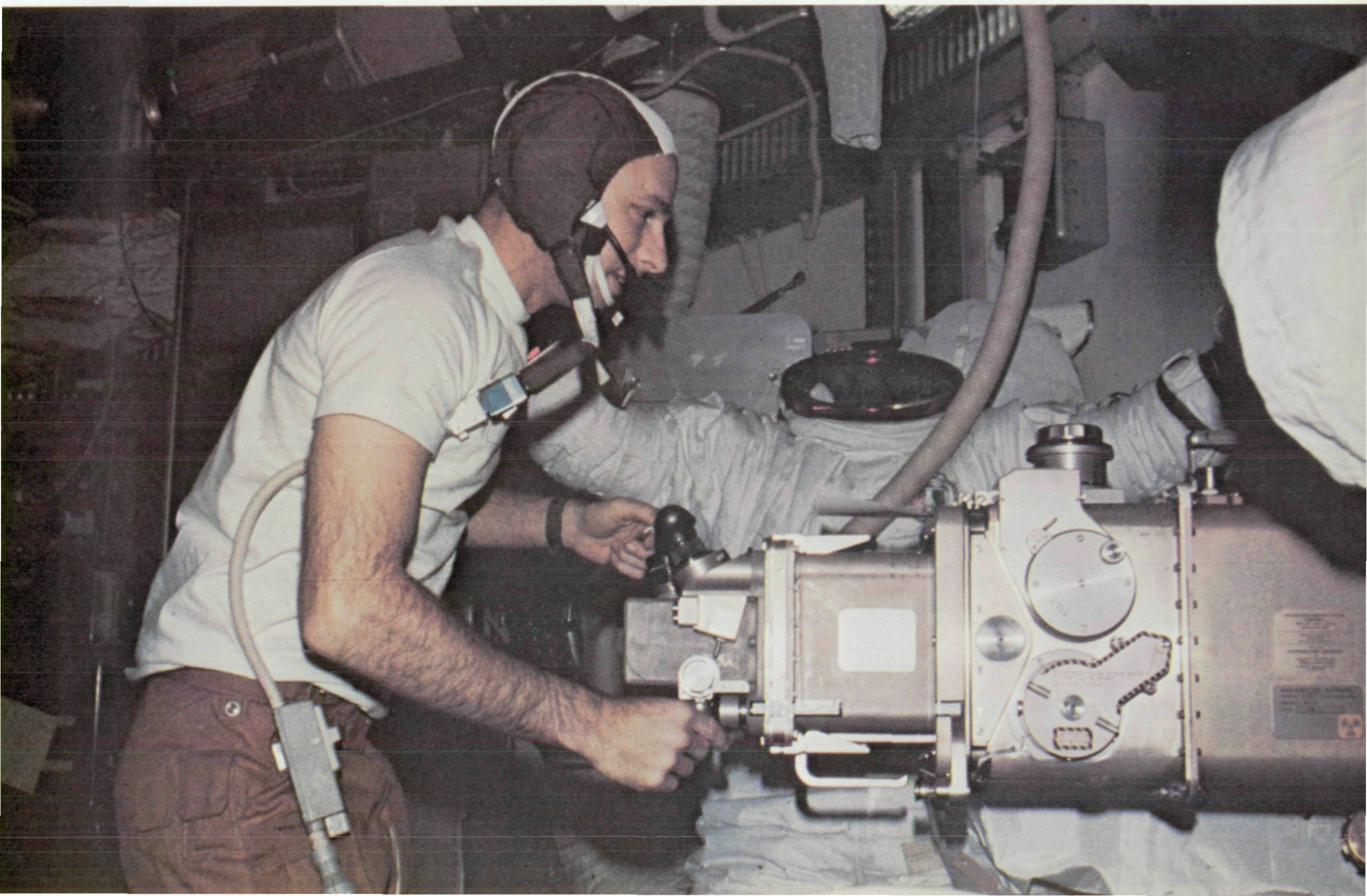
Taken during the last manned mission, this view from Skylab shows smoke from oil well fires along the coast of Louisiana, near Bayou Teche.

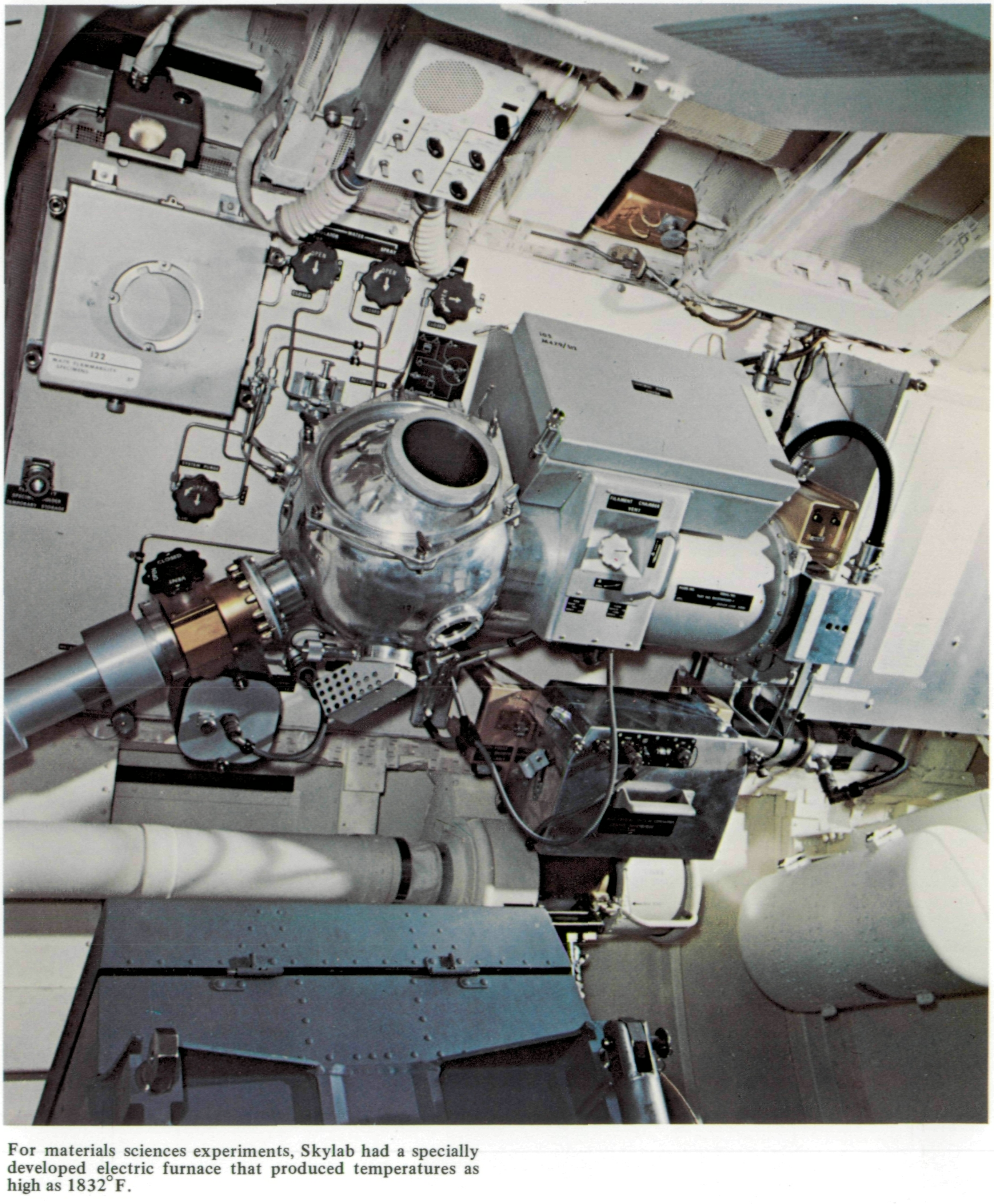
Comet Kohoutek was photographed by Skylab's far-ultraviolet camera. Its hydrogen halo had a diameter of some 1 600 000 miles.



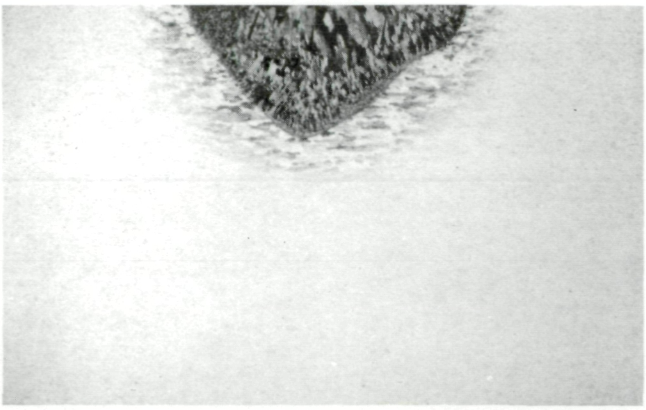
Many photographs of Earth's surface were made with a special camera, seen here being operated by Astronaut Kerwin.

Astronaut Bean became astronomer Bean during his mission. Here he operates a special camera for photographing star fields in their ultraviolet light.

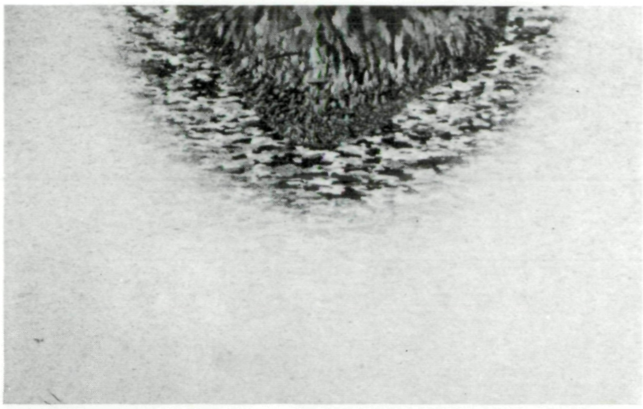




For materials sciences experiments, Skylab had a specially developed electric furnace that produced temperatures as high as 1832°F.

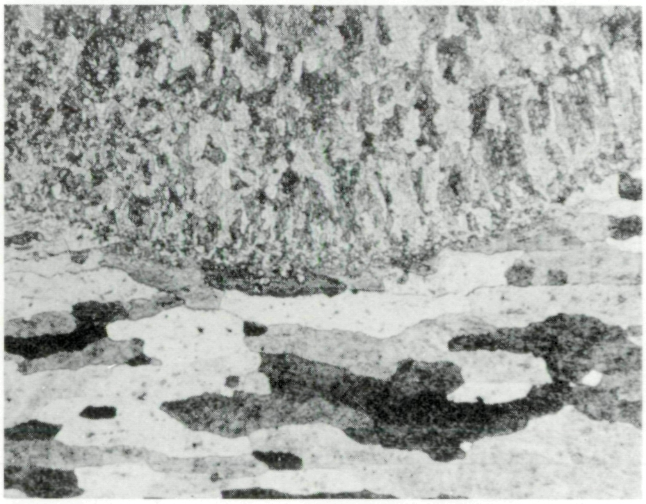


Ground-based cross-section 10X. Aluminum specimen position 5.



Skylab cross-section 10X. Aluminum specimen position 5

Ground-based cross-section 100X. Root of electron beam weld nugget showing banding and columnar grain growth



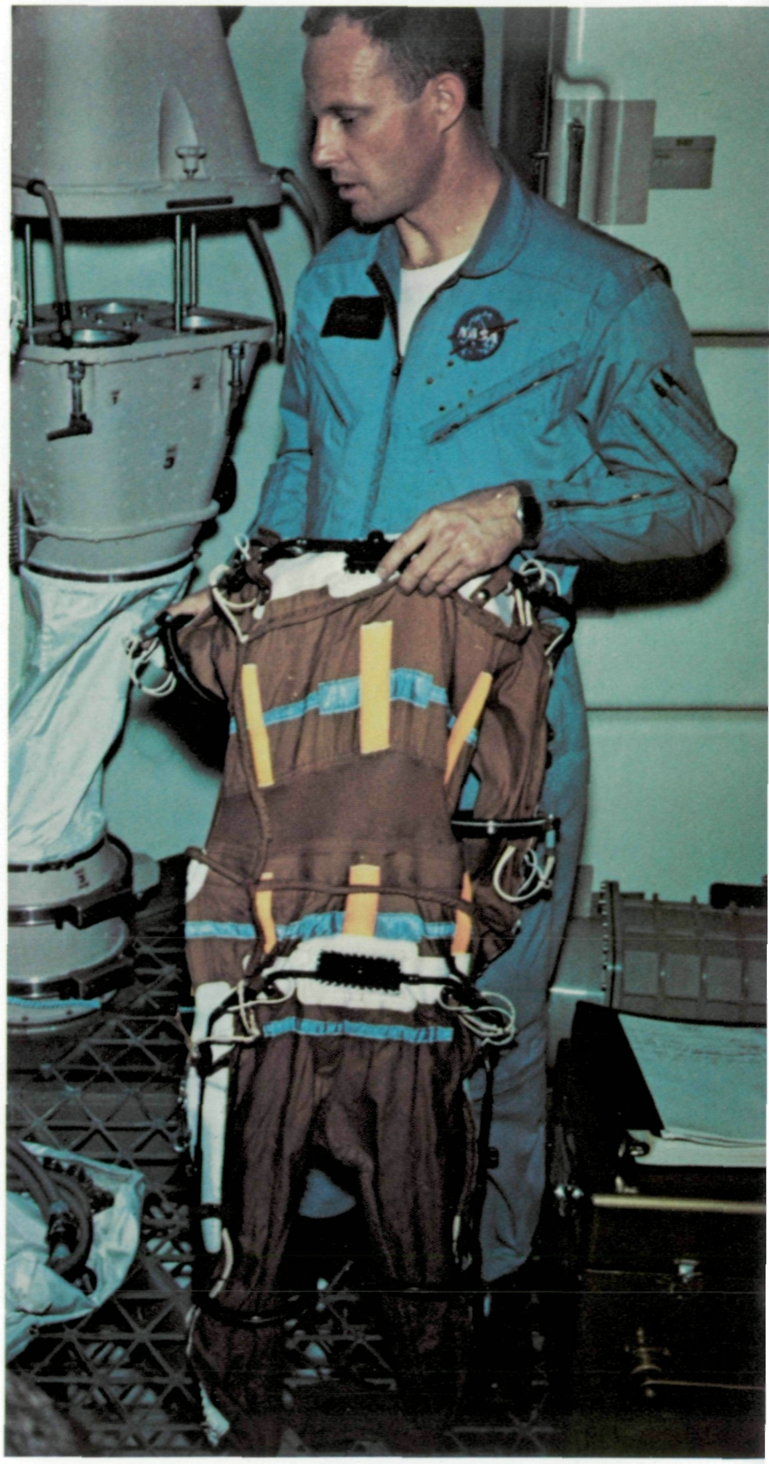
Skylab cross-section 100X. Root of electron beam weld nugget showing lack of banding and columnar grain growth due to reduced convection during solidification

Results of metal-melting experiments made aboard Skylab were studied by microscope after specimens were returned to Earth.

induced. Included in these experiments were two types of rocket-propelled, gyroscope-stabilized astronaut maneuvering units, which were to be tested to see if future astronauts could use them to move about freely, and safely, outside their spacecraft. For experimental purposes the units were flown only in the roomy upstairs of the orbital workshop to demonstrate their fundamental practicality.

Finally, there were the student experiments and science demonstrations. From thousands of experiments proposed by high school students, 25 were selected for use aboard Skylab. Some of them required especially designed equipment to be operated or monitored by the astronauts, while others used data supplied by the experimental instruments already aboard the space station. In addition, the astronauts also performed science demon-

Astronaut Carr tested a special astronaut maneuvering unit by flying it around in the orbital workshop.



One of the engineering and technology experiments aboard Skylab was a special suit intrumented to measure body motions as the wearer went through typical tasks aboard the space station. Astronaut Lousma inspects such a suit during a training session on Earth.

Not all scientists with experiments aboard Skylab were from laboratories or universities. From across the nation, 25 high school students shared honors with them. Shown, left to right, at a picnic at the Marshall Space Flight Center, in 1972, are students Hopfield, Schlack, Zmolek, Astronaut Schweickart, and student Leventhal.

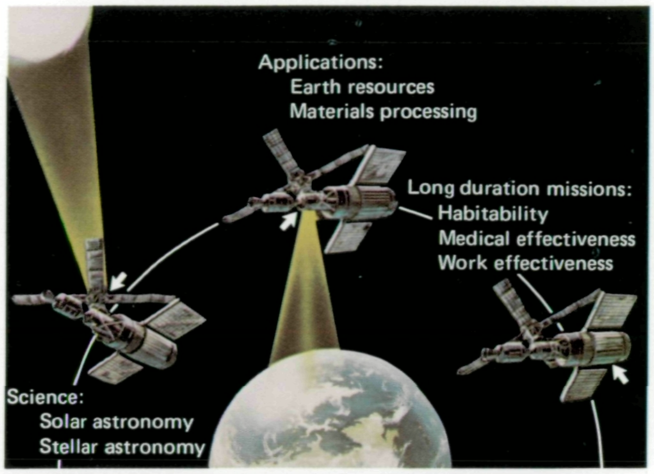
strations on television that could not have been done in the earthly laboratory because of gravity.

Mission in Space—Skylab in Trouble

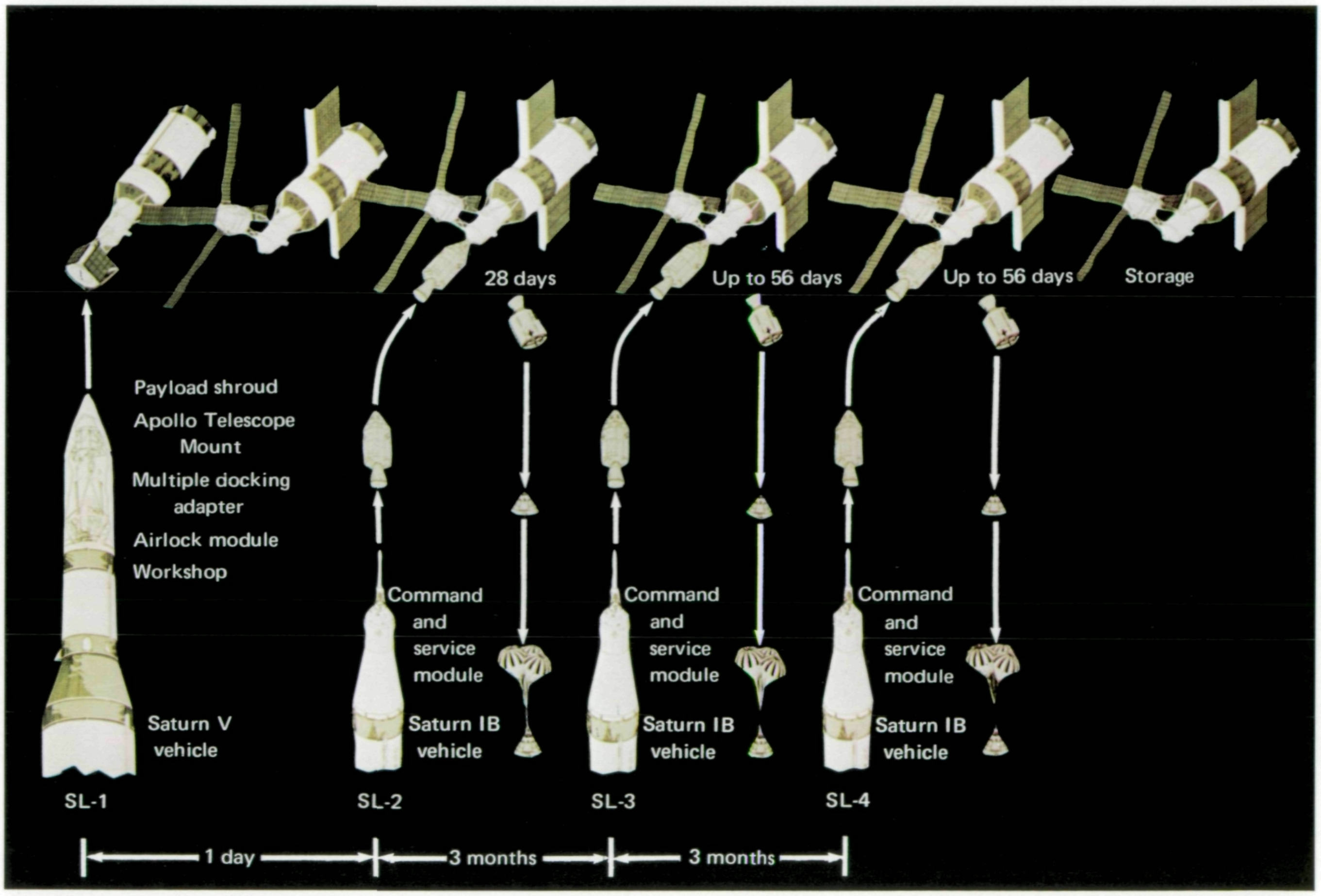
As originally planned, Skylab was to be launched from Kennedy Space Center. The first crew would stay aboard for 28 days; the second and third would remain for 56 days each.

The space station's orbit would trace a wavelike line on Earth's surface from 50 degrees above the equator to 50 degrees below it. Thus, Skylab would sweep over 75 percent of Earth's surface, consisting of some 147 705 000 square miles. Within this area resides 90 percent of the world's food-producing regions. In such an orbit, Skylab would circle Earth every hour and a half.

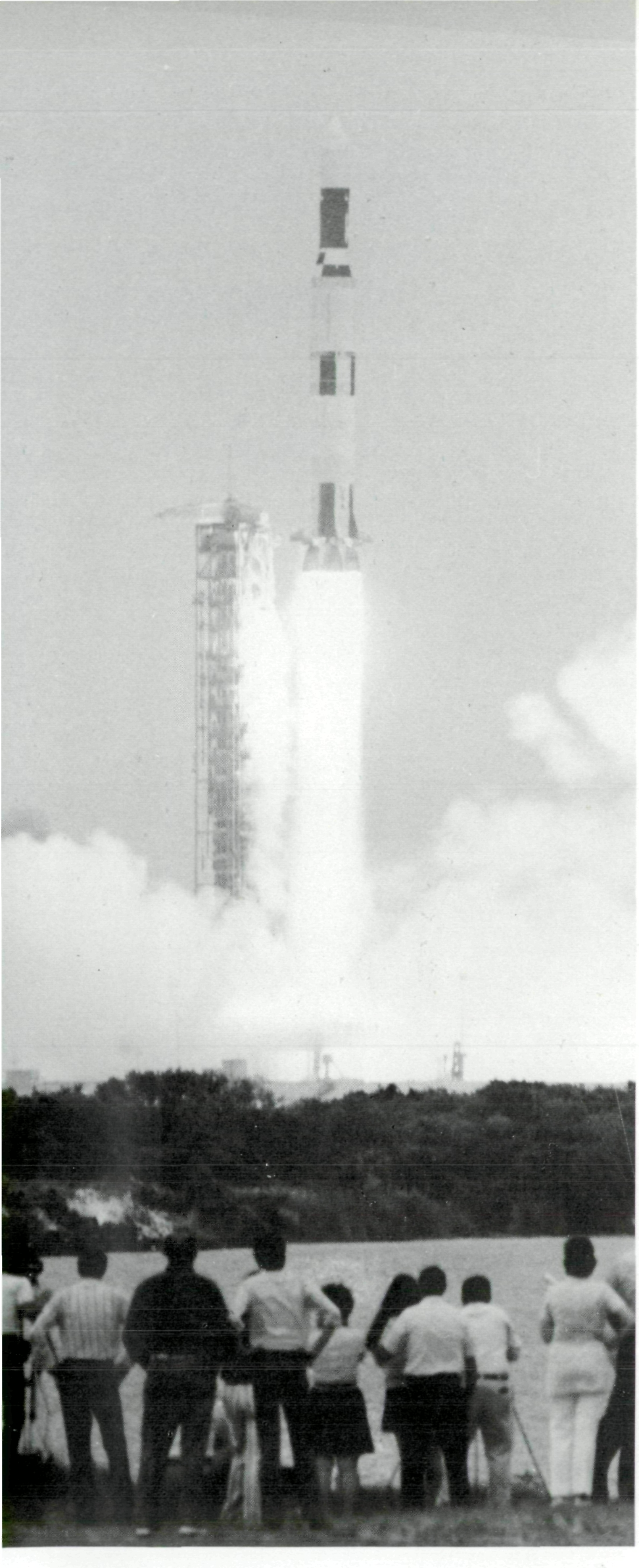
Skylab was to be launched from Cape Canaveral on May 14, 1973. Once it was smoothly in orbit



Skylab's astronauts performed experiments in three primary areas essential to a greater understanding of the processes at work in our universe, on Earth, and on man himself.



When the Skylab mission was first planned, no one could have foreseen that its astronauts would surpass the number of days in space shown on the mission chart.



Liftoff . . . everything OK!

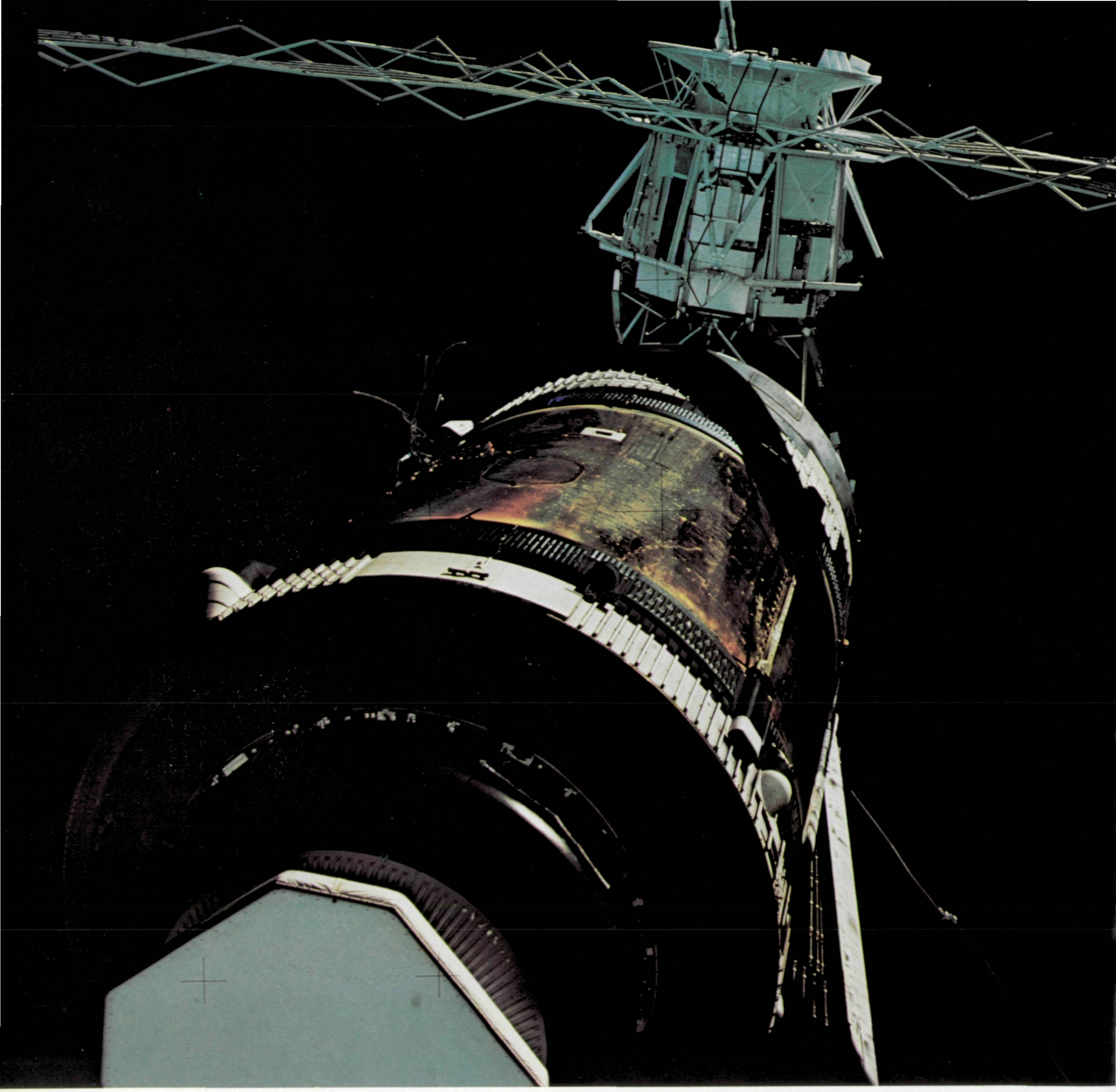
Bad news from space travels at the speed of light. Within minutes after Skylab was launched, flight controllers gathered at the console of Flight Director Donald Puddy, center, in Mission Control at the Johnson Space Center.

and everything functioning on schedule, Commander Conrad and his crew then would be launched a day later.

To the hundreds of thousands of observers at Launch Complex 39 at Kennedy Space Center and nearby, the liftoff of Saturn V with Skylab aboard seemed to be a perfect one. The 334-foot-tall rocket roared off the launching pad and climbed slowly at first. Gathering speed, it passed through a low-hanging cloud and then reappeared briefly, its white contrail twisting behind it.

Within little more than a minute, Skylab was in trouble. Flight controllers of the Saturn V reported "a strange lateral acceleration at approximately 63 seconds after liftoff on the S-II second stage." It happened only 13 seconds before the huge rocket was to pass "Max Q," the point in flight when maximum aerodynamic pressure builds up on the vehicle.

It became apparent from the endless stream of telemetry feeding into Mission Control at the Johnson Space Center that a metal shield only 0.025 inch thick around the orbital workshop had torn loose. This shield performed two critical functions. While it was there primarily to protect the workshop from possible puncture by very small meteoroids, it also protected the workshop from the searing heat of the Sun.



A crippled Skylab in orbit. Members of its first crew found their home in space to be in serious shape: heat shield gone, one solar wing gone, and the other not deployed.

To compound the misfortune, radars in Australia also reported that the two solar cell panels of the workshop had not swung out into the open position. There was practically no electric power in the space station.

Temperatures within Skylab began climbing above 120°F and reached as high as 190°F in places. If this were not bad news enough, telemetry finally confirmed that one of the solar cell panels had been torn away with the meteoroid shield and was tumbling along in orbit behind the space station.

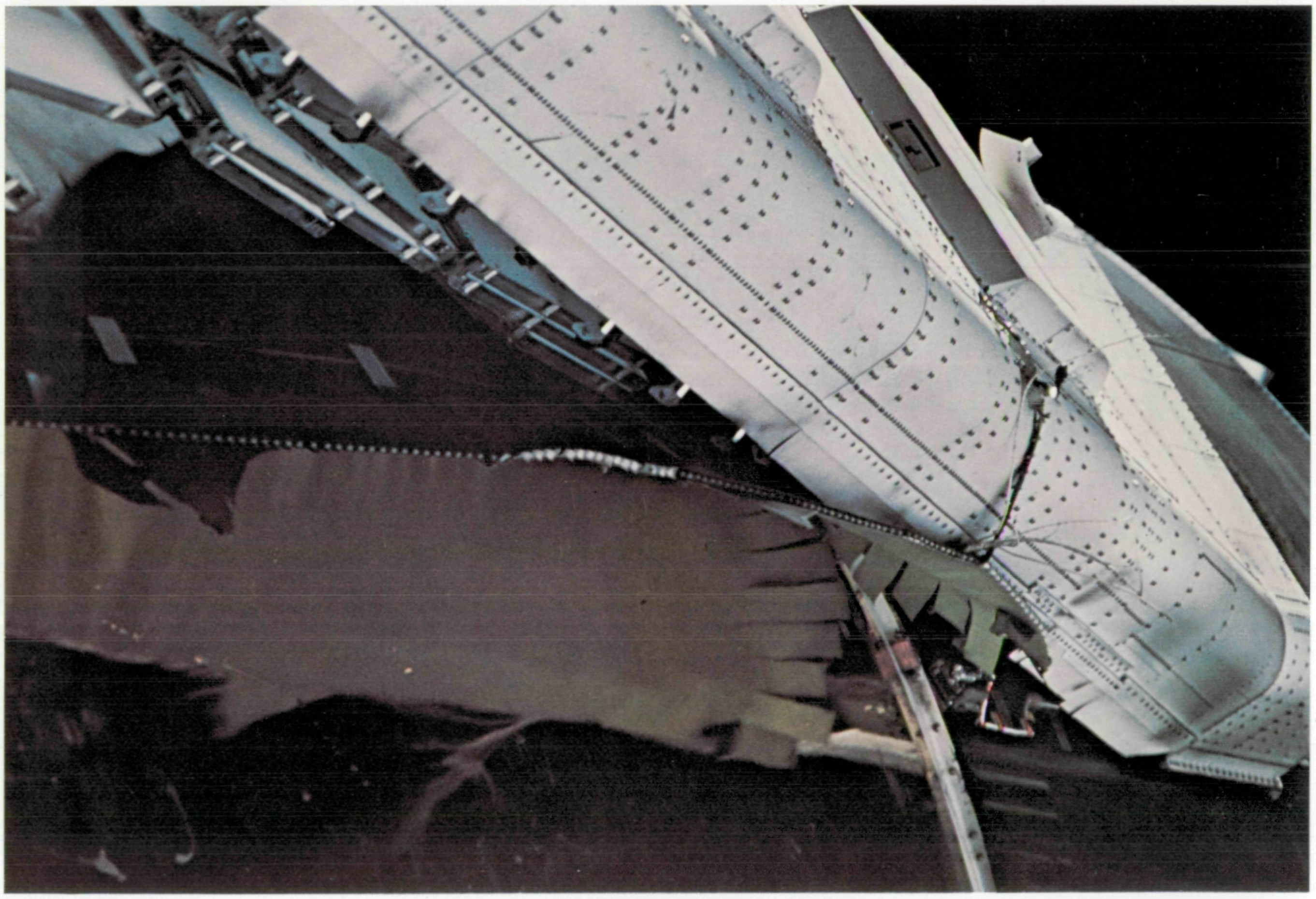
Clearly something had to be done immediately to lower the temperature within the workshop. Flight controllers sent commands for Skylab to go into a "barbeque roll" or to turn slowly as it moved along its orbit. The temperature stabilized between a very uncomfortable 105°F and 110°F.

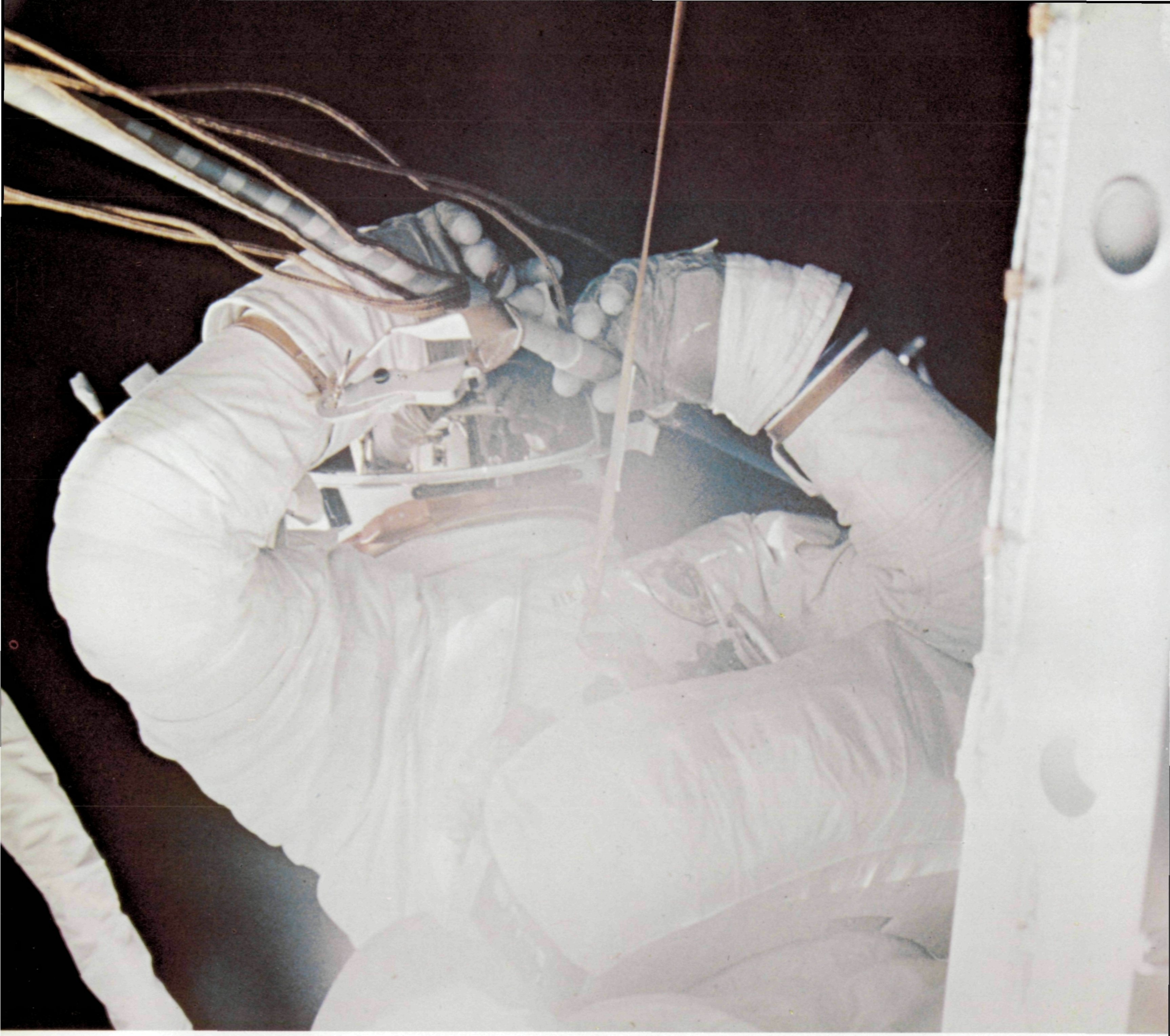
Engineers at the Marshall Space Flight Center and the Johnson Space Center went to work immediately. Their problem was to provide a means of keeping the Sun off the sensitive skin of the nude workshop. A parasol like a giant beach umbrella was developed by the Johnson Space Center. It fitted into a package that could be deployed through the Sunfacing airlock in the wall of the orbital workshop.

With the arrival of the first crew at the stricken Skylab on May 25, the parasol was installed, and the space station's temperature came down quickly. Climbing outside Skylab, Conrad and Kerwin freed the stuck solar panel, and electricity began to flow into it immediately.

Skylab had been saved by its astronauts, and its salvation proved that man is an indispensable part of a complex space venture such as the operation

A closeup view showed that the remaining solar wing was being held by a strap of aluminum. If it could be cut, electric power would flow into Skylab.





Astronaut Kerwin cuts the strap binding the Skylab's remaining solar wing.

of a large space station in orbit about Earth. In the two remaining missions, which left Earth on July 28 and November 16, the Skylab astronauts were called upon time and again to repair failing or malfunctioning equipment or to provide services that simply could not have been programed into an unmanned automated station.

Skylab—The Ultimate Triumph

Skylab provided a unique learning environment. Men had been in space prior to it, but of necessity they had existed in cramped quarters, largely preoccupied with short-term survival and the operational testing of their spacecraft. As in the evolutionary progress of all pioneering efforts in science and technology, the early steps into space had been relatively ill-equipped for making meticulous scientific experiments. Room and time simply did not permit sophisticated scientific or technical investigations by harried astronauts, most of whom were not scientists. However, those brief, early, manned space missions did whet the appetite of Earth-bound scientists and engineers, and such spaceflights provided the impetus for Skylab, America's first laboratory in space.

Experience may be the best teacher, but experience on Earth does not necessarily provide the best learning environment for all forms of scientific study. Earth's gravitational effects sometimes obscure basic physical laws or impede physical or chemical processes. Atmospheric effects limit the astronomer's capability to observe certain celestial phenomena. Agricultural engineers and scientists often (and literally) cannot see the forest for the trees. Above the atmosphere, freed from gravitational forces, and with a broader view of Earth than possible from any point on it, new horizons of learning open to the scientist and engineer.

In Skylab, men adjusted to the space station environment in a freer manner than before. They demonstrated that man cannot only survive for long periods of time in reduced gravity, but that he can also carry out important and useful tasks not otherwise possible.

As an educational experience, Skylab exposed on television the living conditions of its crew and

The astronauts of Skylab took time to perform many demonstrations that visibly illustrated fundamental laws of physics that cannot be done on Earth, where gravity is a factor. Astronaut Kerwin shows how a fluid behaves when it is weightless.

The tasks performed routinely by the men of Skylab proved conclusively that man is an essential element in the operation of large space stations. Here a Skylab crewman changes the film in the solar observatory.

the way in which its astronauts worked within the huge space station. The viewing of their activities helped illustrate the importance and value of the space program to a wide variety of the peoples of the world. In addition, Skylab generated enough scientific and technological data to keep scientists and engineers on Earth busy for a long time to come. Based on their findings, educators will be faced with the job of revising current textbooks and perhaps writing new ones.

Of great value to the teacher of science were the demonstrations by the astronauts of the fundamental principles of physics that simply cannot be done on Earth because of its gravity. Such demonstrations of laws that previously had appeared only in print and mathematical equations for the first time became understandable for many students. In short, the knowledge acquired as a result of Skylab has had and will continue to have significant effect on the lives not only of scientists, engineers, and astronauts, but also of teachers and their students.

The ultimate success of Skylab as a practical and functional scientific laboratory in space was not a unanimous conviction of American scientists prior to its launch. But following its successful conclusion, Leo Goldberg, director of Kitt Peak National Observatory, said in retrospect: "Many of us had serious doubts about the scientific usefulness of men in space, especially in a mission such as the ATM [solar observatory], which was not designed to take advantage of man's capability to repair and maintain equipment in space. But these men performed near-miracles in transforming the mission from near-ruin to total perfection. By their rigorous preparation and training and enthusiastic devotion to the scientific goals of the mission, they have proven the value of men in space as true scientific partners in space science research."

In so saying, Goldberg was unknowingly echoing a sentiment expressed a decade earlier by Wernher von Braun, then director of the Marshall Space Flight Center. He spoke of an earlier, much less complex, manned space program in terms that would apply equally well to Skylab: "I am often asked what reason there is for man's going into space. It seems the notion is popular in this age of electronic and mechanical miracles that man is rapidly becoming obsolete. Computers, for example, are much faster; and other instruments are much more sensitive to physical phenomena about us. Man, in space, some people say, is a liability and a nuisance. Well, men like Glenn, Carpenter, Cooper, Grissom, and Young proved that this simply isn't true. When equipment in the spacecraft malfunctioned, it was man in the loop, the astronaut, who saved the day. Equipment can be designed to react to many known and few unanticipated situations or events; but man can observe and correlate facts and respond to the unexpected. He is not merely going along for the ride. Man is the necessary element."

Thus, in the end, Skylab bore out von Braun's earlier view of the role of man in space. It was men like Conrad, Kerwin, Weitz, and their fellow astronauts of Skylab who saved the mission. Yet, they demonstrated more than man's ability to run a very good repair shop in space. They showed that he can adapt to the space environment, living and working there. As a scientific observer, he can reprogram automated instruments and equipment to take advantage of events which could not have been detected by such machines. Also, he can see, think, exercise judgment, and report things unobservable to unprogramable instruments. In short, the men of Skylab proved that in space man is the necessary element.

Skylab victorious . . . saved by the ingenuity and dedication of men both in orbit and on Earth, the nation's first space station was a scientific and technological success.

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Part II

Student Experiments

The scientific experiments proposed by high school students across the nation constituted an integral part of the Skylab program. Obviously the students could not personally perform their experiments in space; however, they were intimately involved in their planning and the development of special equipment where such was required. They also took an active part, working closely with NASA scientists, in the preparation of the protocol to be followed by the Skylab astronauts who performed their experiments. Finally, the students were responsible for the analysis of experimental data returned to Earth and the preparation of a final report on their work.

Seven basic areas of study were covered by the experiments selected for flight. These were astronomy, botany, Earth observations, microbiology, physics, physiology, and zoology. Some of the experiments were based upon equipment already planned for Skylab, and others required special but simple and inexpensive equipment. The experiments were both rewarding and instructive to the students. Several provided valuable, new scientific data.


USA

2

Skylab and Education

From its beginning the Skylab program was envisioned by its management personnel and by William C. Schneider, its director, as having implications that went far beyond the technological problems of construction and flight, even beyond its significant researches on the frontiers of science and technology. They saw this program with its numerous experiments and long-duration flights as having a societal, as well as a scientific significance.

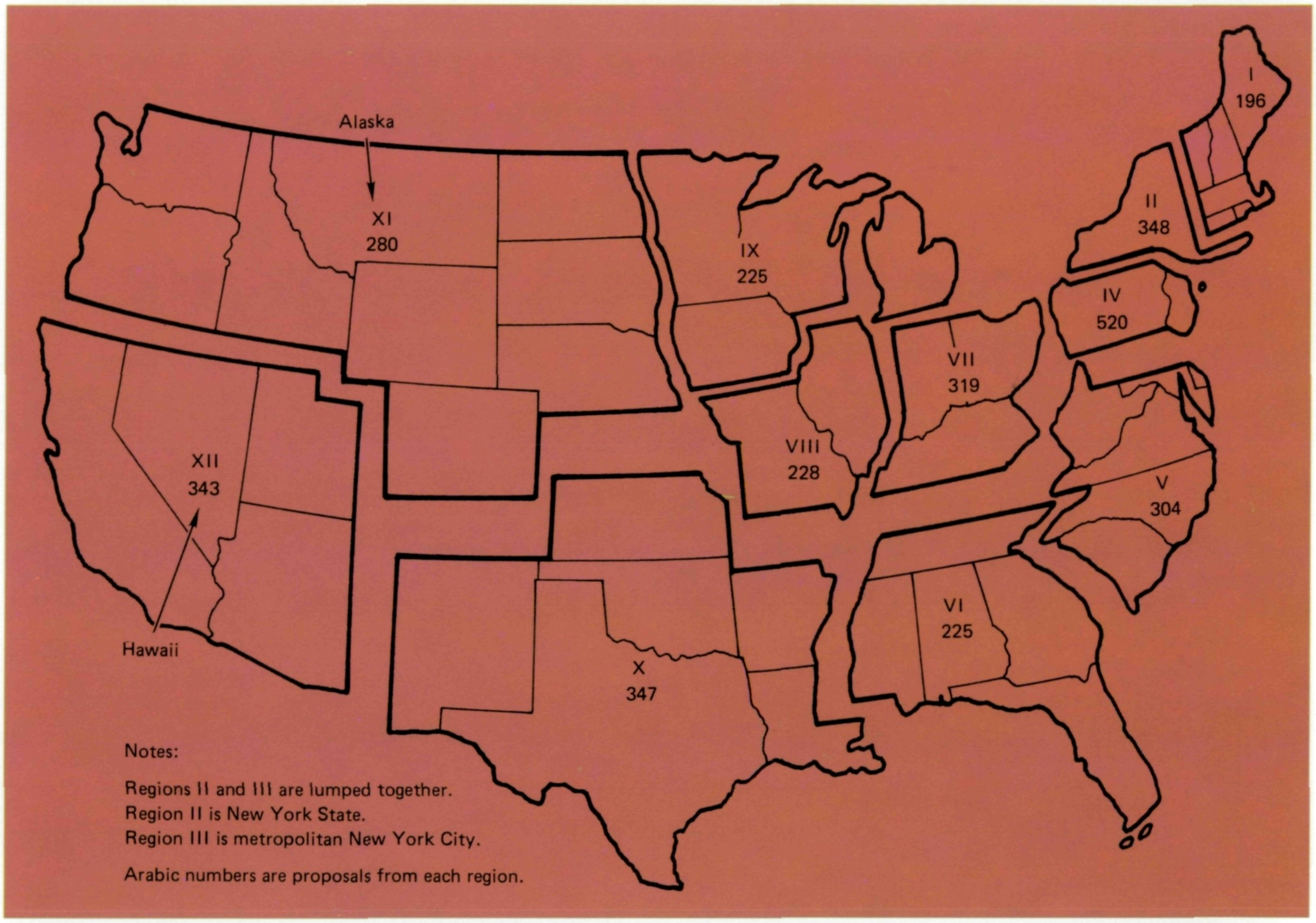
The management group perceived that Skylab's significance would necessitate understanding by those responsible in the schools for the education of future generations of youth. With this in mind, they supported NASA's Educational Programs Division with a program that included not only the pre-flight and flight years, but also the post-flight period.

This support permitted the production of instructional films and curriculum-related publications, and it also encouraged the conduct of educational conferences, including a joint conference of the National Council for the Social Studies (NCSS) and the National Science Teachers Association (NSTA), a conference which some say was the first time that professional associations representative of the social and natural sciences had formally met to discuss the social implications of science and technology. Skylab management also provided speakers for professional associations of educators, and the necessary information and background for NASA's Spacemobile personnel, who meet and address each year hundreds of thousands of adults and students.

One of the most successful of the Skylab educational efforts, however, was the Skylab Student Project. This was a nationwide contest in which secondary school students submitted proposals for experiments to fly on Skylab. The official announcement of the program was made in October 1971. Over 87 500 entry forms were requested by students throughout the country. Over 4000 students responded with 3409 proposals by February 4, 1972, the closing date for the competition. Proposals were received from all 50 states and 9 high schools overseas, from students in grades 7 through 12. From 12 regional eliminations held in the several geographic areas of the United States, 301 of these proposals were selected for screening in March 1972 by a national selection committee. Twenty-five were selected as winners, and 22 others were selected for special mention.

The proposals were evaluated on the basis of creativity, organization in terms of concept and implementation, applicability to the space environment, and adherence to the rules laid down.

In the subsequent evaluations of these 25 proposed experiments in terms of their suitability for flight, NASA's Marshall Space Flight Center (MSFC), Huntsville, Ala., the lead center for Skylab, selected 19. The remaining six were deemed not compatible with Skylab. Estimates made before the contest concerning the number of proposals which would be of the quality to fly



The United States was divided into 12 geographical regions to facilitate handling student proposals for Skylab.

ranged from zero to two or three. The fact that there were 19 experiments to fly, plus another 6 that were eligible, speaks highly of American secondary school science.

The winning proposals were then submitted to MSFC for detailed evaluation in conjunction with other NASA centers involved in the Skylab project. For those experiments requiring especially made experimental equipment, the analysis considered the feasibility of the needed data, conceptual design, and the impact of such a device on the astronauts and various systems of the Skylab. Also considered was the time needed to develop such experiments and the difficulty of fitting them into the Skylab's closely controlled needs for space and power.

As sometimes happens with important ideas, "the time for which has arrived," the idea for a Skylab student project surfaced at several different points in the early years of Skylab planning: at Skylab Program Headquarters, Washington, D.C.; Skylab Program Management, Marshall Space Flight Center; NASA Educational Programs, Washington, D.C.; Martin Marietta Aerospace, Denver, Colo.; the several elements of the National Science Teachers Association (NSTA); and the personnel of Science Service, Washington, D.C. The factor that led to the decision to conduct a student project was a phone call from Leland F. Belew, Skylab Program Manager, MSFC, to Schneider at NASA Headquarters. Belew's initiative grew out of conversations he had had on the subject with Kenneth P. Timmons, Skylab Program Director, Martin Marietta Aerospace. The final decision to conduct the project was made in February 1971.

Project policy, guidelines, general procedures, and budget were decided in Washington; problems of accommodation of student experiments to Skylab requirements were worked out in Huntsville. In the summer of 1971, NASA Headquarters contracted with the National Science Teachers Association, the professional association of science education with approximately 30 000 members and strong regional as well as national leadership, to conduct this project.

The profession of secondary school science teaching welcomed the concept. Faculty and students recognized that by it they would be introduced to the conduct of research in the medium of a vacuum, at zero gravity, and amid the cosmic forces of space. Never before had secondary school science teaching been introduced at such an early stage to an emerging realm of scientific investigation. The project also provided for most secondary school science teachers and pupils their first direct experience with the procedures incident to conducting research in large-scale, complex government projects.

The NSTA admirably took responsibility for the conduct of the regional and final evaluations of the thousands of student proposals. It also handled the logistics for conferences of the selected 25 students at MSFC in May 1972 and at the NASA Kennedy Space Center (KSC) during launch time, May 1973.

At the MSFC conference, in addition to talks by scientists, introduction to Skylab by managers, and a tour of the center, the students and their teachers met with their respective science advisers of the MSFC Skylab team to grapple with problems of integrating student experiments with Skylab. At the KSC conference the students, their teachers and parents, and NSTA leaders who worked on the project heard talks by leading scientists, held discussions with other principal Skylab investigators, toured the Kennedy Center, and witnessed the Skylab launch.

The conference at MSFC was organized to give the students direct experience with the problems of experiment integration on a spacecraft. Midnight oil was burned on numerous occasions during

The twenty-five winners in the Skylab student program met for the first time at the Marshall Space Flight Center, in Huntsville, Alabama, in May 1972.

A preliminary design review for students' experiments at the Marshall Space Flight Center in 1972 was hard work, but Daniel Bochsler, center, and his teacher-adviser Richard Putnam, left, had the opportunity to meet Astronaut Owen Garriott, right.

the week in preparation for the individual experiment presentations. Students, teacher sponsors, NASA-appointed science advisers, and members of the experiment integration team worked diligently in reviewing, revising, and making final preparation of the students' material for the review board. The climax came when each one presented to the board his or her proposal, together with any necessary modifications recommended by the science adviser.

For those experiments requiring specially built equipment, a prototype was shown, together with development and test plans for the flight version. For those experiments that were to utilize Skylab's experiments, the specific unit was identified, and a plan for using it was discussed. If the proposed experiment was associated with a major experiment of a scientist or principal investigator and he was available, he also participated in the review.

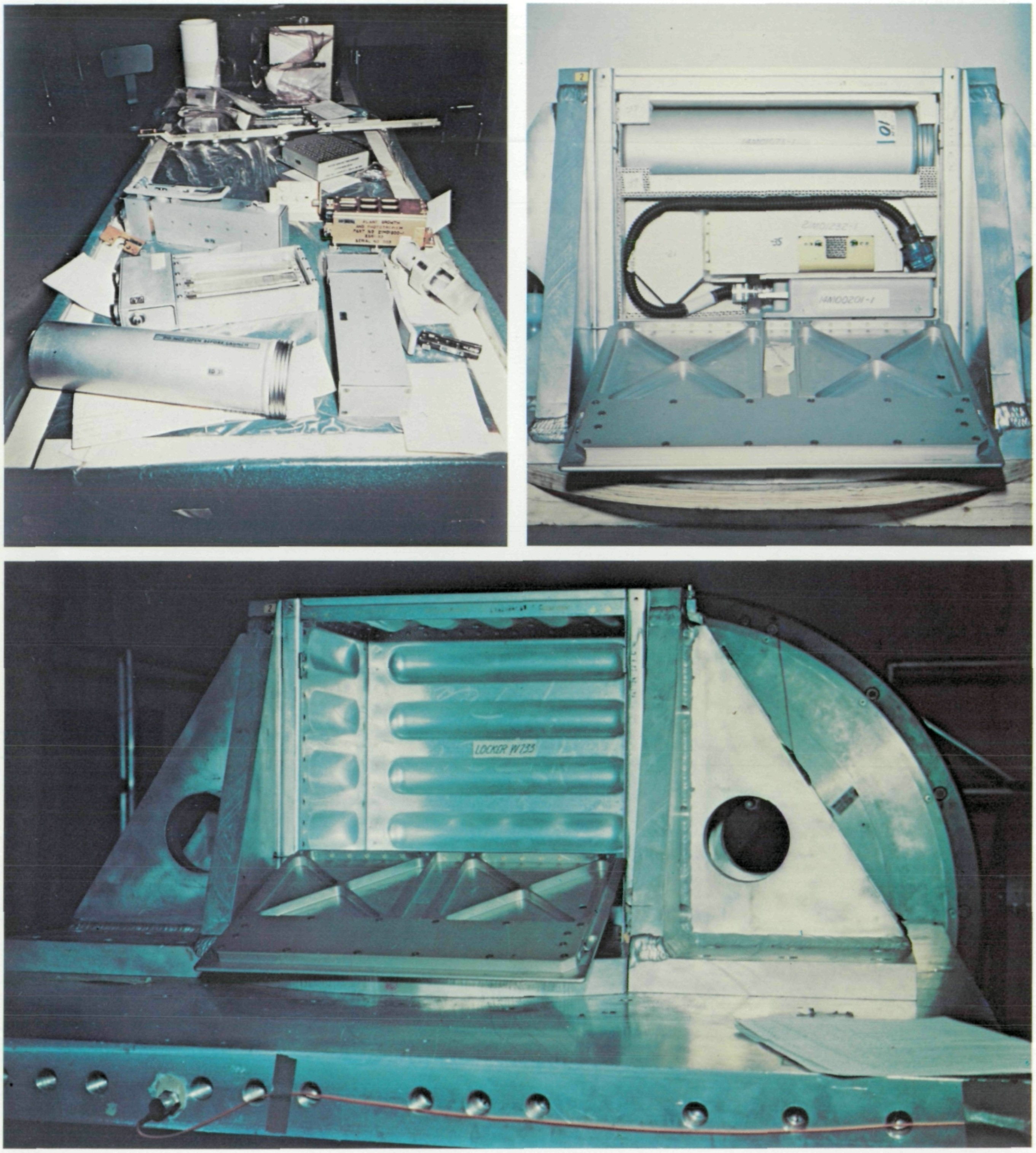
The result of the preliminary design review was the definition of 8 experiments not requiring new instruments, 11 needing them, and 6 that were not compatible with the Skylab. Efforts were made to permit students whose proposals were judged incompatible to participate through affiliation with principal investigators having experiments in related fields.

A mission-planning meeting was held at Johnson Space Center (JSC), in Houston, Tex., on May 23, 1972. The experiments to be included in Skylab were reconfirmed, together with the rationale for elimination of 6 of the 25 experiments from further Skylab development. Also, problem areas were defined, and various solutions were considered.

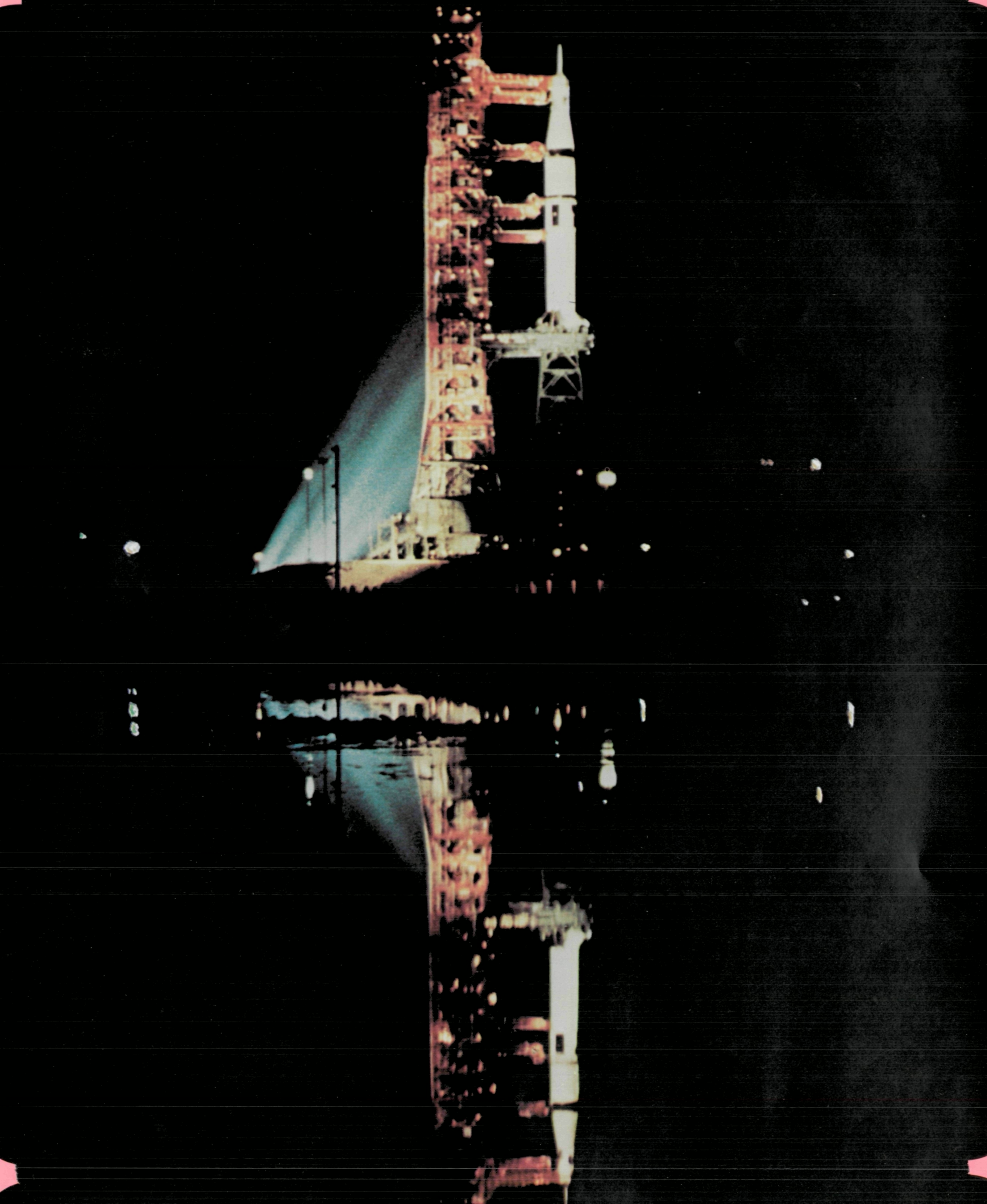
The student experiment critical design reviews were held at MSFC between August 8 and 10, 1972. The 11 students whose experiments required new equipment attended with their science advisers. The final selection of student experiments, by category, is shown in table 1. Development and program planning for the student experiments proceeded at an accelerated pace. All student experiments were delivered to Kennedy Space Center for installation aboard Skylab during the last week of January 1973.

TABLE 1.–*Skylab Student Experiments*

Category I	Duplication of data planned to be acquired using Skylab experimental equipment
ED11	Atmospheric attenuation of energy
ED12	Volcanic study
ED21	Lunar libration clouds
ED22	Objects within Mercury's orbit
Category II	Data from Skylab experiments with program impacts
ED23	UV from quasars
ED24	X-ray stellar classes
ED25	X-rays from Jupiter
ED26	UV from pulsars
Category III	New experiments required
ED31	Bacteria and spores
ED32	In vitro immunology
ED41	Motor-sensory performance
ED52	Web formation
ED61	Plant growth
ED62	Plant phototropism
ED63	Cytoplasmic streaming
ED72	Capillary study
ED74	Mass measurement
ED76	Neutron analysis
ED78	Liquid motion
Category IV	Experiments requiring other disposition or affiliation
ED33	Micro-organisms in varying gravity
ED51	Chick embryology
ED71	Colloidal state
ED73	Powder flow
ED75	Brownian motion
ED77	Universal gravity



Student experiments underwent a receiving inspection upon arrival at Kennedy Space Center after they were tested on a vibration table inside their storage locker at Marshall Space Flight Center.



3

Studies of the Central Nervous System

All vital activities of living beings are controlled by their nervous systems. These communications networks, much like those of a large telephone system, carry information that is derived either from the five specialized senses or internally produced stimuli to the brain. The brain and spinal cord make up the central nervous system and, with the peripheral nerves, control voluntary activities such as reaching and walking. The autonomic nerve system, with the endocrine system, controls most of the involuntary activities such as breathing.

The spinal cord contains the nerves controlling reflex actions. From these reflex centers, motor nerves lead to all of the muscles in the arms and legs and most of the trunk. The spinal cord also carries the sensory nerve signals between the brain and parts of the body below the neck.

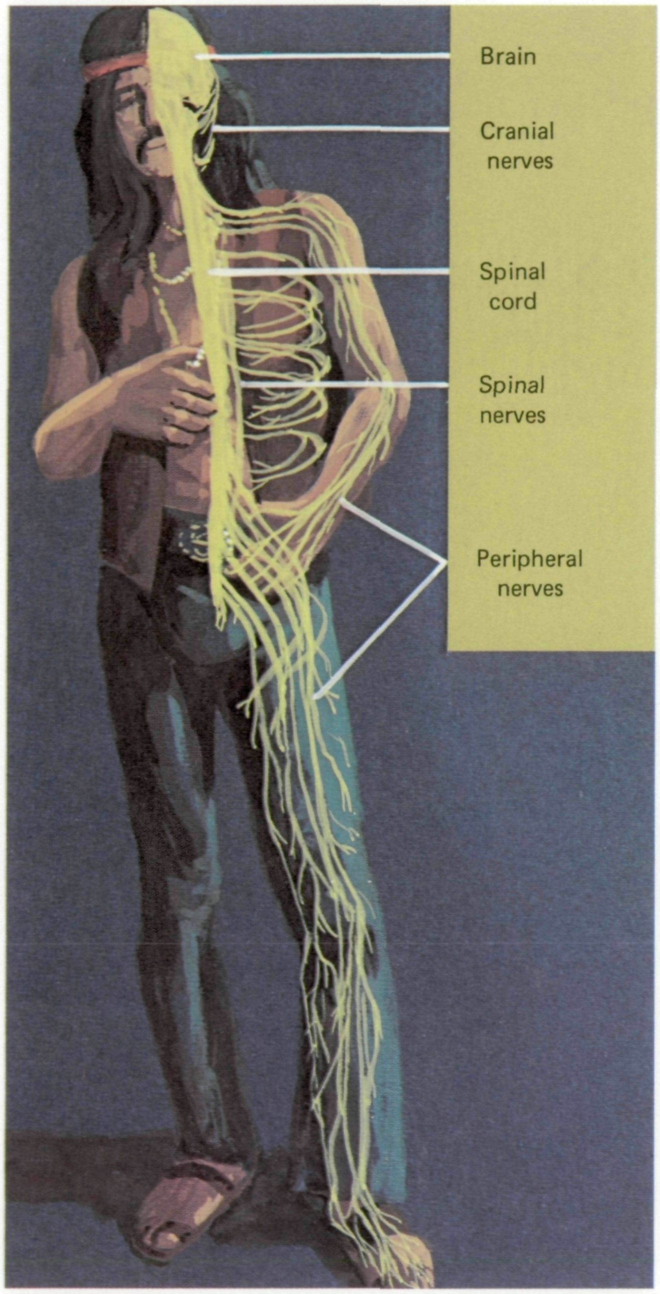
The largest part of the brain, the cerebrum, contains sensory, motor, and association regions. The sensory portion is made up of centers which are responsible for such functions as seeing, hearing, smelling, tasting, and touching. The motor region controls all voluntary movements of the body. The least well-known area of the brain is the association region. It is apparently responsible for an individual's awareness of the meaning of things. It allows him to relate sensory perceptions to motor actions. These three parts of the brain are interconnected so that signals can be carried from centers in one area to those in others.

Two of the student experiments involved investigations of the nervous system. One was directly concerned with the effects of prolonged weightlessness on man's motor-sensory performance. The other studied the web-spinning characteristics of spiders.

Motor-Sensory Performance

The Mercury, Gemini, and Apollo programs proved that man could function in a capable manner in space. However, in each of these programs there was some evidence of physiological damage, loss of bone calcium and general muscle tone being the most often mentioned. None of the missions included tasks that produced a quantitative measure of the physiological effect, if any, on man's capability to perform delicate tasks with his hands. Since the early beginning of man's exploration of space, there have been questions concerning his ability to perform such movements. The establishment of large space stations and interplanetary travel involve extended tours of duty in an alien environment. The possible establishment of space manufacturing facilities, and certainly the need to make repairs, require that the crew perform a variety of tasks with hands and fingers. Without knowing whether or not man can retain a high level of competency in the performance of such tasks after long exposure to weightlessness, this capability could not be fully known. Skylab, with its long-duration missions, provided an ideal testing situation.

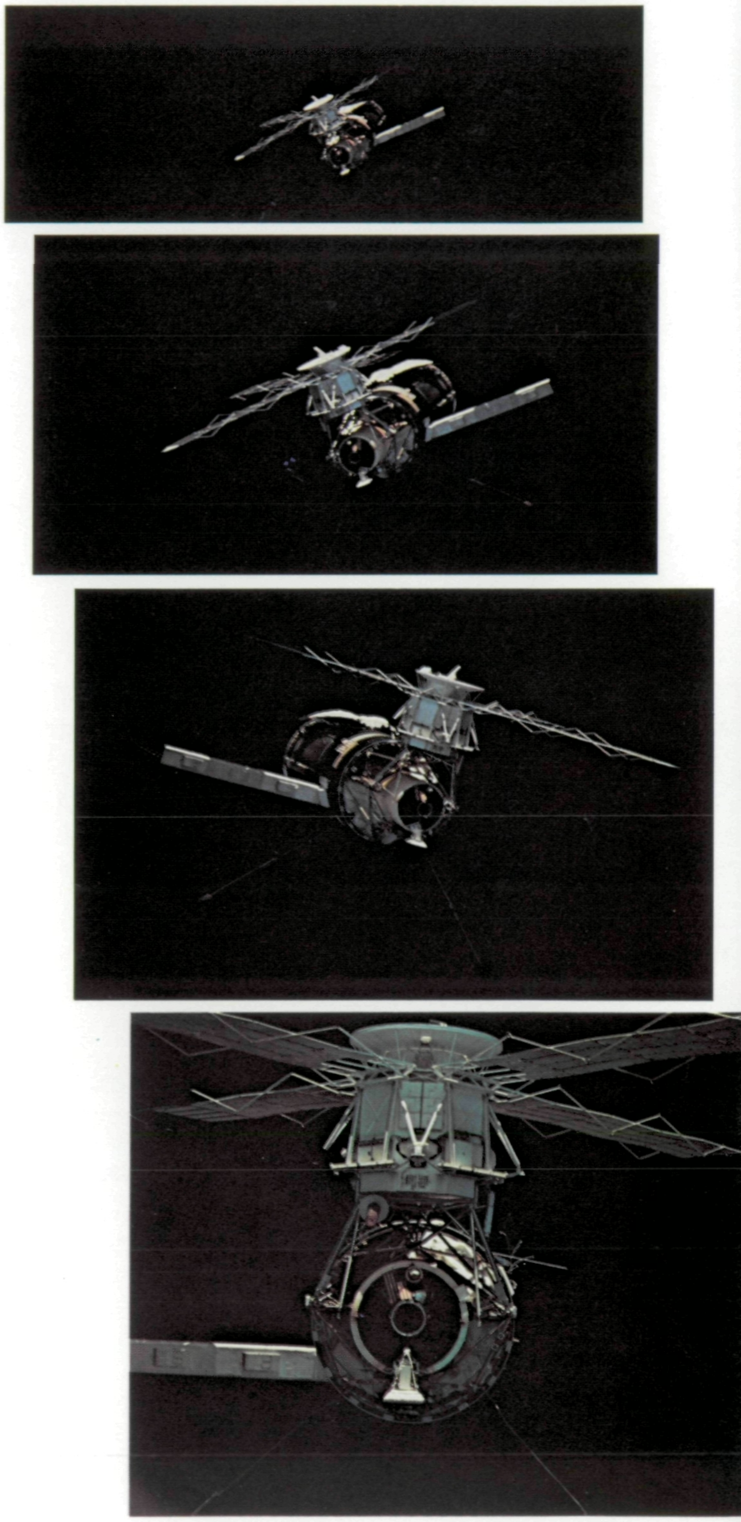
Kathy Jackson of Clear Creek High School,



Man's nervous system is an intricate network of nerves, with the brain and spinal column forming its coordinating center.

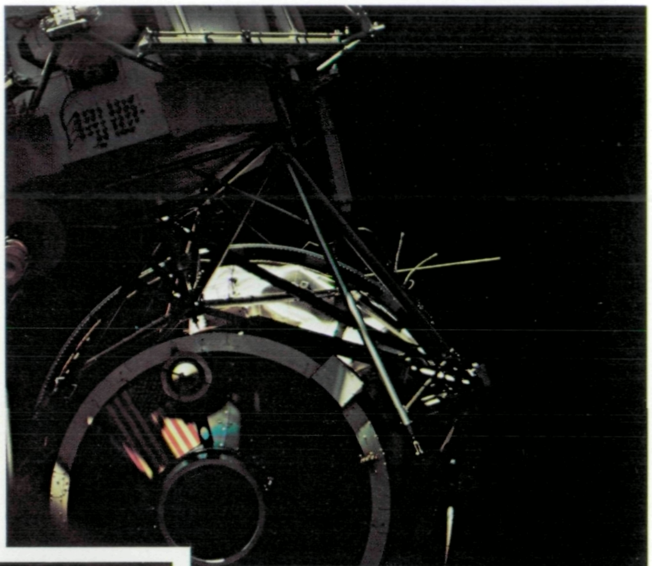
Houston, Tex., proposed a very simple but effective test to measure the potential degradation of man's motor-sensory skills while weightless. It is generally accepted that fatigue can affect both the sensory and motor centers of the brain. The

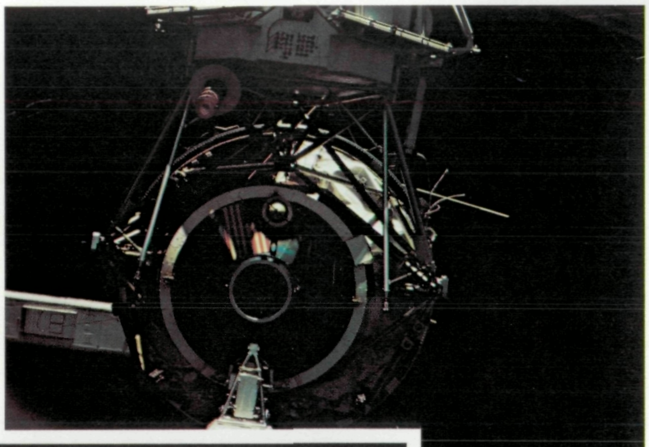
Docking one spacecraft with another requires one of the greatest tests of the motor-sensory capabilities of man.

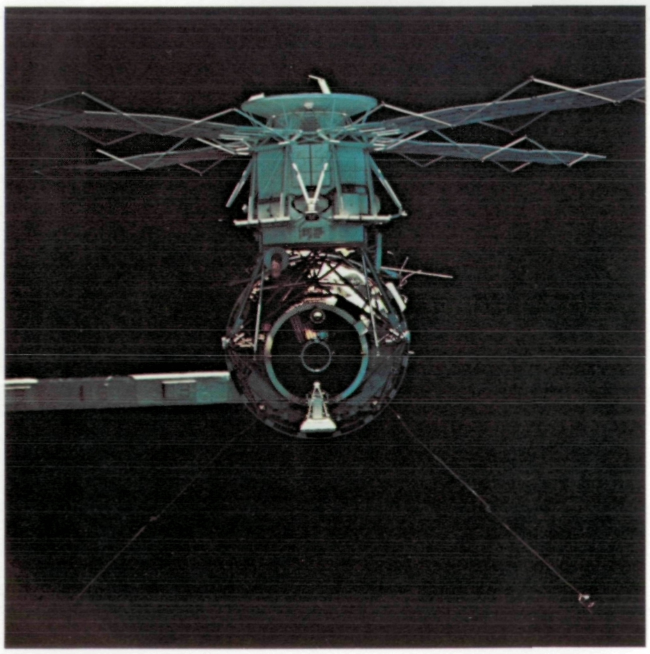


sensory receptors must recognize the requirement for action. The association center of the brain then calculates the proper action necessary to respond to the sensory center's signal, and the motor center issues the necessary commands for the muscles to react appropriately. The experiment Kathy Jackson proposed is similar in application to the tasks involved in docking one spacecraft to another using manual control. It is a familiar manual tracking task.

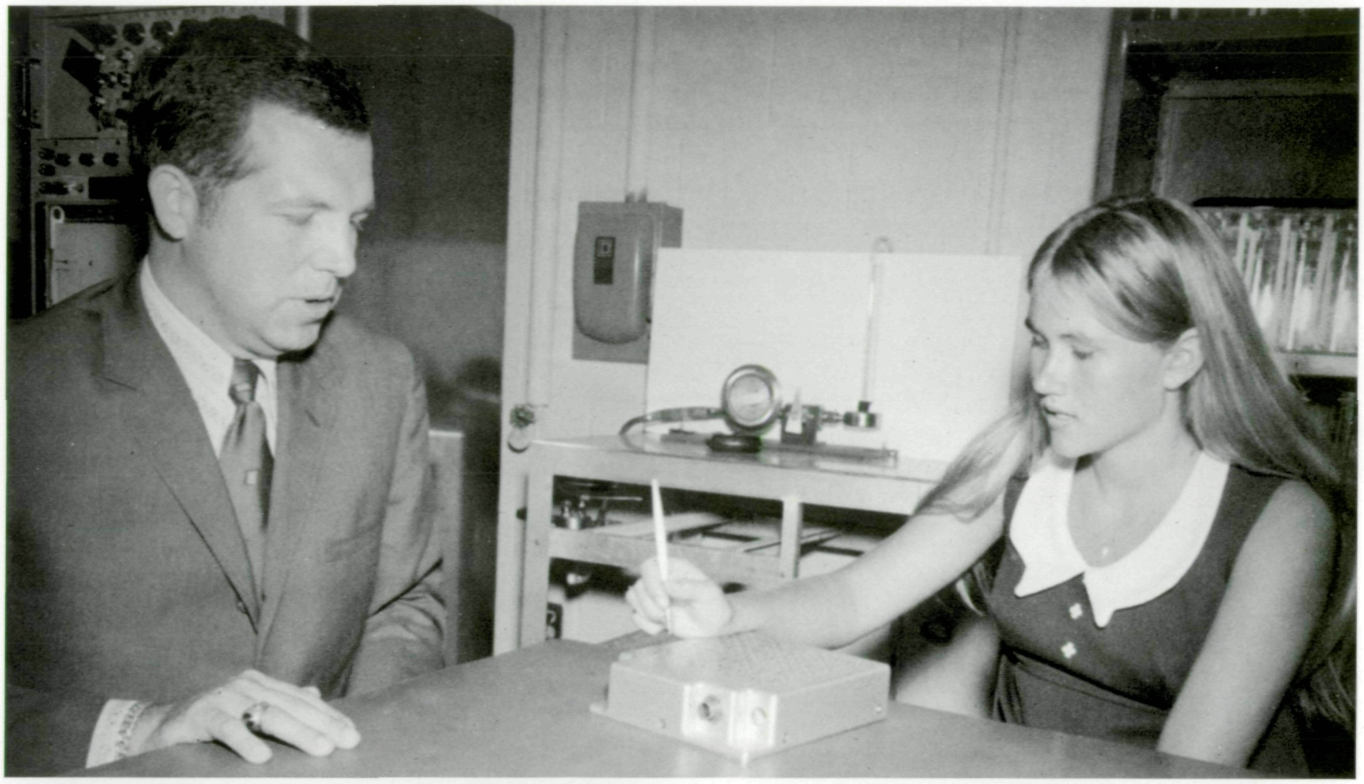
She suggested use of a standard eye-hand coordination test developed by the industrial engineering department of the University of Michigan. It was designed to measure an individual's capacity to direct hand movements with the aid of visual monitoring. The test consisted of a visual maze and aiming pattern with 119 holes connected by straight lines. The astronauts inserted a probe in each hole in sequence, following the maze pattern. Thus, the visual perception and motor response was measured quantitatively by recording both the total time required to traverse the entire maze and the time required to move the probe from hole to hole.

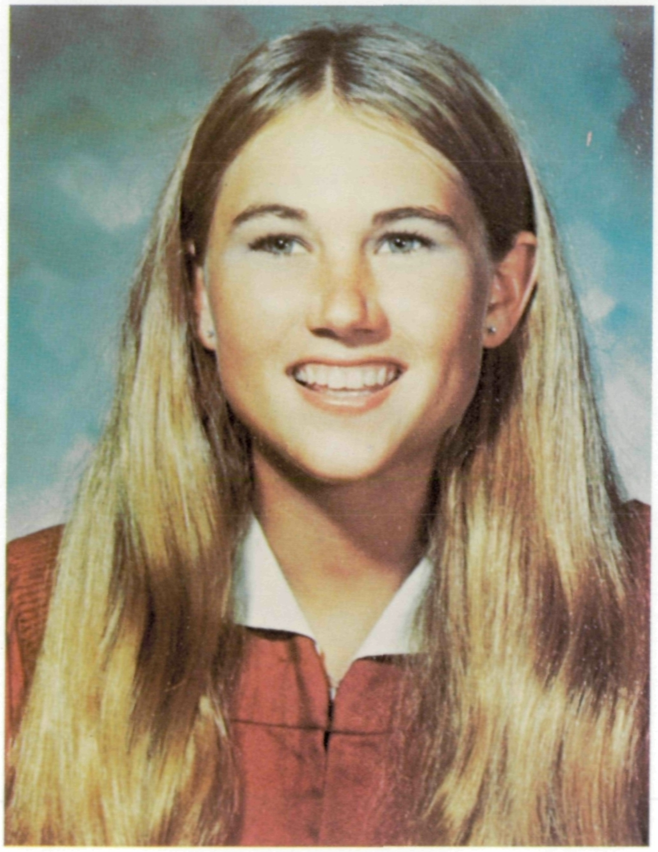




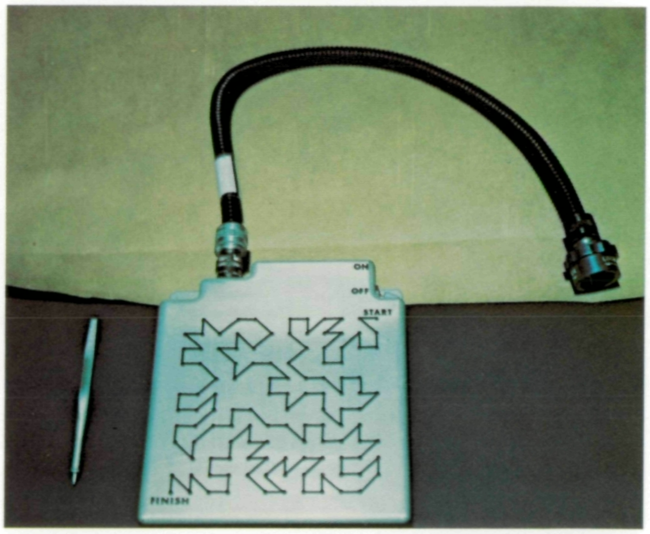


The test was performed by each member of the third Skylab crew. They worked through the maze early in the mission, again approximately at midmission, and then late in the mission. The crew reported that they enjoyed this test and regretted that there was not time to work with the maze more often.



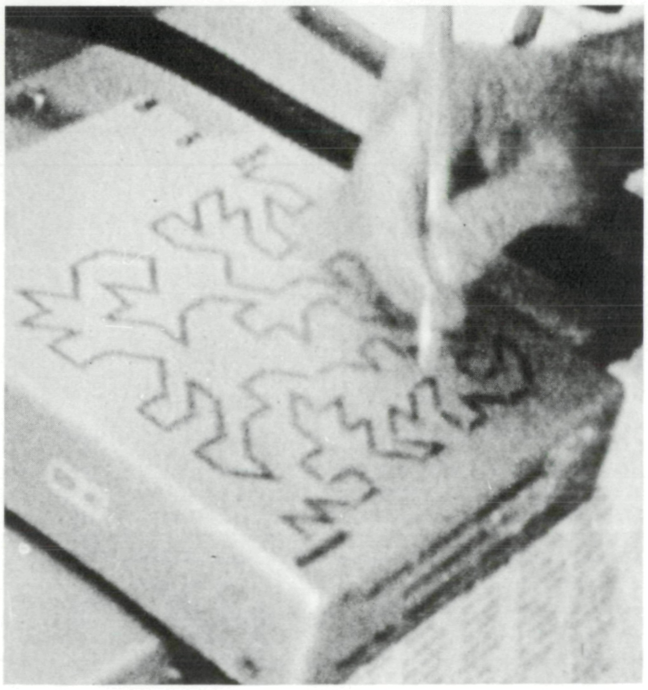


Kathy Jackson (at left), shown above with science adviser Robert Allen of the Marshall Space Flight Center, devised a simple but effective means of testing the potential loss of motor-sensory skills of men who are weightless for long periods of time.



The motor-sensory experiment consisted of a maze and a small stylus, shown above. By having an astronaut insert the stylus into each hole in sequence, the time between holes as well as total time could be measured as an index of his skill.

Scientist Pilot Gibson displayed the experiment during the third manned period of Skylab's mission for TV viewers on Earth.



In this closeup view, Gibson demonstrated how the experiment worked. Each member of the third crew performed the test satisfactorily.

Analysis of preflight, inflight, and postflight data indicated that there was no significant change in the eye-hand coordination of the crew. This fact was further evidenced by the outstanding performance records of all three Skylab crews. The installation of the Sun-shield parasol by the first crew, the twin-pole Sun shield by the second crew, and the repair of the coolant system by the third crew are but a few examples of the normal motor-sensory capabilities of the Skylab astronauts. Further, none of the crews reported any noticeable deterioration throughout the missions in performing tasks that required them to handle experiments and controls.

Web Formation

Motor response is an indication of the functioning of the central nervous system. Drugs such as stimulants and sedatives affect the nervous system by causing degradation of certain motor responses. In an effort to study the effects of drugs, researchers have often utilized spiders as test subjects. The geometrical structure of the web of an orb-weaving spider provides a good measure of the condition of its central nervous system.

After reading an article in the *National Geographic* magazine describing the behavior of the spider, Judith Miles of Lexington High School, Lexington, Mass., suggested a study of the spider's behavior while weightless. Since the spider senses its own weight to determine the required thickness of web material and uses both the wind and gravity to initiate construction of its web, the lack of gravitational force in Skylab would provide a new and different stimulus to the spider's behavioral response.

The common Cross spider (*Araneus diadematus*), an orb-weaving spider that produces a web of nearly concentric circles, was selected for the experiment. The Cross spider can live approximately 3 weeks without food if an adequate water supply is available. The female spider will build a web each day at approximately the same time, in the pre-dawn hours. The web is constructed in a very orderly fashion, starting with a bridge and frame. Using this rudimentary structure, the spider adds radial threads. A temporary spiral emanating from the hub is constructed next. It serves to give the spider a measure of the distance around the hub or central region of the web. Thus, the spider is able to judge the amount of silk required for the

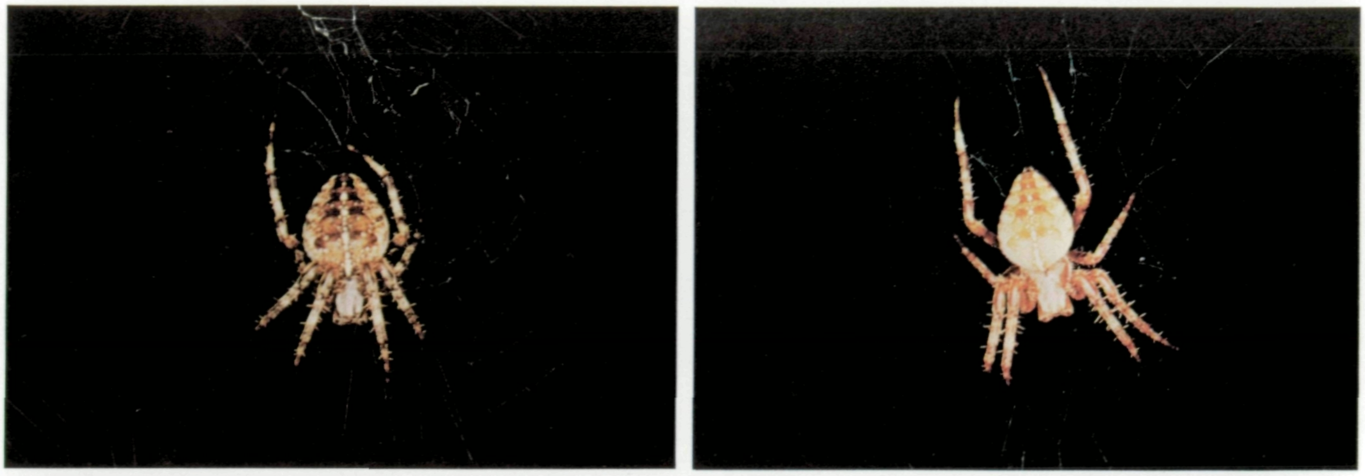
Judith Miles wondered whether spiders could build webs while weightless. She proposed an experiment for Skylab which was performed by the second crew.

Orb-weaving spiders spin webs familiar to everyone; however, their construction technique is a complicated one.

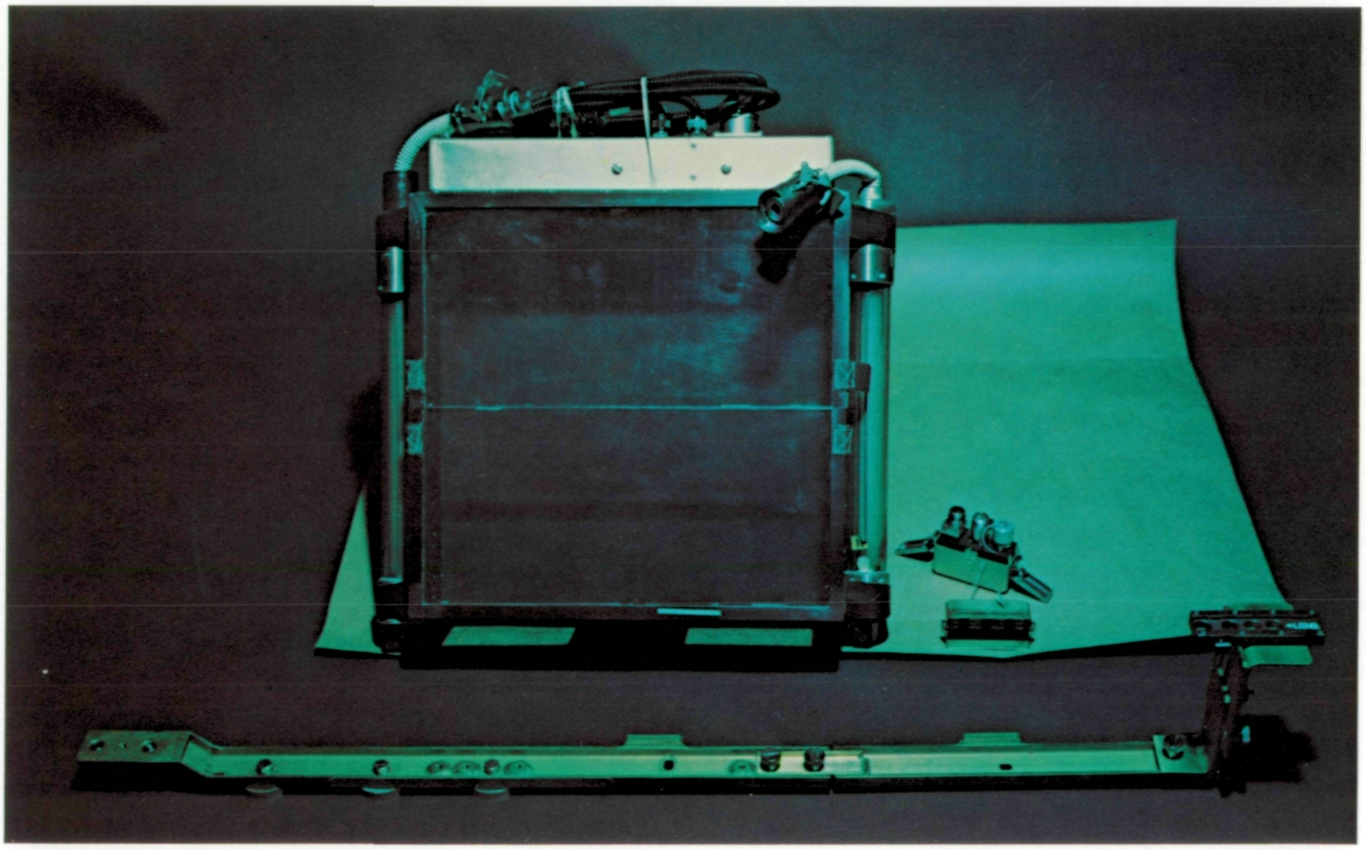
web, and it establishes the mesh size. The next step is the construction of the sticky, or catching, portion of the web. A free section of the web provides an area for spinning a signal thread from the spider's retreat to the limb of the web. This thread alerts the spider to the presence of prey in the catching spiral. The normal adult spider will utilize 66 to 98 feet of silk thread in constructing her web and will usually eat the sticky portion of the web daily. The web will generally consist of 30 to 40 radials and 25 to 35 spiral turns.

A specially constructed cage, provided with attachments for two portable utility lights, a camera-mounting bracket, and an ultrasonic actuator for a movie camera, was launched aboard Skylab. Two spiders, named Arabella and Anita, were each fed a housefly, installed in a small vial provided with a water-saturated sponge and an additional housefly, and launched in the Apollo spacecraft with the second Skylab crew.

On August 5, 1973, Scientist Pilot Garriott placed Arabella's vial in position on the cage and



Launched with the second Skylab crew were the space spiders Arabella and Anita, both common Cross spiders (*Araneus diadematus*).



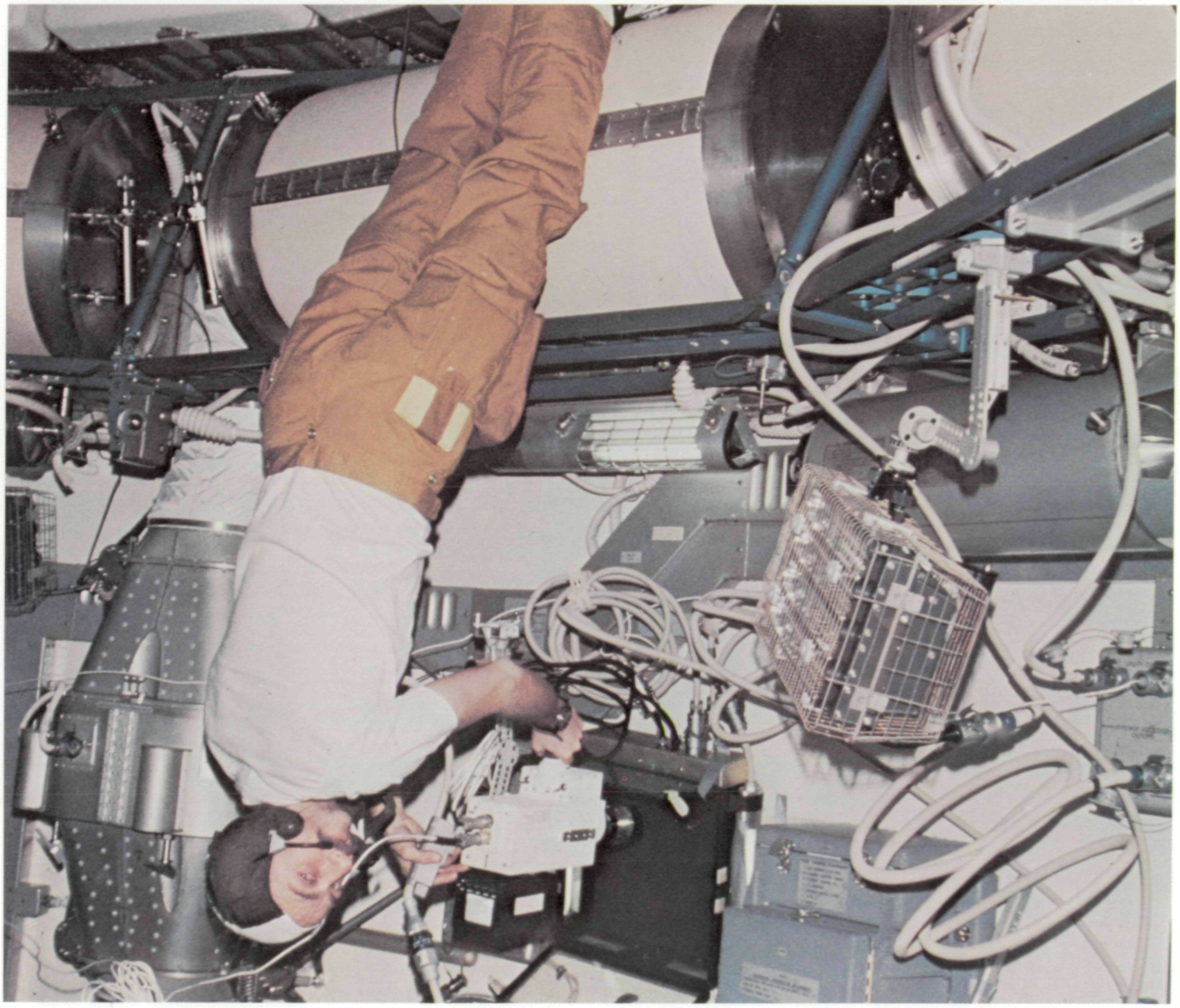
The orbital home of Arabella and Anita aboard Skylab was a specially lighted cage. The two spiders rode into space in the small capsules to the right of the cage.

A control spider on Earth built a perfect web in a Skylab cage to use as a comparison with those being built in space by Arabella and Anita.

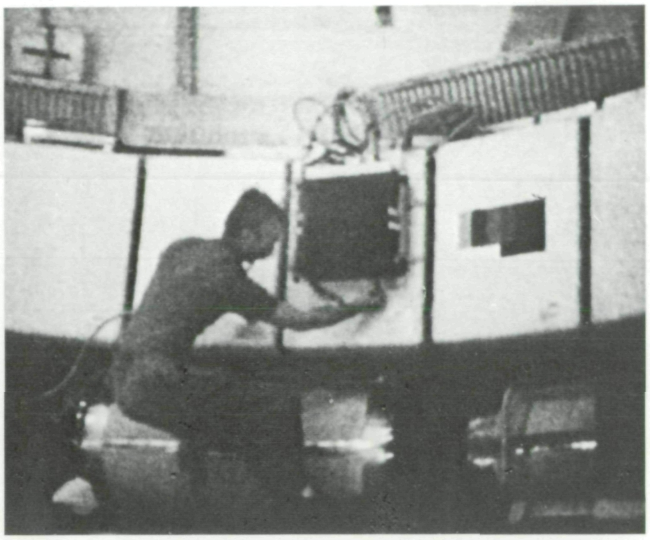
fully expected her to move out into the cage from the cramped quarters. However, she refused to do so. After several hours Garriott forcibly shook her from the vial into the cage. Arabella bounced back and forth, moving erratically in a swimming motion before she affixed herself to the screen covering on the cage surface. The crew reported the next day that Arabella had constructed a rudimentary web in the corners of the cage. Her first complete web was observed after 2 days in the cage.

At this point, Garriott expressed interest in carrying this experiment beyond the planned protocol of terminating the experiment after allowing one spider to build three webs. As a result of this request, a new protocol was approved which involved feeding the spiders rare filet mignon, providing an additional water supply, deploying Anita at midmission, and returning both spiders together with samples of the webs.

Both spiders were subsequently fed, and on August 13, Garriott removed half of Arabella's existing web. She promptly ingested the remaining half and refused to rebuild. Garriott then provided Arabella with water, whereupon she proceeded to build a new web. On August 21, Arabella's web



Lost in a maze of electrical wires and cables, Scientist Pilot Garriott operated a TV camera to record the web-weaving of Arabella. Up and down had no meaning in the workshop.



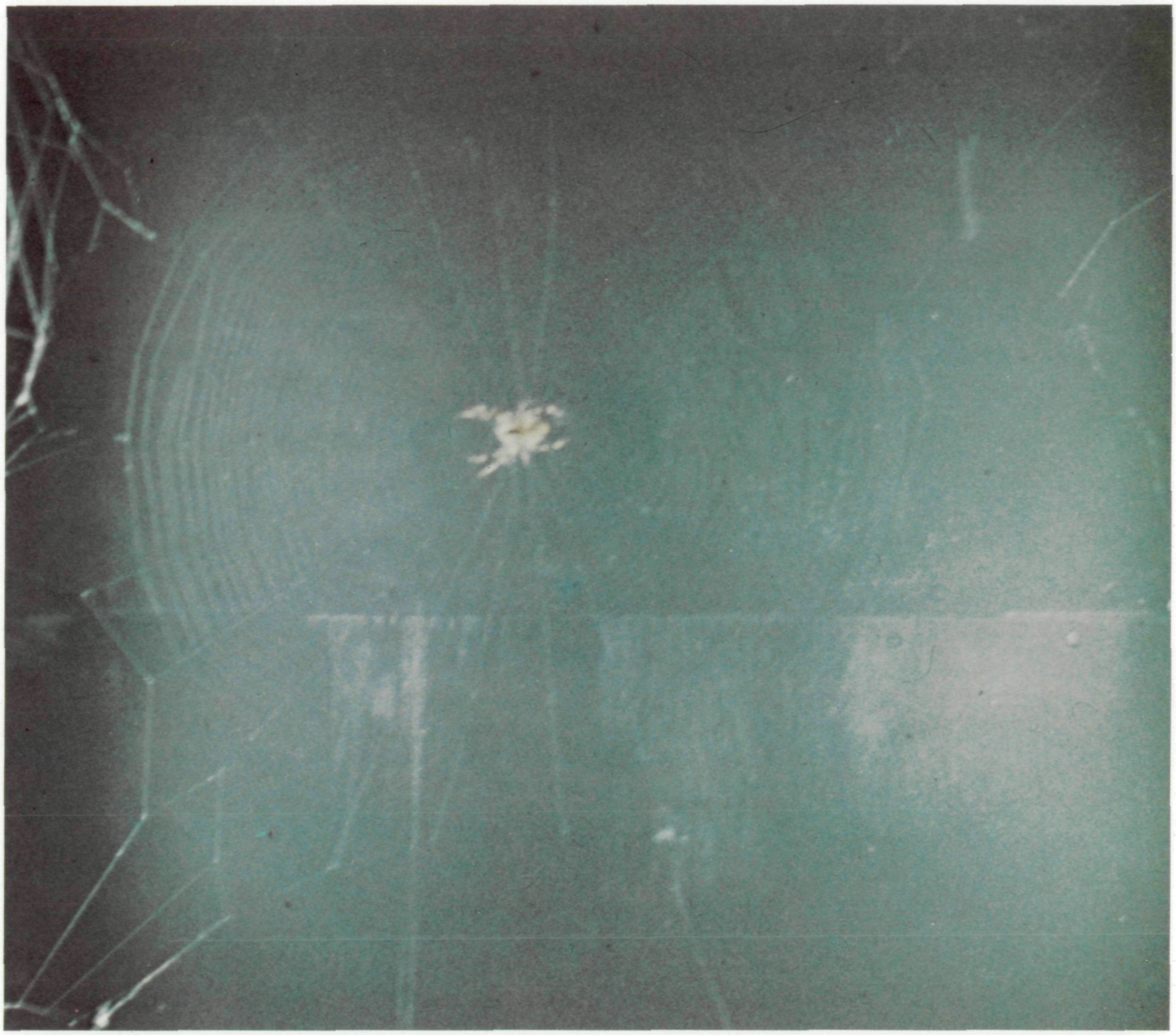
To initiate the spider experiment, Garriott attached Arabella's vial to the cage and tried to coax her out.

was completely removed, and the web found in her cage the following day was observed to be her best to date.

On August 26, Arabella was returned to her launch vial, and Anita was placed in the cage. A videotape recording and 16-mm movies were made of Anita's first reactions to weightlessness. She, too, had to be forcibly ejected from her vial and, in fact, had to be picked off Garriott's arm before she could be induced to "swim" into place on the side of her cage. Anita performed in a manner similar to Arabella until September 16, when the astronaut found her dead in the cage. The dead spider was transferred to her launch vial for return to Earth.

Back on Earth, Arabella was found to have died also. Both spiders showed signs of dehydration, the only visible evidence of the cause of their death. Examination of the returned web materials indicated that the thread spun in flight was signifi-

At first, Arabella did not do too well at spinning a home in space.



Once she had grown used to being weightless, Arabella spun webs that compared with those she had made on Earth.

cantly finer than that spun preflight, giving positive evidence that the spider utilized a weight-sensing organism to size her thread.

It appeared that Arabella adapted quite well to the weightless environment. Control tests on Earth indicated that confinement in the launch vial did not affect the spider's ability to construct a quality web. Similar confinement, accompanied with vibration at the levels encountered during launch and followed by a "rest" period corresponding to the flight delay in deployment, resulted in an adaptation period of 2 to 3 days before the control spiders built webs comparable to their pretest quality. While Arabella performed her space task, the extended "rest" period experienced by Anita in her launch vial allowed her to build at least one quality web almost immediately when she entered the cage.

Had the original planning included keeping the spiders in the cage for the full mission rather than 3 to 5 days, a method could have been developed for feeding them and providing them with water in a more reliable fashion than was done.

Judy Miles' experiment received a great deal of attention both within NASA and in the world press and indicated that there was keen interest in space experiments involving living organisms. It also established that biological experiments involving simple life forms are compatible with manned spaceflight.

Anita proved that she, too, could produce almost Earth-like webs once she had adapted to weightlessness.

Both spiders and specimens of their webs were returned to Earth for Judith to examine. She was assisted by Raymond L. Gause, a physicist and her adviser at the Marshall Space Flight Center.


UNITED STATES

4

Cells in Space

Just as the atom is fundamental to all matter, the cell—composed of atoms—is fundamental to all living organisms. A cell can be an extremely complex thing, as found in higher forms of life, or a relatively simple one such as those characteristic of micro-organisms.

The knowledge and study of micro-organisms and the cellular basis of life was impossible until the invention of the microscope. The observance of such organisms was first reported more than 300 years ago by Anton van Leeuwenhoek, a Dutch scientist. At about the same time, an English physicist, Robert Hooke, conceived of the cell concept during his examination of a sample of cork with the microscope. The term "cell" was used because of the similarity of what he saw to the cells of a beehive. The improvements in microscopes through the ensuing years greatly increased our knowledge of micro-organisms. However, only with the advent of the electron microscope, which can magnify up to 1 million times, were we able to solve the mysteries of the cell.

Several Skylab student experiments were proposed to investigate various aspects of cellular behavior. These included the study of bacterial growth, immunology, the streaming of cytoplasm in a plant, and micro-organisms.

Bacteria and Spores

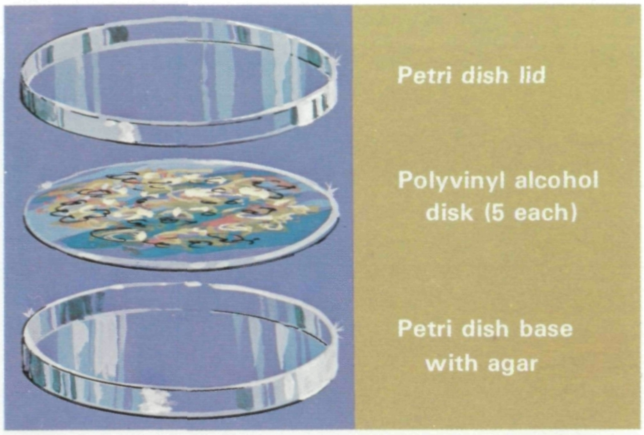
An experiment involving bacteria and spores was proposed by Robert L. Staehle of Harley School, Rochester, N.Y. He wanted to determine the effects of the Skylab environment (particularly weightlessness) on the survival, growth rates, and mutations of certain bacteria and spores.

Live bacteria (*Bacillus subtillus* and *Escherichia coli*), grown from a broth culture by Staehle at the laboratories of Rochester Institute of Technology, were suspended in a water solution of polyvinyl alcohol (PVA). The PVA was used to keep the bacteria alive but dormant until the experiment could be started. The solution was then dispensed on the surface of a disk of filter paper, where the bacteria remained in a vegetative form or reverted to a spore stage. The PVA coating on the bacteria protected them during the required storage period and enabled the establishment of an excellent growth condition when the filter paper was placed on the surface of nutrient agar.

Fifteen petri dishes containing nutrient agar, together with one petri dish containing 15 filter disks of bacteria, were launched in Skylab. Each inoculated disk was sandwiched between sterile paper disks for additional protection and isolation.

The experiment was initiated by placing a single bacteria and spore impregnated disk in each of the agar-filled petri dishes. Very shortly after that inoculation procedure, the water from the agar dissolved the PVA and provided nutrients to the bacteria and spores. Nine of the petri dishes were placed in an incubator at approximately 95°F, and six were incubated at the Skylab ambient temperature of approximately 77°F.

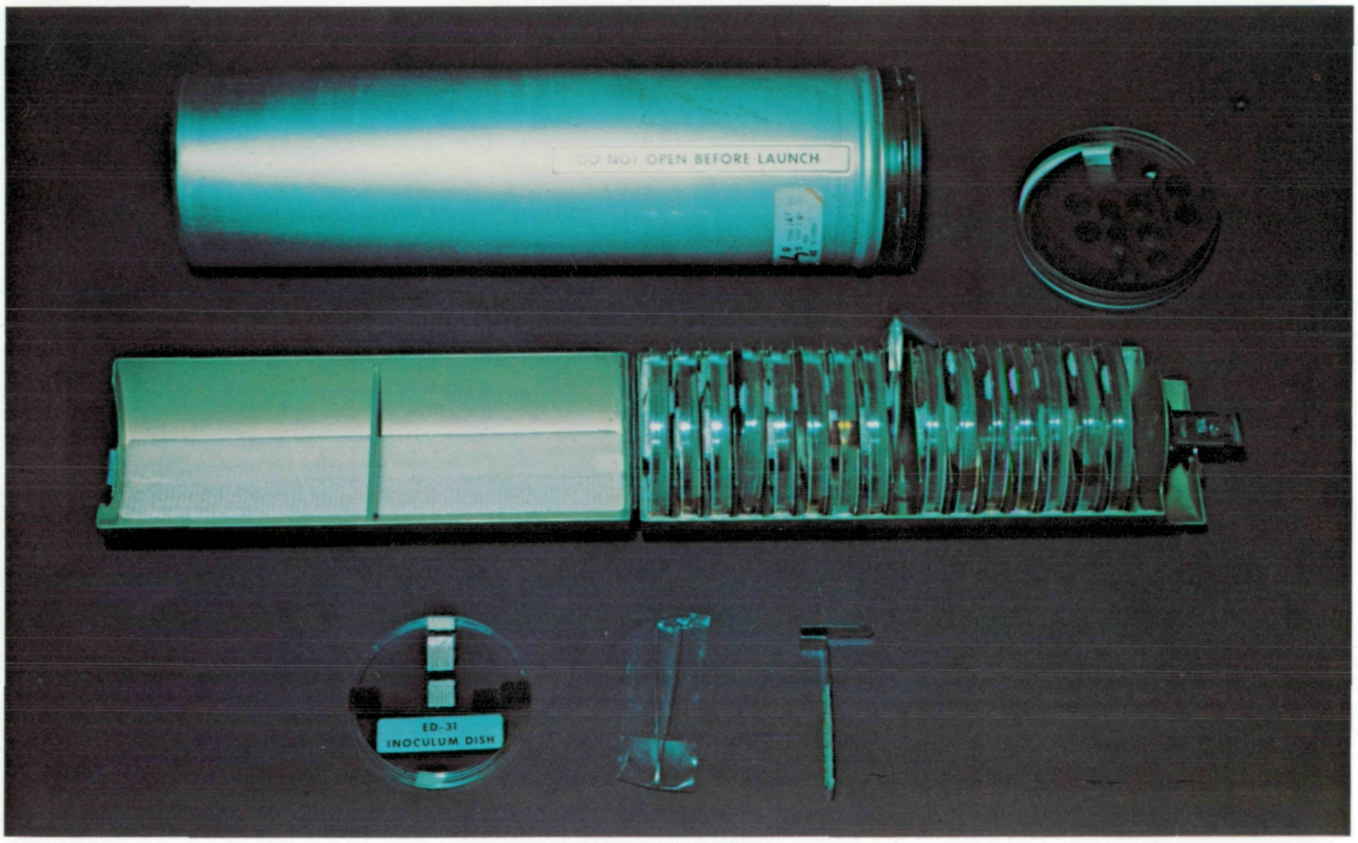
Robert L. Staehle, shown above with his science adviser Steven Hall, believed that Skylab would be a unique laboratory in which to study the effects of weightlessness on the survival, growth, and mutations in bacteria and spores. He later became a "co-op" student at Purdue University, alternately studying aeronautical engineering and working at the Marshall Space Flight Center.



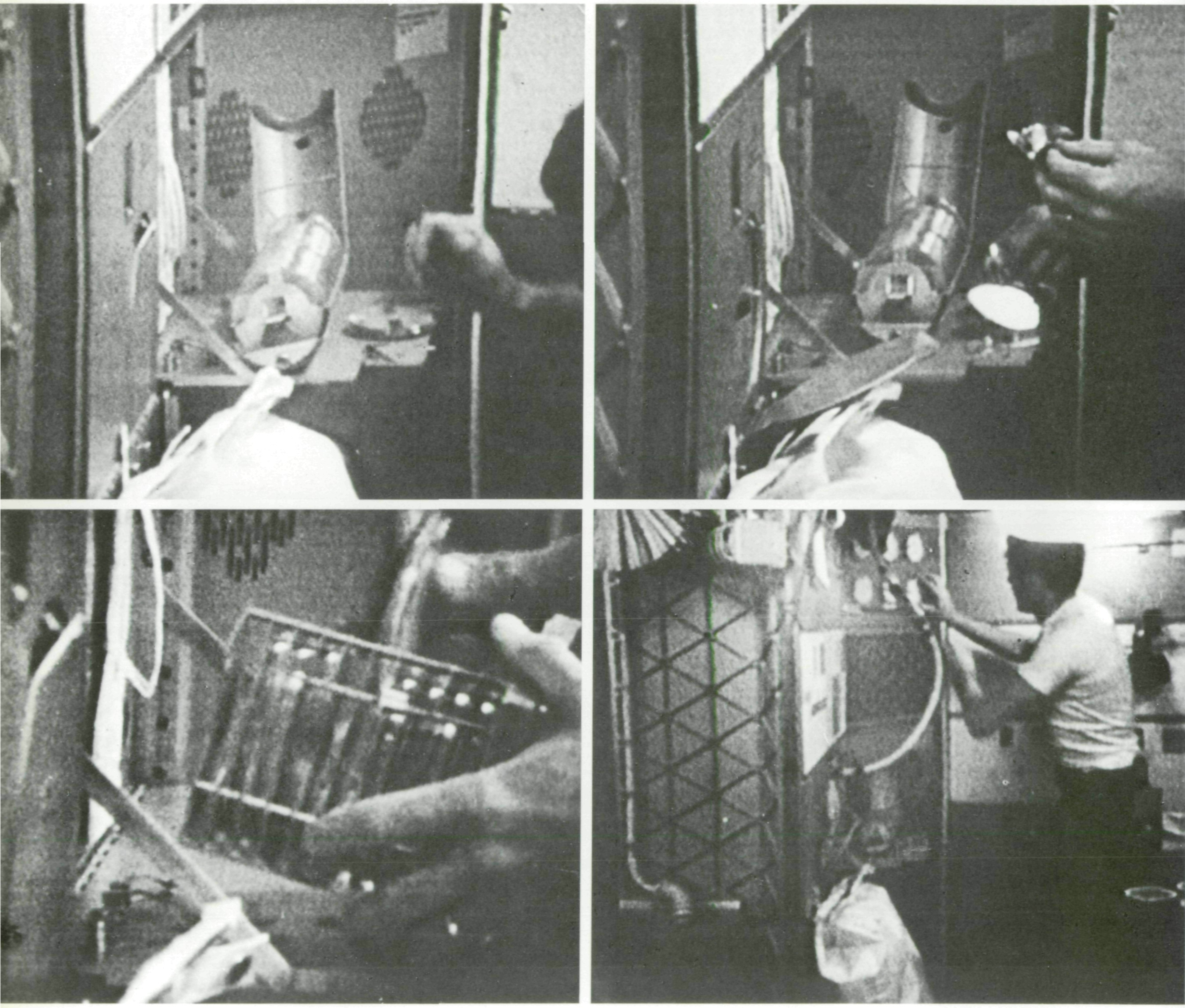
The heart of Staehle's experimental apparatus was a filterpaper disk impregnated with a bacterial culture suspended in polyvinyl alcohol and placed within an agar-filled petri dish.

The petri dishes were incubated for 68 hours. Photographs were made of the bacterial colonies periodically throughout the incubation period to record the colony growth rates. Return of the petri dishes by the astronauts at the end of the first mission revealed that only a small portion of *B. subtillus* and none of the *E. coli* had developed. This result was not surprising in view of the overheating of Skylab after the loss of its meteoroid shield during launch.

As a result, a repetition of the experiment during the third mission was authorized, and the species *Bacillus mycoides* was selected to replace the *E. coli.* The same protocol or experimental procedure was repeated, except that the petri dishes were incubated for 88 hours. Once again, however, only *B. subtillus* colonies developed.

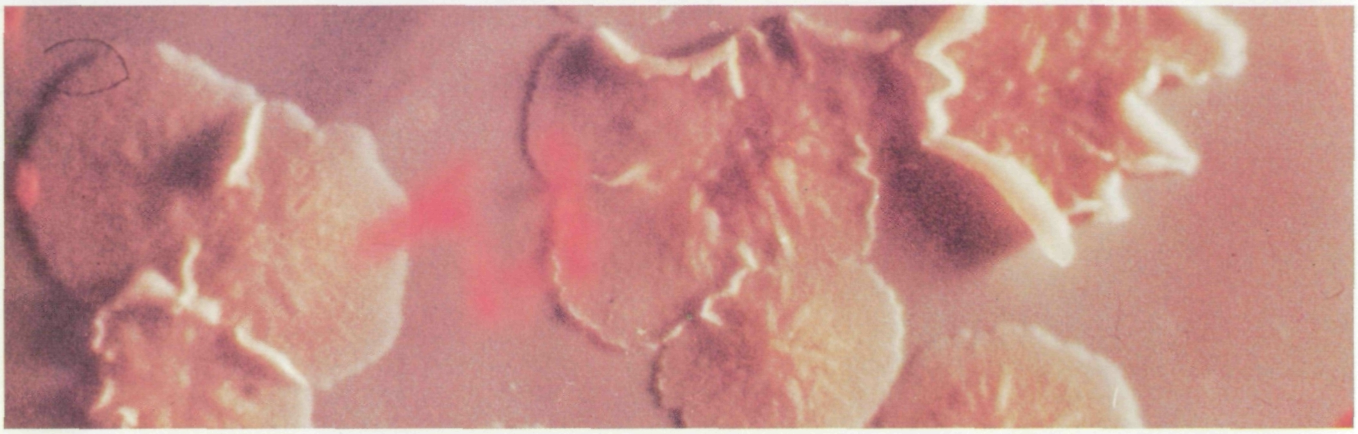


The experiment developed by Staehle fitted neatly into a standard Skylab food container, shown above. Its 16 petri dishes and associated equipment are shown below the food container.



To prepare the Staehle experiment, individual petri dishes (1) were inoculated by the astronaut (2). The dishes were then incubated in a special oven (3) and within ambient Skylab temperatures (4).


1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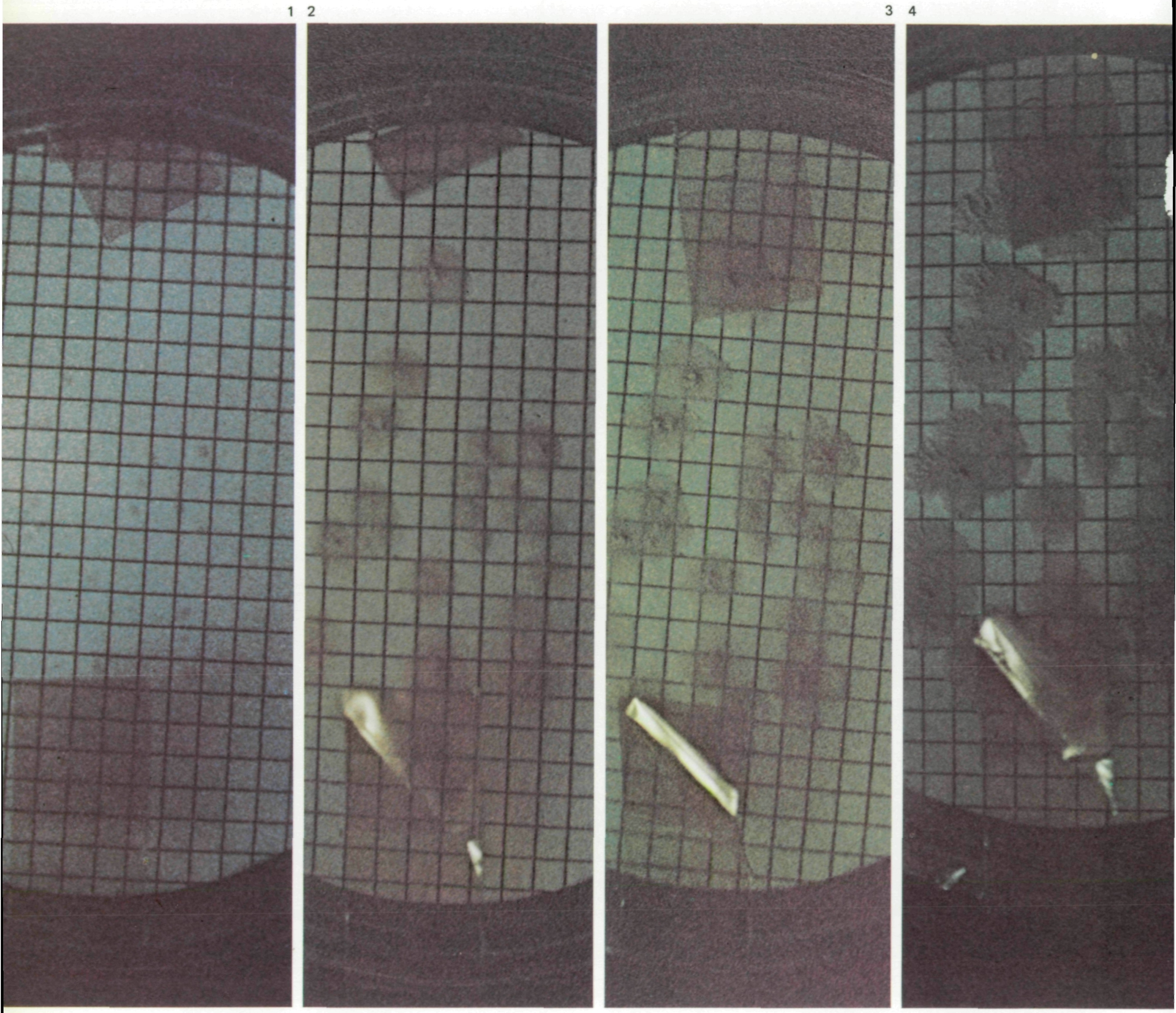
Pictures 1 and 2 show samples of *Bacillus subtillus* grown during the first performance of Staehle's experiment aboard Skylab. Pictures 3 and 4 show colonies of the same bacteria that developed during the second performance of the experiment.



14 hr, 30 min

24 hr, 30 min

38 hr

88 hr, 30 min

The growth rate of *Bacillus subtillus* during the second performance of Staehle's experiment is shown here. The times shown represent the period from initiation of the experiment until the picture was taken.

Scientist Pilot Kerwin performed Staehle's experiment during the first Skylab mission, using a small microscope to examine bacteria and spore changes.

In general, fewer bacterial colonies developed aboard Skylab than in control experiments on Earth. But those that did develop on Skylab were usually larger, grew faster, and were more irregular or asymmetrical that the control colonies. There was wide variation in texture, shape, size, and topography (surface irregularity) among the colonies returned from the first visit. For some unexplained reason, many of the colonies' edges grew curled away from the surface of the disk.

The *B. subtillus* colonies from the third mission grew up to 50 percent larger than identically prepared and incubated control colonies on Earth. The individual cells grew larger in diameter but did not significantly increase in number. The Skylab colonies exhibited a more pronounced topography. They also appeared to be somewhat more sensitive to several antibiotics to which they were exposed upon return to Earth.

The implications of Staehle's experiment have not yet been fully resolved. The descendants of the bacteria that spent their entire life cycle in the zero gravity of Skylab were scheduled to be observed for many generations. The effort to understand the effects of long-term spaceflight on bacteria has just begun.

Colonies of *Bacillus subtillus* cultured on Skylab are shown in dish No. 1, while a colony grown under the same ambient conditions on Earth, with the exception of weightlessness, is shown in dish No. 2. For comparison, dish No. 3 shows bacteria cultivated under standard laboratory conditions on Earth.

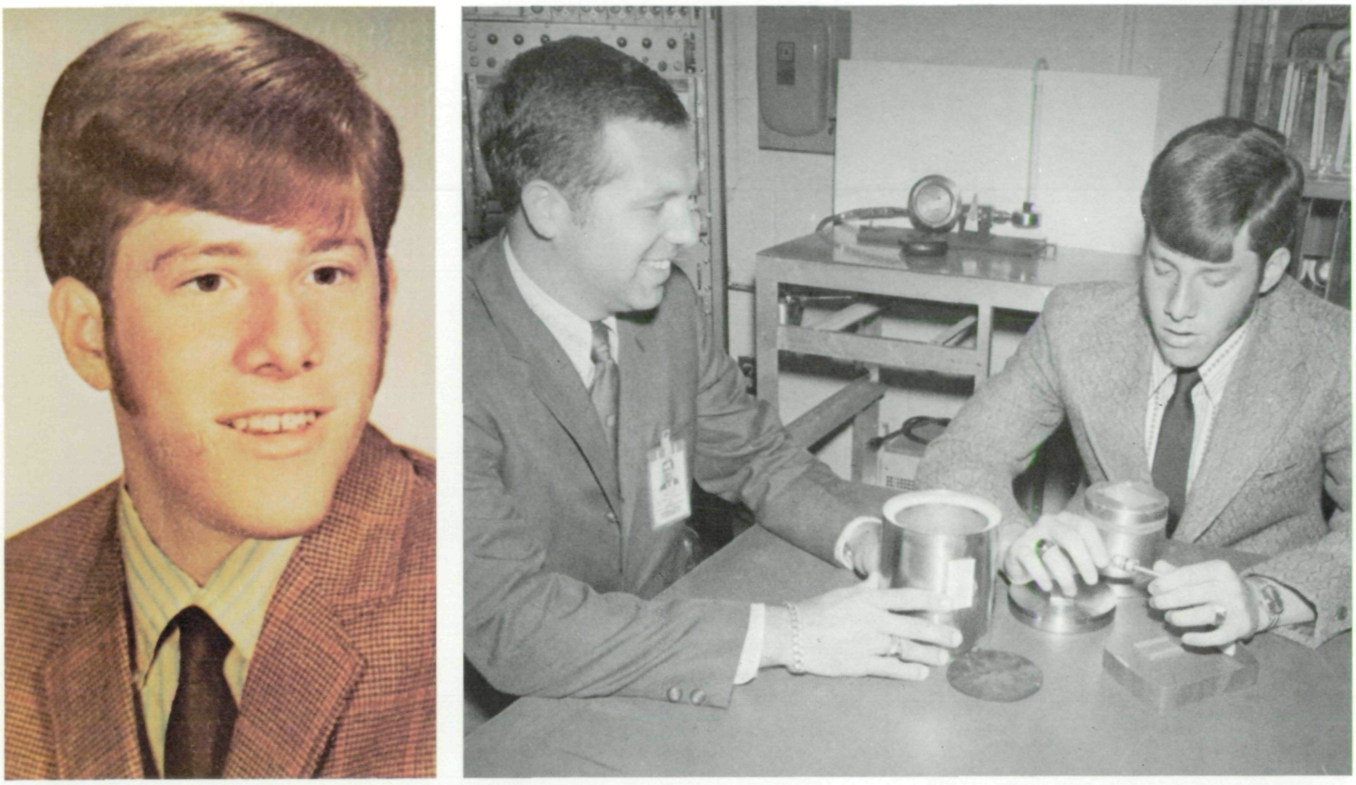
In-vitro Immunology

The human body constantly resists infection from invasion by harmful micro-organisms. This resistance, called an *immune reaction*, also guards against the introduction of foreign tissue. The study of this process is called *immunology*. If the study is conducted with living organisms, it is called *in vivo;* if conducted in a test tube, it is called *in vitro.*

An invading organism usually contains a specific protein or carbohydrate that stimulates immune reaction. The invading organism is called an *antigen* and reacts with the host's blood cells, which produce antibodies to counteract it. These antibodies attack and neutralize invading organisms in various ways. Some, called *precipitins,* precipitate the antigens so that they can be discharged from the host. Some produce agglutinins which cause clumping of bacteria and thus prevent their spread.

The study of this antigen-antibody reaction in space was proposed as a Skylab experiment by Todd A. Meister of the Bronx High School of Science, Jackson Heights, N.Y. He suggested an *in vitro* observation of the effects of zero gravity on a precipitin-type antigen-antibody reaction, as compared with the same reaction carried out in an Earth-based laboratory.

The experiment consisted of three plates containing agar and antibodies, three prefilled syringes containing dilutions of human antigen test inoculations (inoculum), and a cooler in which the



Todd A. Meister, shown with science adviser Robert Allen, proposed using Skylab to study the reaction of antigens and antibodies in a weightless environment. After graduating from high school, he entered medical college to major in neurosurgery.

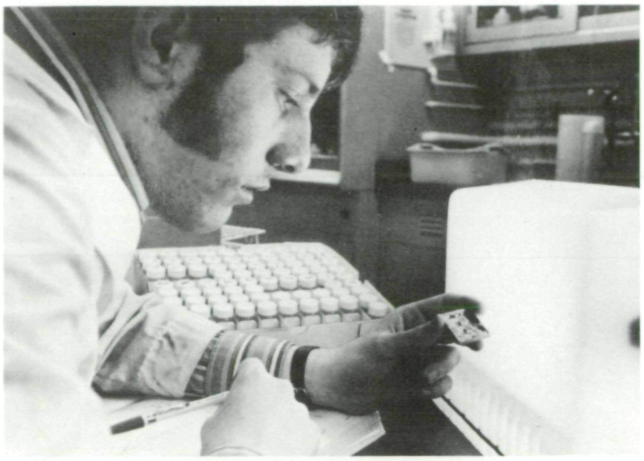
containers of antigens and antibodies were stored.

The cooler was installed in a locker in the Apollo spacecraft 15 hours prior to launch of the second crew. After docking with Skylab, it was transferred to the work area in the wardroom. To initiate the experiment, a measured amount of antigen was placed in the agar holes. Each plate was provided with a different combination of antigen/antibody. The plates were then stored at Skylab's room temperature for approximately 2 days. Photographs of the three chambers were taken about every 5 hours, starting 24 hours after the inoculation and continuing through the 2-day incubation period, so that the growth rate of the precipitin rings could be compared with those in the control experiment on Earth.

The crew reported that 5 to 10 minutes after inoculation, the agar had absorbed all of the antigen, as expected. The astronauts later observed that the small rings which grew during the 48-hour duration of the experiment were visible in only

Meister's experiment was packaged in an ordinary thermos bottle that had been modified slightly to hold the syringes containing antigens and immunodiffusion plates with antibodies. The white device on the left was part of the packing, while the aluminum cans on the right held ice for cooling the experiment.

To perform Meister's experiment, Scientist Pilot Garriott (1) first removed the protective packing from the thermos bottle, (2), took out the immunodiffusion plates, (3), attached them to the workbench, (4), and then filled the wells of the plates with antigens from the syringes.

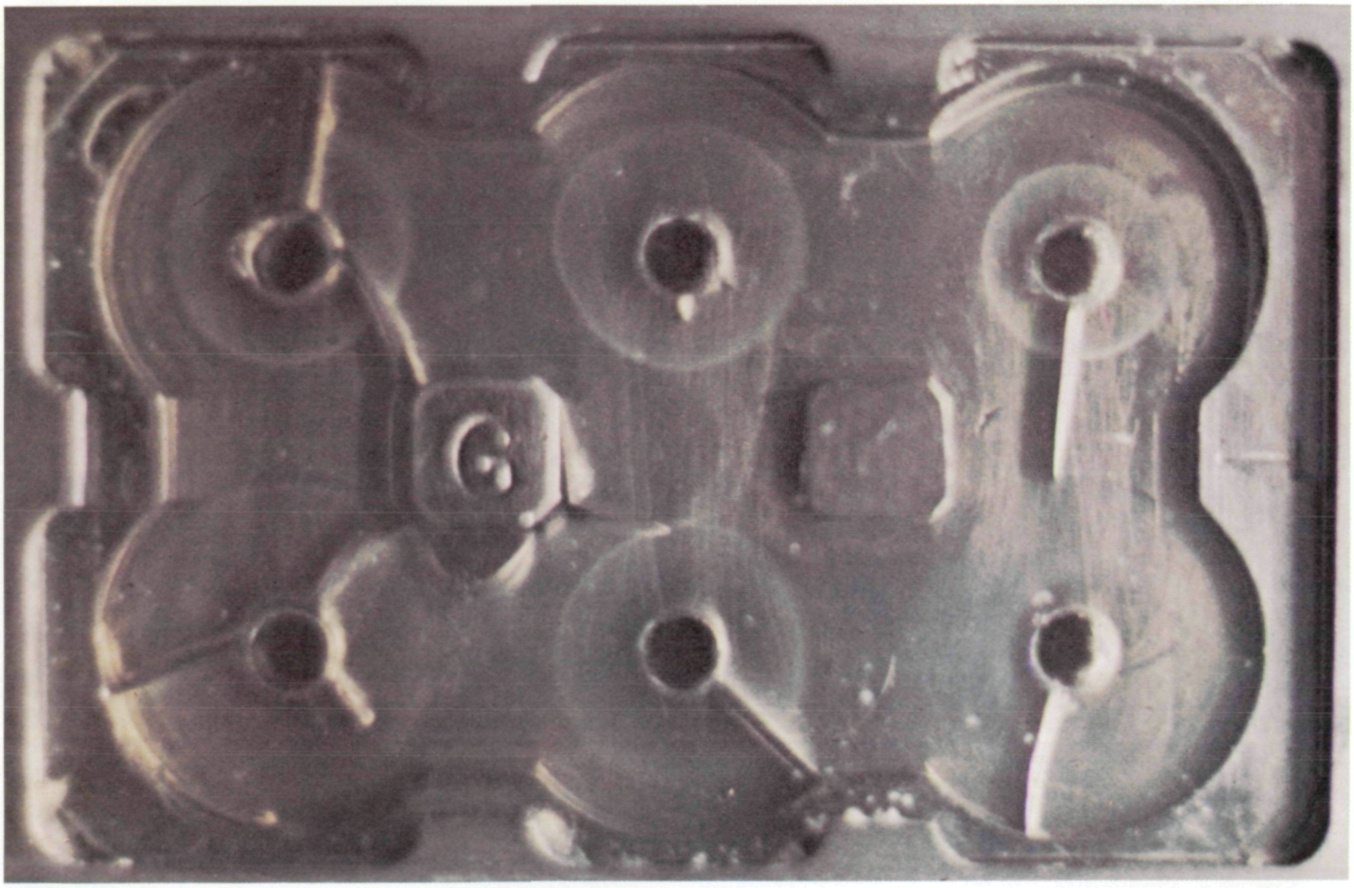


Meister periodically examined control plates in the research laboratory of Rensselaer Polytechnic Institute as his experiment progressed aboard Skylab.

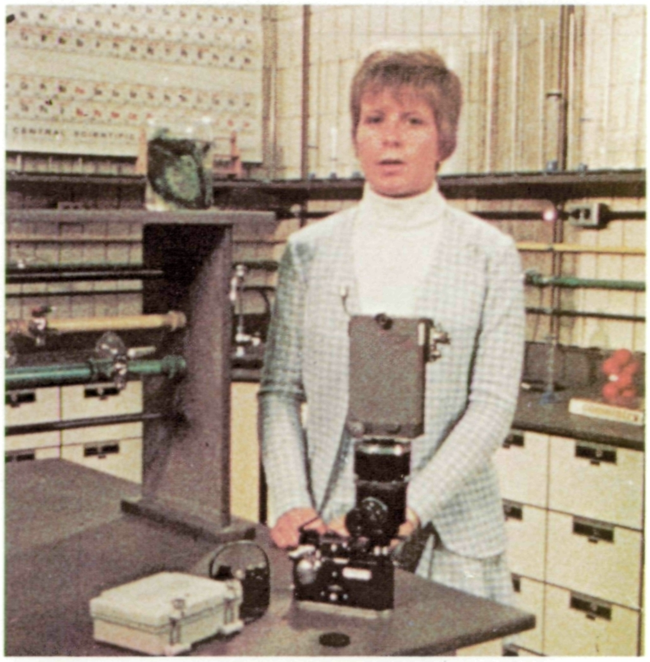
some of the chambers. Thirty-nine still photographs of the chambers were taken.

In analyzing the photographs after the mission, Meister observed that much of the agar within the plates had dried and cracked. Evidence of this drying appeared in photographs taken after 23 hours of incubation. The drying of the agar probably contributed to the failure of some of the chambers to exhibit precipitin rings. Additionally, the agar could have separated from the chamber, allowing antigen to spread under it. These complications prevented the precipitin rings from forming in 9 of the 18 chambers.

The nine precipitin rings that did appear formed at approximately the same growth rates and with similar intensities as those in control experiments on Earth. The conclusion is that this segment of



Precipitin rings are seen as cloudy circles surrounding the well into which antigens were introduced. They were formed by the reaction of the antigen to the antibodies in the agar of the plate.



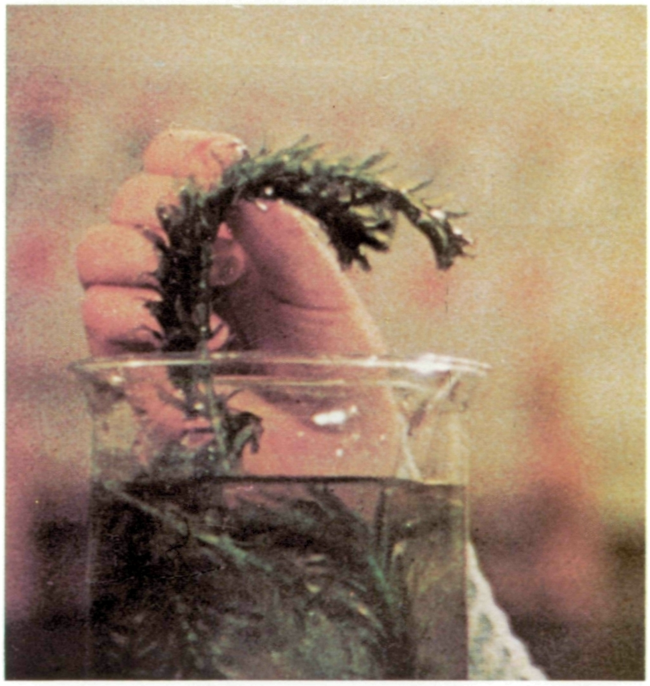
Cheryl A. Peltz proposed an experiment to investigate the phenomenon of cytoplasmic streaming or circulation of materials within the cells of a water plant named *Elodea* (commonly called water weed or water thyme).

the immune reaction system functioned normally in the Skylab environment.

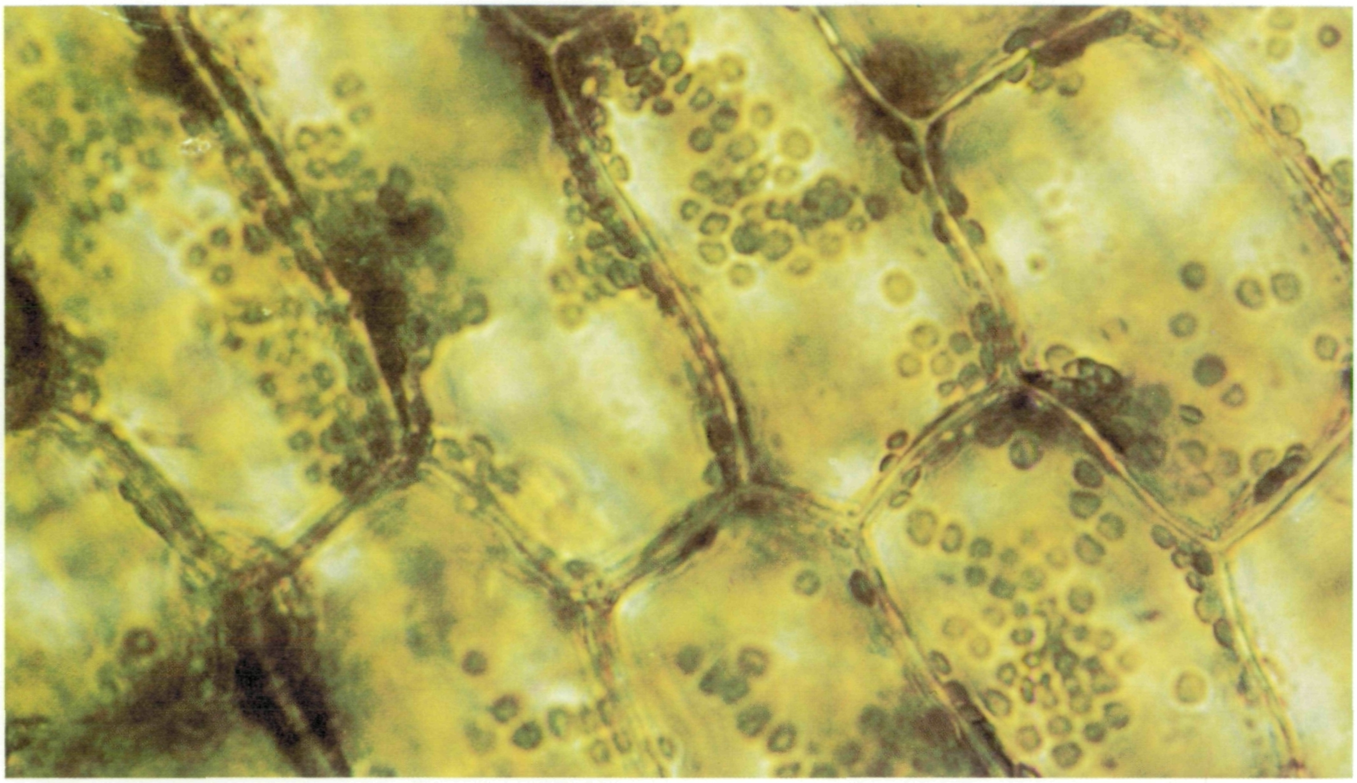
Cytoplasmic Streaming

An experiment to observe the effects of zero gravity on cytoplasmic streaming in the aquatic plant *elodea* was proposed by Cheryl A. Peltz of Arapahoe High School, Littleton, Colo.

The phenomenon of cytoplasmic streaming is not well understood, but it is recognized as the circulation mechanism of the internal materials, or cytoplasm, of a cell. Cytoplasm is a gelatinous substance that has the ability to change its viscosity and flow, carrying various cell materials with it. The activity can be stimulated by sunlight or heat. Through this flow, the cytoplasm appears to place the cell's chloroplasts, or chlorophyll receptacles, in the optimum position for photosynthesis. The conversion of carbon dioxide and water into oxygen and sugar, and the oxidation of sugar and its conversion to starch, is a process requiring an interchange of these compounds among the various parts of a cell. Cytoplasmic streaming is believed to be a transport mechanism for the exchange of



Elodea was selected because its leaf simplifies preparation of specimens for microscopic examination.



At a magnification of 450×, the structural components of the *Elodea* cells can be clearly seen. The small spheroid elements within each cell are chloroplasts. In the presence of light, they convert carbon dioxide and water into oxygen and sugar.

proteins and byproducts among the cell components.

The experiment utilized three vials containing *elodea* sprigs suspended in a nutrient agar solution, a set of microscope slides and cover slips, and a pair of tweezers, all packaged in a container. Support equipment included a microscope, a microscope-camera adapter, and a 16-millimeter motion picture camera. Three additional vials containing *elodea* were prepared as control units on Earth.

The Skylab vials were loaded aboard the Apollo spacecraft prior to launch of the second crew, and the control units were stored in a similar environment on the ground. The experiment timetable called for a maximum of 6 days of storage during the launch, docking, and preparation portions of flight. Once aboard Skylab, the vials were to be placed in an open area near a source of light. Experiment scheduling difficulties delayed the deployment until the 8th day. When the experiment was finally performed on the 15th day, the crew reported that the plants had died, probably because of the 2 unscheduled days of darkness. The control plants were stored and deployed on the same schedule and, hence, were also dead.

The experiment was rescheduled for the 3d mission, and the plant vials were packaged in transparent containers to allow exposure to ambient light. The first observation was made on the 11th day of the mission, and streaming was observed. In a second observation of the plants on the 18th day, no streaming could be detected. The returned film verified that the plants had died by that time. Unfortunately, the film of streaming from the first observation was improperly exposed, and comparison to cytoplasmic streaming on Earth was limited to the crew's observation that it appeared the same as it had during training.

The control *elodea* plants survived longer than those on Skylab. Ms. Peltz inferred that in addition to the problem of excessive dark periods, it may have been difficult for the plants' waste products to diffuse away from the leaf surface in conditions of zero gravity. In other words, the *elodea* on Skylab may have "smothered" in oxygen, unable to obtain necessary carbon dioxide for photosynthesis.

She further believed that future research of fundamental plant-cell processes in space must be pursued. The ability of the human being to exist for as long as 3 months in space was proved by the men of Skylab, but an understanding of any adaptations required for truly long-term exposure to zero gravity must begin with research at the cellular level.

Micro-Organisms in Varying Gravity

Keith Stein of W. Tresper Clarke High School, Westbury, N.Y., proposed a highly sophisticated experiment to assess the effects of both zero gravity and various levels of gravitational forces on several species of micro-organisms and enzyme action.

As an elementary life form, micro-organisms can provide the first step in the chain of investigations leading ultimately to the effects of adverse environments on higher life forms, including man. The concept of the experiment required a micro-organism that utilized carbon dioxide to generate oxygen as well as to provide a potential food source for man. Stein wanted to investigate the impacts of the orbital environment, the launch and reentry accelerations, and the effects of prolonged weightlessness. He proposed a large number of samples and a rigidly controlled regime for his experiment.

Stein's concept proposed two centrifuges rotating in opposite directions to minimize the interchange of angular momentum with the Skylab. Sample containers were to be placed at different radii on the centrifuge to produce simulated gravitational forces ranging from 1*g* to near 0*g*.

Clearly, the development time for such a centrifuge, the special purpose microscope, and the camera, together with the large amount of crew time and film required to obtain data, made it impractical.

As a result, Stein became affiliated with microbiologists at the Johnson Space Center. J. K.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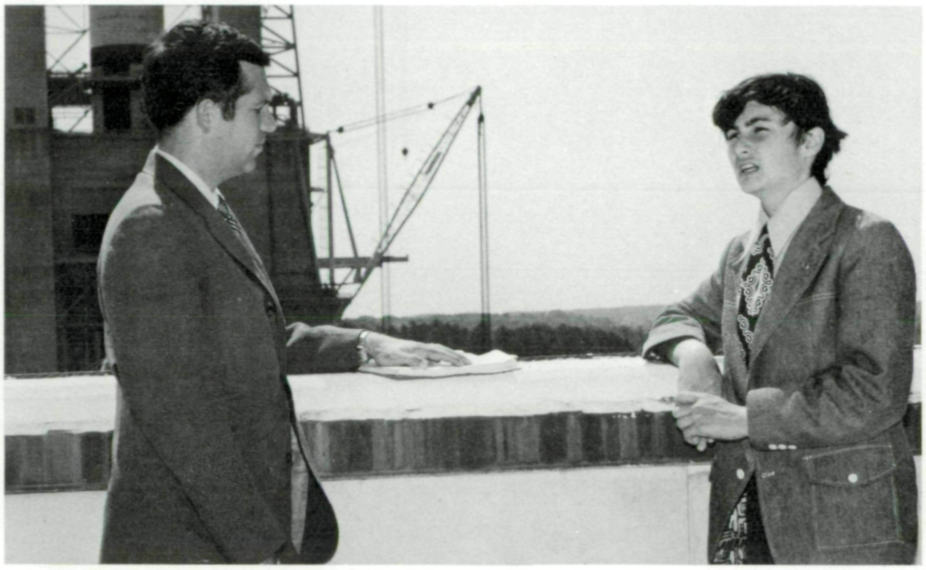
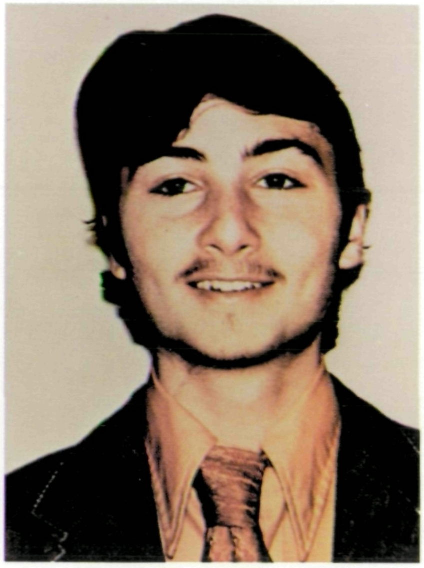
Garriott performed the cytoplasmic streaming experiment by first attaching a camera to the Skylab microscope (1). He then opened the vial containing the plant (2), and examined the specimen visually (3) before placing it under the microscope for filming.





Keith Stein proposed a very sophisticated and ambitious experiment to use Skylab for studying the effects of varying degrees of gravity, produced by a centrifuge, on several species of micro-organisms and enzymes. While it proved beyond the resources and time available in the program, he was affiliated with scientists who studied the microbial environment of the space station. He is shown above with science adviser Robert Allen.

Ferguson was investigating the microbial environment on Skylab. Through Dr. Ferguson's efforts, Stein was provided with bacteriological samples from Skylab for his analysis. Through his volunteer work at the Nassau County Medical Center, Stein was permitted to use their laboratory facilities in making his analysis. He carried out some 15 analytical tests on the samples and determined that only two of four samples supplied had survived the repeated reculturing. Of these two, Stein could identify nothing abnormal in the *Staphylococcus epidermidis.* Tests of the bacteria showed a reaction, but it may have been due to contamination of the sample. Analysis of microbiology samples by the scientists at Johnson Space Center showed no increase in the presence of medically important bacteria throughout the Skylab mission. Even though Stein's original experiment could not be performed, he gained valuable experience in microbiology which has furthered his studies in the field.

Again, Skylab's unique scientific facilities had proven useful as a laboratory for students interested in performing life science experiments at the cellular level in space.


USA
SA

5

Embryo Development in Space

Not only is the cell fundamental to all living organisms, it is also the seat of all life. Whether it be the seed of a plant or the egg of an animal, all life begins with the cell. The fertile seed or egg undergoes cellular division and growth as the embryonic stages of life develop.

Some plant development begins in the seed. Although plants have evolved reproductive mechanisms quite different from those of animals, the basic steps are much the same. The new plant life begins when a sperm nucleus from a pollen grain unites with an egg nucleus, and the resulting cell begins developing into a seed. The seed, in turn, develops into an embryo and begins to grow after it is exposed to water. Other lower forms of plant life, such as algae, develop directly through cell division without the seed or embryo stages.

Animal life begins in a manner similar to that of the higher order plants. The union of the sperm and the egg initiates the cell division that ultimately results in the embryonic development of a new animal.

Two of the Skylab student experiments involved aspects of embryonic development. One proposed a rather complete investigation of the embryonic development of a chicken; the other was concerned with the development of seedling rice plants.

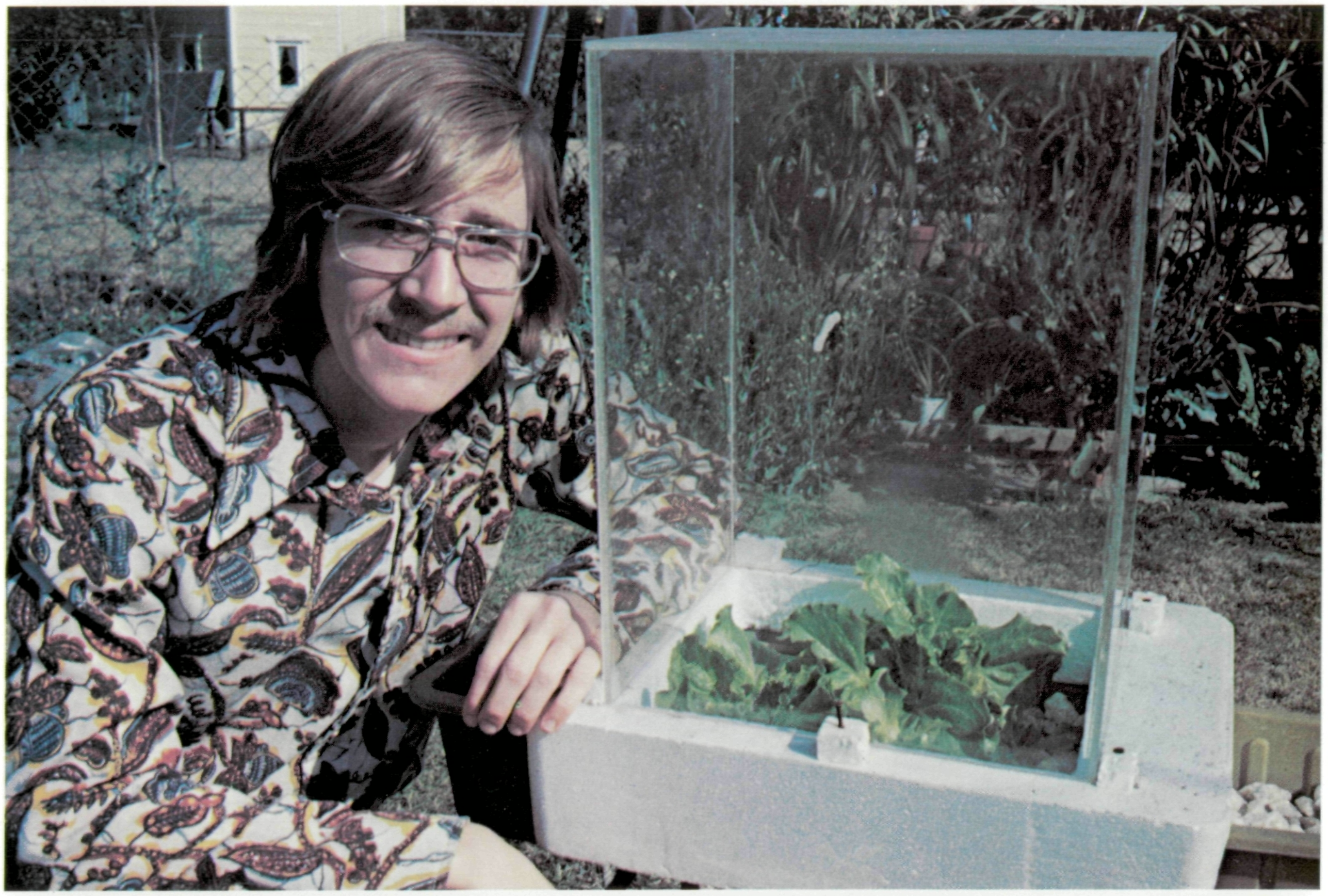
Plant Growth and Plant Phototropism

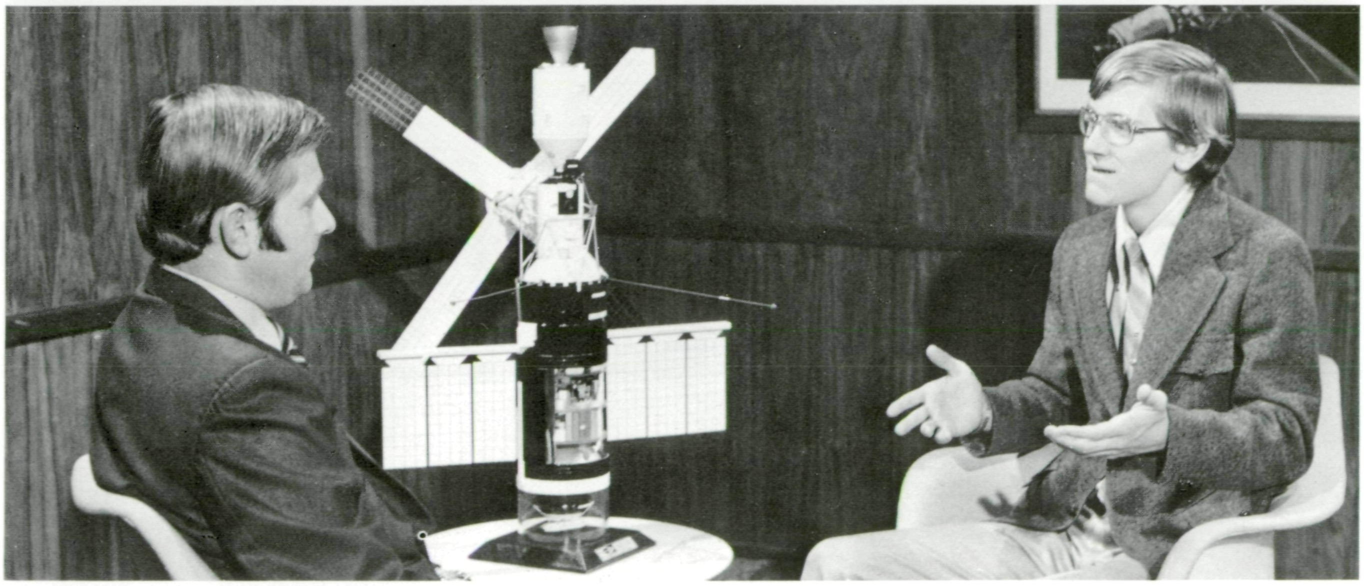
Two similar proposals were submitted by Donald W. Schlack of Downey High School, Downey, Calif., and Joel G. Wordekemper of Central Catholic High School, West Point, Nebr. Wordekemper was interested in discovering how the roots and stems of germinating seedlings would orient themselves without the influence of gravity in Skylab. Schlack's idea was to germinate seedlings within an enclosed cell of agar, exposed to light from only one side to determine if phototropism would influence the direction of growth of both stems and roots in the absence of gravity. He also suggested that exposing different seedlings to various light intensities would determine the illumination level required to produce the phototropic effect. The objectives of these two experiments were similar enough that they could be accommodated in a common experiment.

Phototropism is the characteristic exhibited by plants as they grow in the direction of their primary light source. It is commonly observed that leaves of plants by a window or along a wall orient themselves toward the Sun. Geotropism is a plant's reaction to the force of gravity. Plant roots react positively to geotropism and grow down, while the stem exhibits a negative response and grows in the opposite direction.

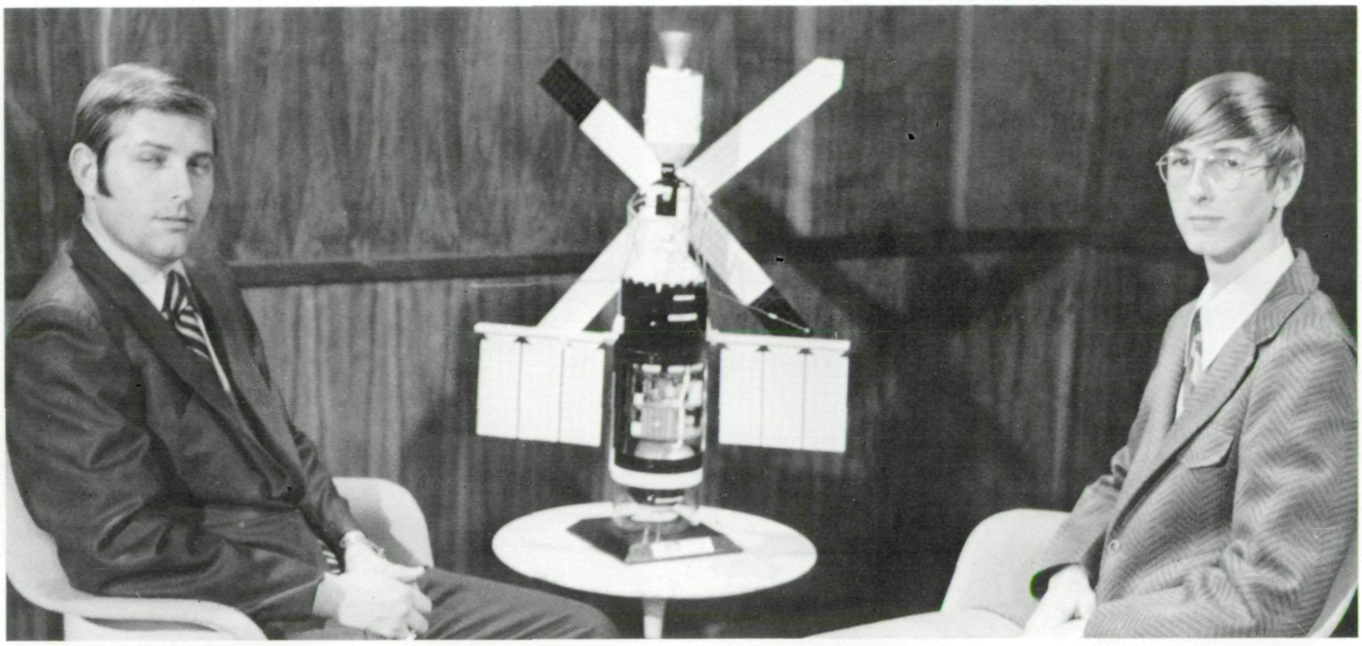
The growth container for their experiment consisted of eight compartments arranged in two parallel rows of four. Each had two windowed surfaces to allow periodic photography of the developing seedlings from both a front and side view. The side windows were always covered except during the photographic sessions, so that as

The second crew saw this view of the spent Saturn rocket from its Apollo spacecraft.

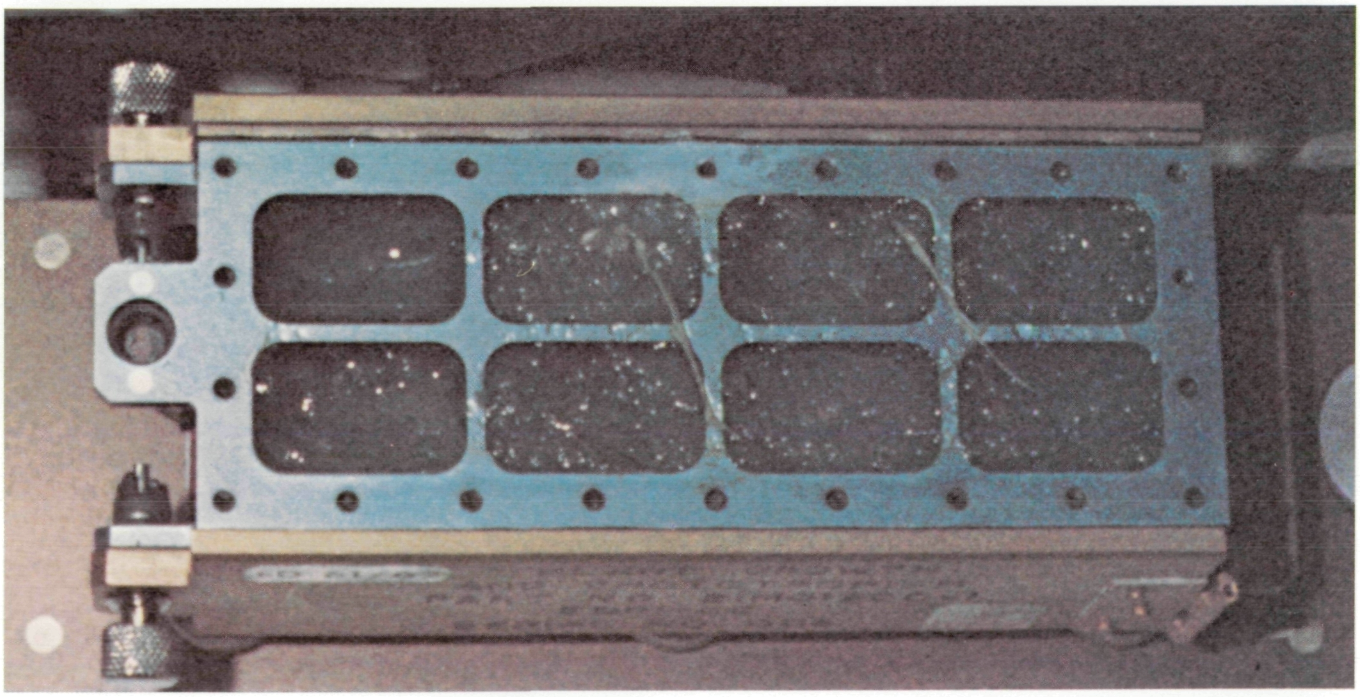




Donald W. Schlack suggested an experiment for Skylab wherein the effects of light on a seed developing in zero gravity would be studied. He is shown above with science adviser Loren Miller.



Joel G. Wordekemper, shown seated above with science adviser Loren Miller, had an idea similar to Schlack's. He proposed an experiment to see how the lack of gravity would affect the growth of roots and stems of plants.



The container for the seedlings was positioned near one of the high-intensity lights used in the orbital workshop of Skylab.

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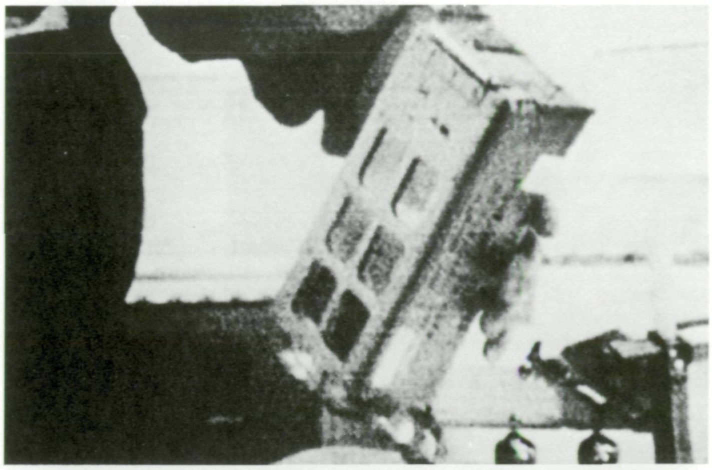

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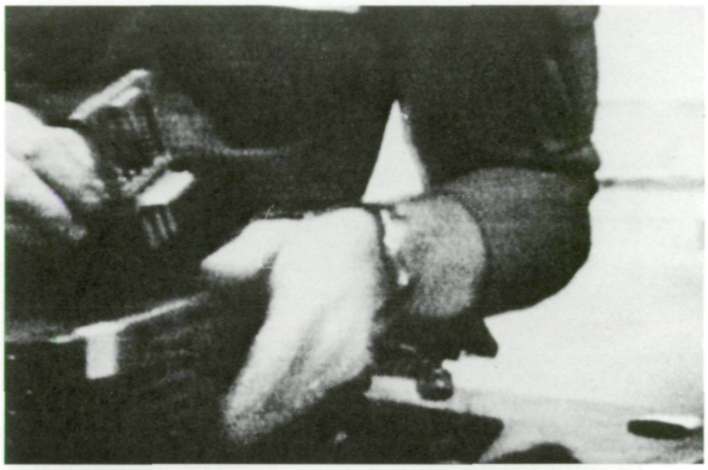

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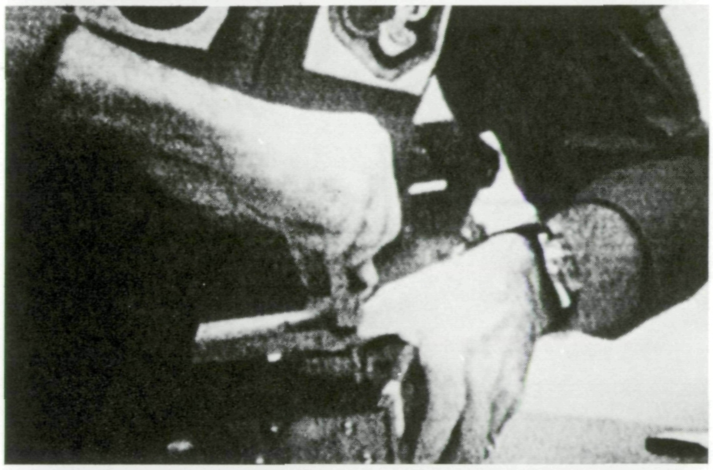

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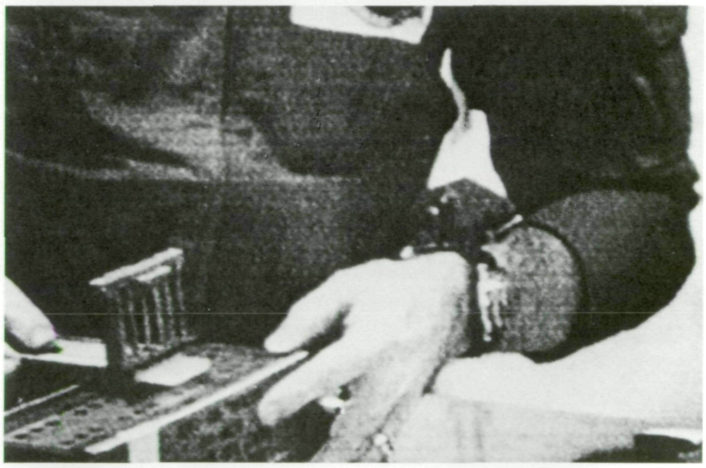

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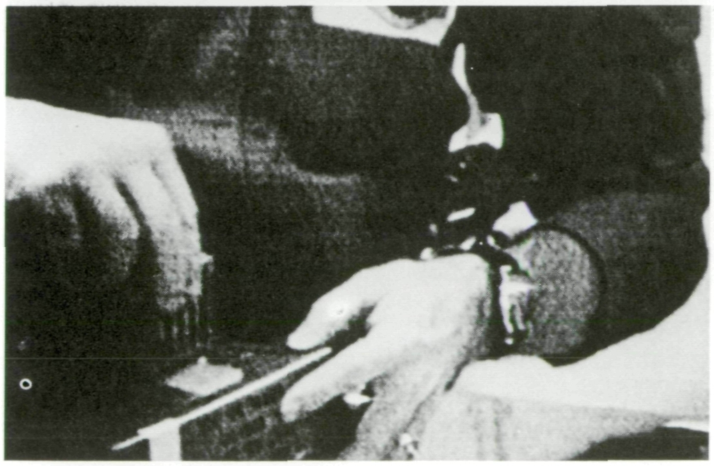

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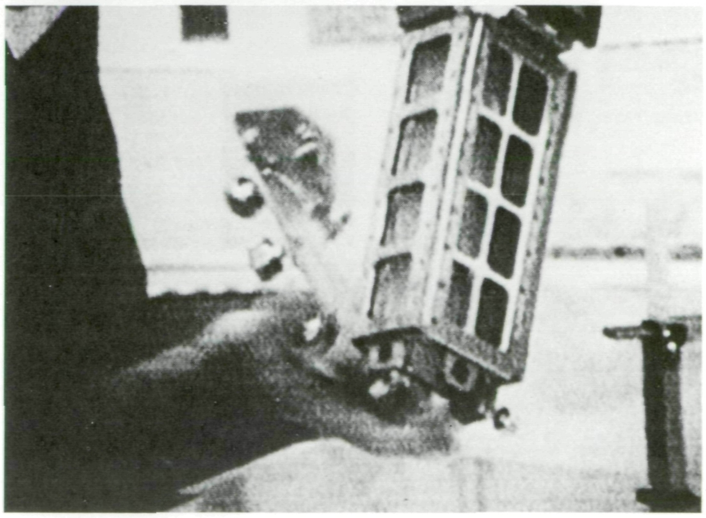


To activate the experiments proposed by Schlack and Wordekemper, Scientist Pilot Gibson used the technique shown in this series of pictures made aboard Skylab. After removing the back cover from the container (1), the seeds were planted three each to the eight compartments (2), (3), (4), (5), and the windows were exposed for photography (6).

the seedlings grew, they received light from only the front window. If the seedlings exhibited phototropism, the stems would grow toward the window, their only light source. Five of the front windows were covered with special filters and two were blocked to prevent any light from reaching the seedlings, while the remaining window had no filter, allowing passage of all ambient light. Three rice seeds were inserted into each compartment through covered holes in the back wall. This technique allowed 24 rice seeds to be planted, to germinate, and to grow in the weightless environment of Skylab. The plants were not under the influence of gravity. Those in the two dark compartments were not influenced by phototropism and served as a control group to determine how light affected the development of the other seedlings. The filters were to determine the illumination level required to influence the plants to grow toward light in zero gravity.

The rice seeds were implanted in the nonnutrient agar medium by Edward Gibson, scientist pilot of the third crew. He thus became what might be called the first space farmer. Photographs of the seedling development were taken at regular intervals for 30 days. Dr. Gibson also recorded his visual observations of the plant development. (Unfortunately, due to a camera malfunction, the photographs taken on four of the days were not exposed. Analysis of growth for a period of 14 days was, thus, based entirely on Gibson's verbal descriptions, which are subject to interpretation.) On the 25th day the front container cover, with the neutral-density filters, was removed and the plants pulled to the surface of the agar to allow them free access to the Skylab environment.

Schlack and Wordekemper analyzed their data after the mission and found that plant growth was first observed on the 4th day after seed planting, somewhat slower than expected for Earth-grown rice. Growth then progressed at a normal rate, but the direction was extremely irregular and inconsistent, with stems for some reason making 180-degree turns away from the light and many plant tips demonstrating curled patterns. The stems seemed to exhibit no phototropic effect.

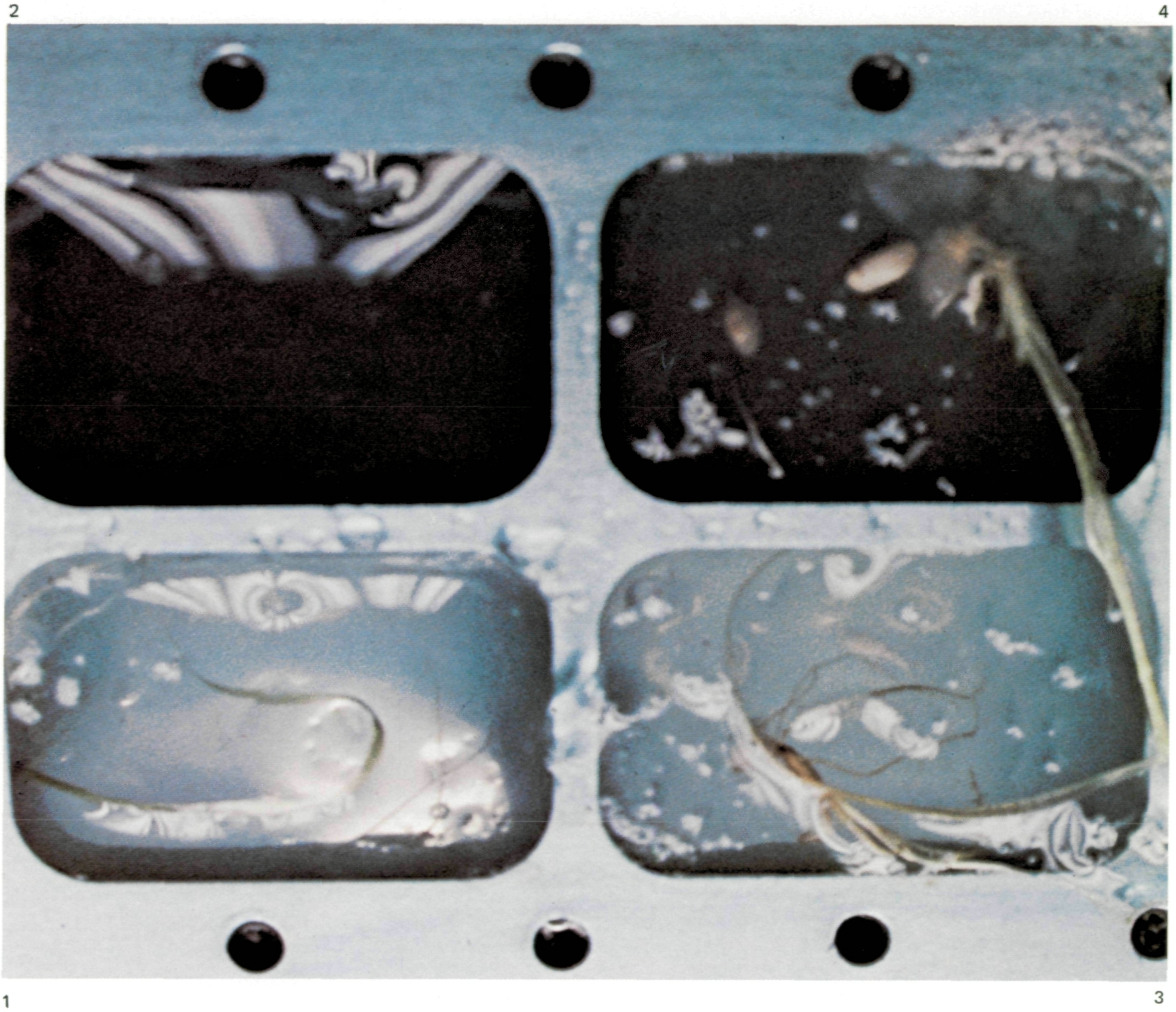
Gibson's commentary on the 22d day of growth summarized the plant development, "... Okay, generalizations. Those [seeds] which have long stems that make it to the point where they can see some light, turn green. I would not say there's any preferential growing, though, toward the front of the case [light source]. I see green stems turn around and start heading right on back toward the other direction. One case is here in compartment 1, it just makes a 135-degree turn, [and] goes straight back, looks like it was folded. Now, the one over in compartment 6. The stem which comes down, goes toward the back, makes a big U-turn from the bottom right-hand side and then goes up toward the front again, and that's one that has turned slightly green . . . But that's the only one that demonstrates it [phototropism] to me . . . I've got to face it right now. I can't find any consistent pattern . . . Some make a turn and go back; some make a turn and go forward . . . No consistent trend, unfortunately. Roots go to the front, toward the light; stems go to the back, away from the light; some do; some don't."

From photographs as well as Gibson's observations, Schlack set about the task of reconstructing the growth patterns of the roots and stems of each seedling. Of the 24 seeds planted, only 10 developed. This is a number which is close to the germination ratio of 12 out of 24 observed in the control group planted on Earth.

The longest stems to develop in testing on Earth were approximately 2 inches long. It is interesting that one leaf from compartment 4 of the Skylab container grew to 4.2 inches. While it was impossible to measure precisely the leaf and root dimensions or growth rates from photographs, the results indicated that the Skylab rice plants grew as fast or faster than the Earth plants after the seeds had germinated.

The percentage of seeds that developed was too small to provide significant information regarding the threshold light level required for seed development in zero gravity. Two plants grew in totally dark compartments, while the three largest plants grew in compartments 1, 4, and 6, with filter transmission factors of 100 percent, 3 percent, and 2 percent. Thus, the illumination level did not appear to be a contributing factor to the growth rates of the small sample of seeds aboard the space station.

The proposed explanation for the lack of any phototropic effect demonstrated by the rice seedlings is that the auxin distribution system of the plants relies upon gravity. Auxins are plant-growth hormones that cause cells to elongate or grow. They are produced in the tips of both the stems

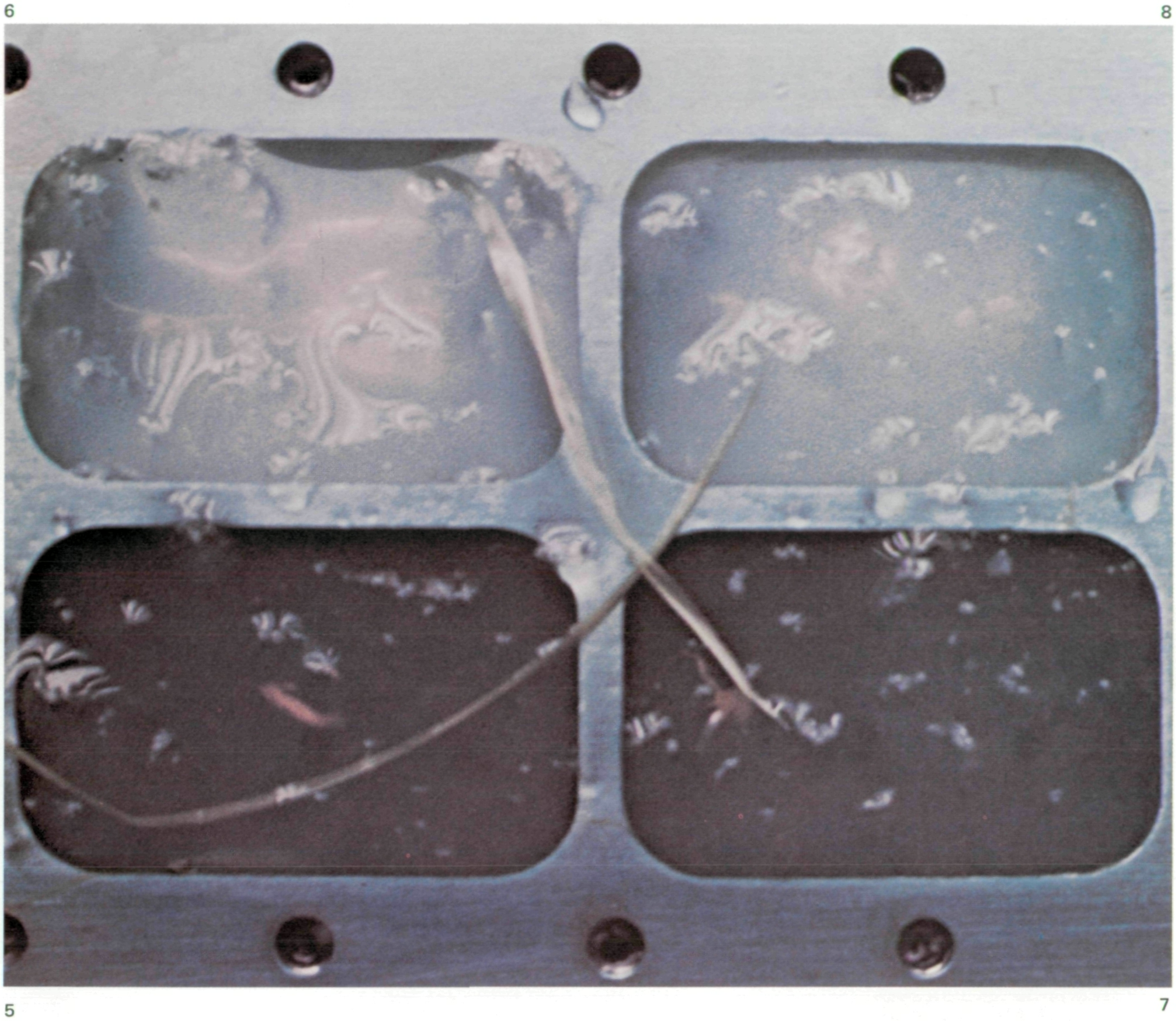


After 27 days in orbit, the seedlings looked like this when the front cover of the experiment was removed. The main shoot of the plant in compartment No. 4, approximately 4.2 inches long, extends all the way to compartment No. 8. One of its leaves also branches into compartment No. 3.

and the roots, and are distributed basipetally (away from the tip) into the "area of elongation." Without gravity the auxins may have been distributed unevenly, with pockets collecting somewhat randomly, causing irregular stem and root growth.

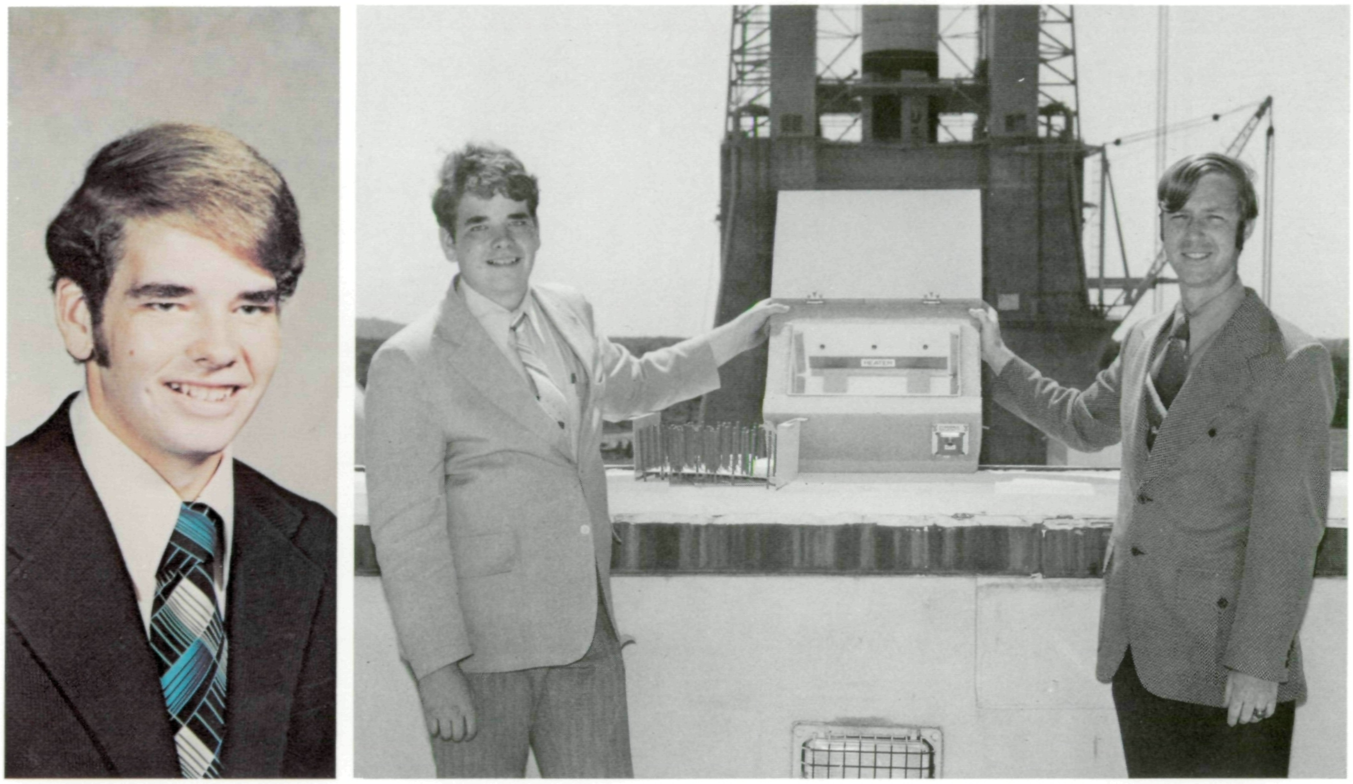
It is also possible that the light-sensing mechanism in the stem tip that triggers the auxin distribution reacted differently in zero gravity. But the operation of this sensing mechanism is not understood well enough to hypothesize its reaction to zero gravity, and it is not obvious that there should be any effect at all.

Research is conducted on Earth with clinostats, devices that rotate slowly so that the plants on



them are inverted the same amount of time as they are upright, with results that many believe to be comparable to the effects of short-duration zero-gravity exposure. Skylab experiment results suggest that the effects of longer duration spaceflight is not simulated by testing with clinostats.

The student experiment program presented the first opportunity for botanical experiments of longer than 3 days' duration to be performed in space. The results of this experiment indicate that much can be learned about plant physiology through chemical analysis of plants in space, an environment that cannot be duplicated in a laboratory on Earth.



Kent M. Brandt, shown with science adviser Jack Skadman, proposed one of the most complex experiments for Skylab. It consisted of hatching at least one chicken and returning it alive to Earth.

Chick Embryology

A classic high school biology investigation was proposed: the development of a chicken embryo. Kent Brandt of Grand Blanc Senior High School, Grand Blanc, Mich., suggested such an investigation for Skylab. He designed a rigorous experiment involving the incubation of eggs, opening eggs periodically for 20 days to observe and photograph the developing embryos until one chick was allowed to hatch, providing for the sustenance of the chick during its stay in Skylab, and ultimate return of the chick to Earth for further analyses.

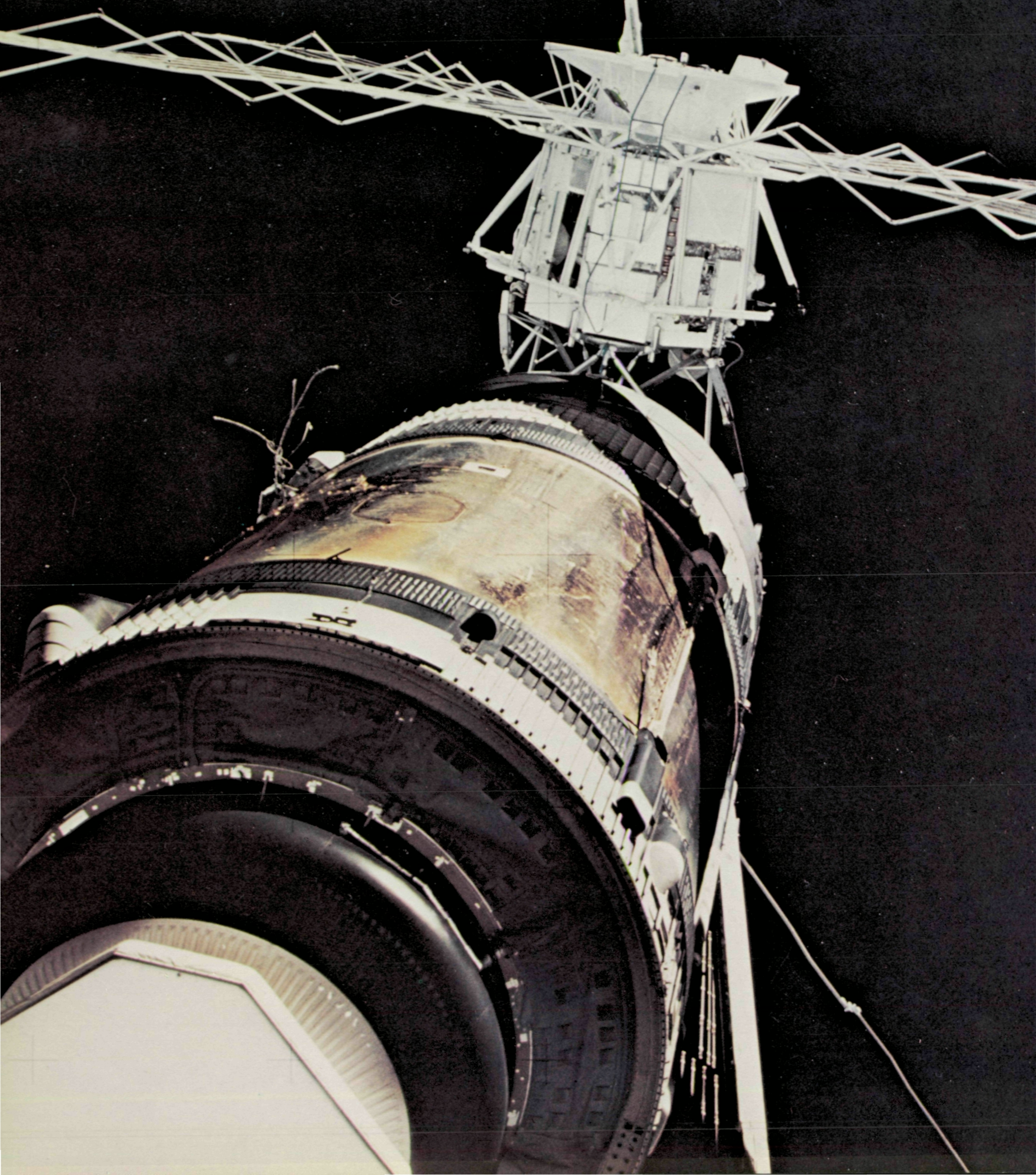
Of the 25 student experiments, Brandt's was probably the most intriguing to the review committee. Significant efforts were made to define the container required to insure that the eggs survived the launch, incubation over a 21-day period, and safe return of at least one chick.

A protocol was developed whereby further development of the embryo could be chemically terminated and each of the six eggs preserved at different stages of development for return to Earth. An experimental model of an incubator that could maintain the critical temperature and humidity ranges required for development of fertile eggs was built.

With regret, the decision was made that the experiment required too much crew time, and the weight and volume requirements were greater than could be allocated to a single student experiment. Also, the detail design, fabrication, testing, and flight qualification of the necessary incubator could not be carried out in the 9 months available prior to launch.

Brandt was therefore affiliated with John Lindberg of the Northrop Corporate Laboratories, on his experiment concerning the circadian rhythm of pocket mice. Unfortunately, this experiment experienced a power failure early in its performance, and no data were returned.

Despite the disappointments accruing to Brandt, Skylab did provide laboratory facilities for significant experiments in the study of cellular development and plant growth with experiments such as those of Schlack and Wordekemper.



6

Weight and Weightlessness

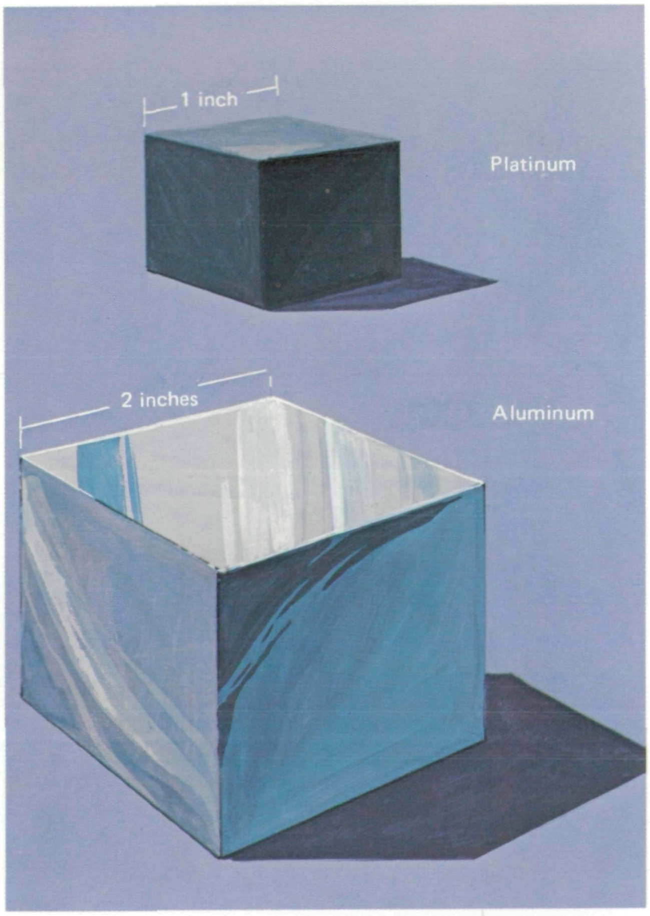
Mass is the quantity of matter in any object. Gravity is a force that tends to draw massive objects together. The magnitude of this force is proportional to the product of their masses. A "gravitational constant" relates this force to the masses of the objects and their separation distance.

The gravitational force between an object and the Earth is called *weight,* which is a result of the Earth's gravity acting upon the object's mass. In orbit, mass measurement is important for measuring food quantities, changes in weight of astronauts, and the results of scientific experiments. However, an object orbiting Earth effectively counteracts the pull of Earth's gravity. A space station such as Skylab, orbiting 270 miles above Earth, is held in orbit by the equilibrium between Earth's gravity and the "centrifugal force" associated with the space station's path and velocity. Unrestrained objects, then, are for practical purposes as weightless as Skylab itself.

Two of the Skylab student investigations were concerned with mass properties. One proposed a method for determining mass in the weightless space environment, while the other suggested a means of calculating the gravitational constant in that environment.

Mass Measurement

Even though objects in Skylab were apparently weightless, their mass properties were unchanged.



Mass is the quantity of matter. A 1-inch cube of platinum has approximately the same mass as a 2-inch cube of aluminum.

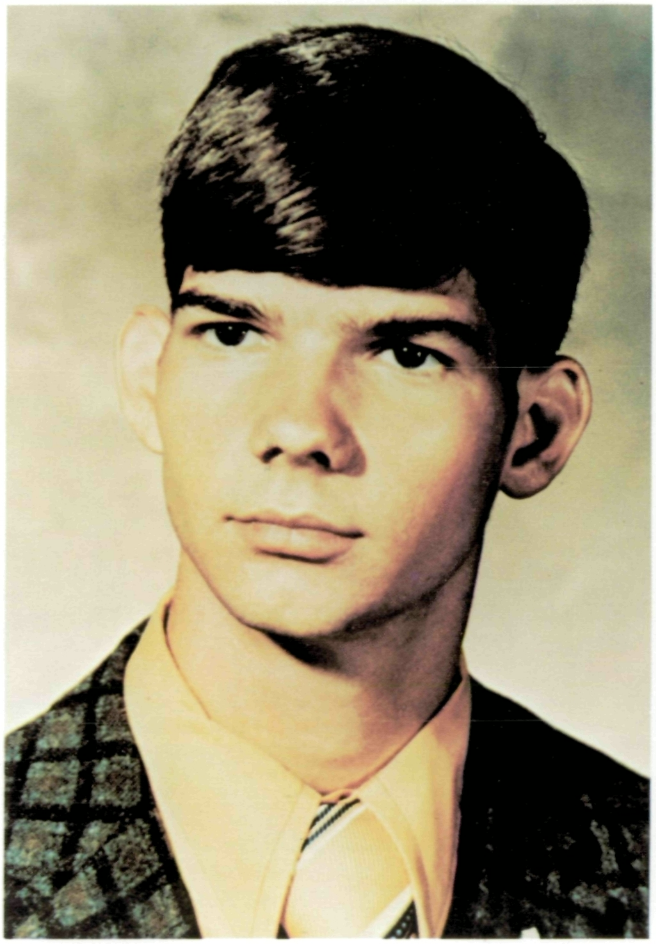
Measurement of mass is therefore an acceptable alternative to measurement of weight. An experiment to measure mass was proposed by Vincent B. Converse of Harlem High School, Rockford, Ill. His idea was to measure the periods of oscillation of a spring mass system to which various masses were attached.

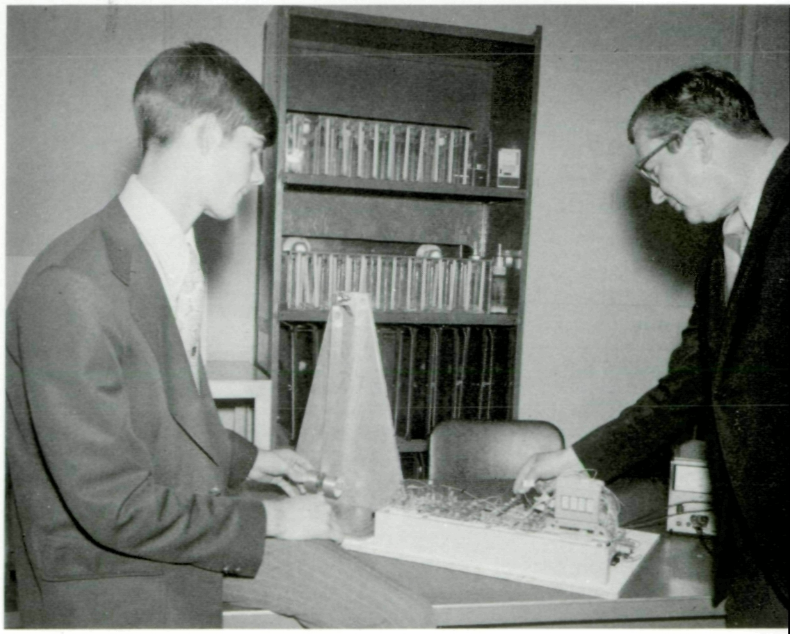
The experiment consisted of a cantilevered beam, firmly attached to a frequency counter but free to vibrate, six test masses, a motion picture camera, and a data table. The table listed results of a theoretical calculation, against which the measurements made in Skylab could be compared.

The masses were attached to the free end of the beam, one at a time. The weighted beam was deflected from its rest position, storing energy in it, which acted as a spring. When the end of the beam was released, the stored energy caused it to vibrate. A strain-gauge sensed the oscillation and provided a signal to a frequency counter, which had a visible readout of the vibration period in seconds. The camera was programed to operate at 24 frames per second for 50 oscillations after the initial beam deflection, and to photograph the readout.

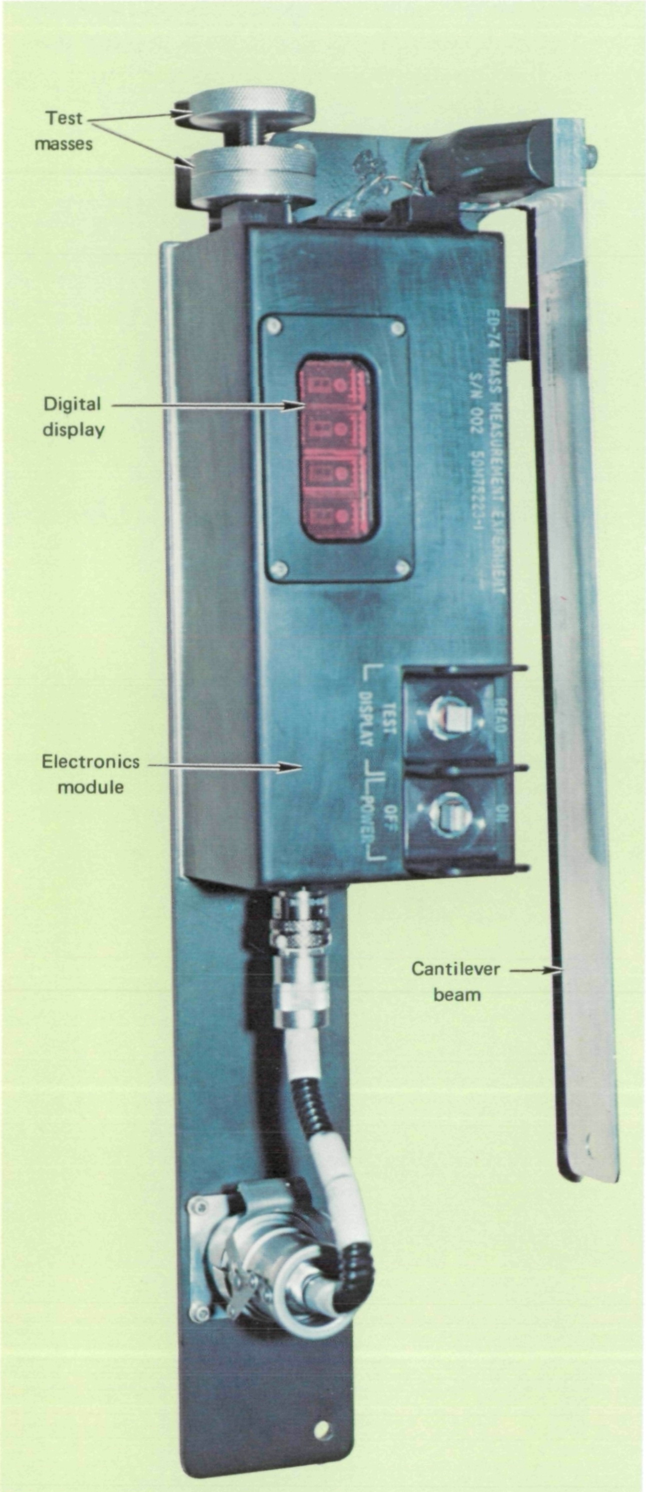
On August 27, Owen K. Garriott, scientist pilot on the second mission, operated Converse's experiment with excellent results. Oscillation periods for five different masses were obtained, and the entire operation was recorded on 16-mm movie film and on videotape. Each mass was calculated from the frequency of the beam oscillations, which were then compared with the ground-based calculations. There was a 3- to 4-percent difference between the ground-based data and the flight-measured data, but it could be attributed to an inexact knowledge of the beam's physical properties. After completing his final report, Converse recommended the use of a centrifugal device for the measurement of loose material while in zero gravity.

The Skylab devices that measured the mass of the astronauts, residual food, and other objects

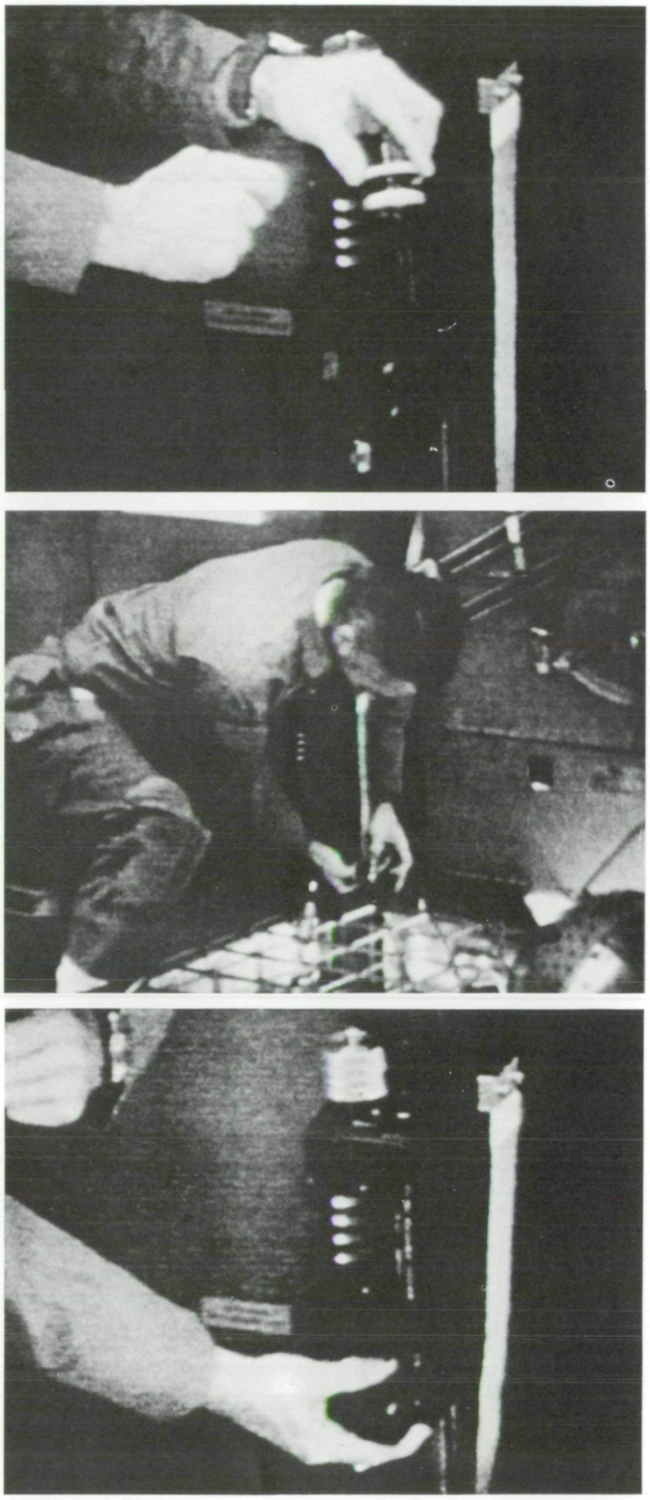




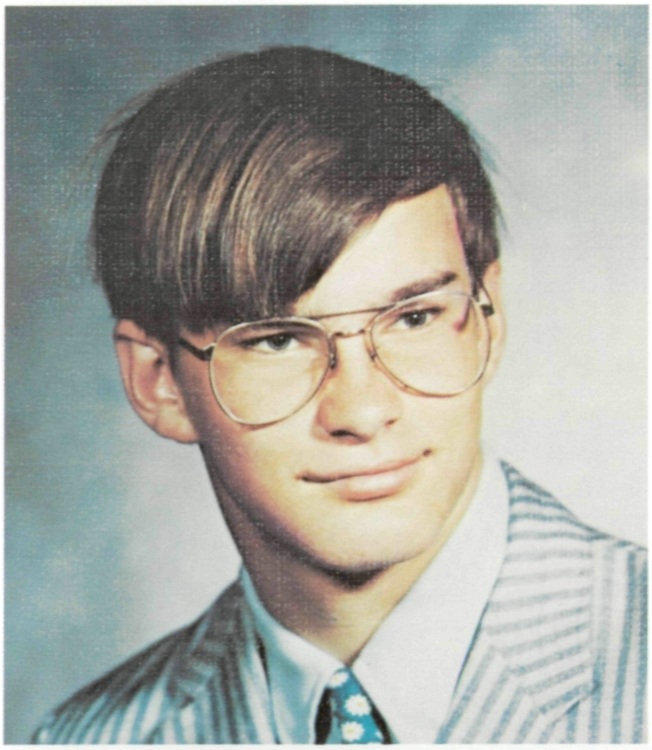
Vincent B. Converse proposed an experiment aboard Skylab to measure mass in a weightless environment. He is shown, above right, with his science adviser Robert Head, checking out equipment used in his investigation.



The experiment developed by Converse used a simple but precision scientific instrument.



Scientist Pilot Owen K. Garriott performed Converse's experiment during the second Skylab mission by attaching masses to the end of its cantilevered beam and deflecting it so the beam could oscillate freely.



operated on the same spring-mass oscillation principle. These devices provided accurate mass measurements of the astronauts' weight, intakes, and body wastes throughout each mission.

Universal Gravity

James Healy, a student at St. Anthony's High School, Bayport, Long Island, N.Y., suggested a repetition in space of an experiment performed on Earth in 1798 by Henry Cavendish, the famous English chemist and physicist. Healy proposed to duplicate Cavendish's experiment to measure the force of gravity between two masses by means of a modified Cavendish balance. But because the forces involved were so very small, such an experiment would have been very difficult to construct and to conduct within the environment of Skylab. Since the huge space station had to maneuver slightly in order to remain in a stable position in orbit, forces would have been created that were greater than those that could have been

Top: James E. Healy worked with NASA engineers to determine the long-term effects of astronauts' movements within a space vehicle upon its dynamics. Above: Healy discusses his experiment with his science adviser Harry Coons.

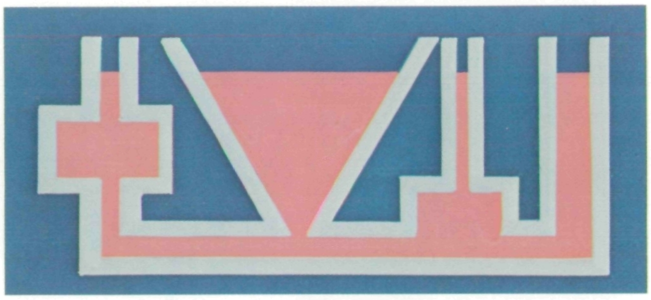
measured. Thus, Healy's experiment could not be implemented for Skylab.

As an alternative project, he became affiliated with Bruce Conway, a principal investigation for another experiment. Conway, an engineer at NASA's Langley Research Center, had instruments aboard Skylab to measure the effects of various crew movements on the dynamics of the space station. While Conway's analysis of data was to be concerned with the short-term effects of such movements, Healy's analysis would consider the long-term effects. Thus, what he learned would be of assistance to designers of future large manned spacecraft.

7
Fluids in Zero Gravity

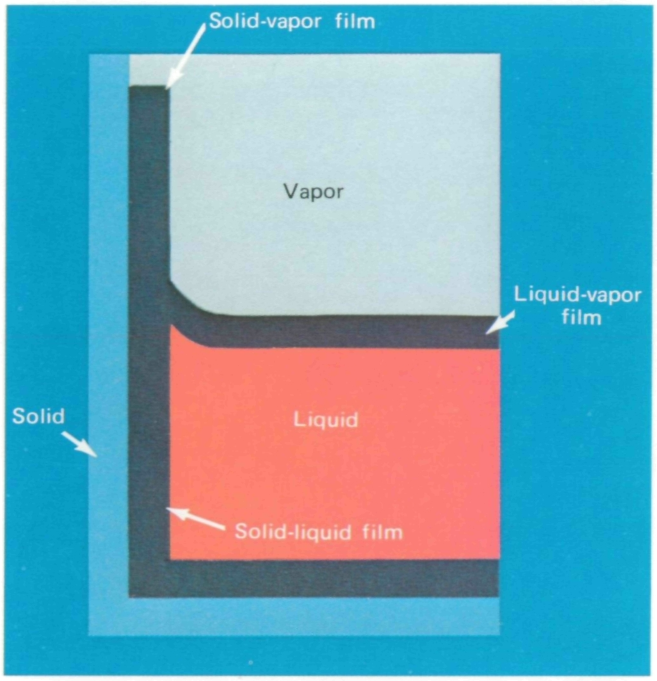
The behavior of fluids on Earth, where there is gravity, is well known. Water seeks its own level, often described as the hydrostatic paradox. For example, if a number of containers of different shapes, heights, and volumes are interconnected and a liquid is poured into them, the liquid will stand at the same level in each. This phenomenon is caused by pressure. On Earth, liquid conforms to the shape of its container and at any given level, exerts equal pressure in all directions. This pressure is the product of density and liquid depth plus atmospheric pressure. This equality of force is evidenced by the shape of a freely falling drop of liquid. In an ideal situation, such a drop assumes the shape of a sphere. A famous landmark in Baltimore, Md., is the 234-foot-tall Shot Tower, once used for the manufacture of cannonballs. Molten metal dropped from the top of this tower reached the bottom in near-spherical form.

Liquid in a container presents the problem of three boundary surfaces. There is a solid-liquid film, a liquid-vapor film, and a solid-vapor film. They are only a few molecules thick and exhibit the effects of both cohesion forces (the mutual attraction of like molecules) and adhesion forces (the attraction between unlike molecules). The interaction of these two forces results in the curvature where a liquid and a solid meet. The cohesion between molecules in a liquid surface is called *surface tension.* This is the force that draws a drop into a spherical shape. The adhesion between a liquid and a solid surface determines the wetting characteristics of the two, that is, whether the liquid beads up on the surface like water on wax or spreads out like oil on water.



The hydrostatic paradox is illustrated by the fact that the top of the liquid stands at the same level in each container when the liquid is in a gravity environment.

Certain forces are also present on Earth that cause water and other liquids to flow in directions other than downward. These include the circular motion of water within waves (or as it goes down a drain), the random motion within the body of a liquid, called Brownian motion, and the movement of a liquid by means of capillary attraction. All these forces have major effects on Earth, from the supply of moisture to plant roots to erosion of sea shores, as well as in certain various manufacturing processes. But how do these forces act and react in zero gravity? The answer is important to space science because of the effect of these forces on the behavior of liquid rocket fuel, potential space



The three boundary surfaces of liquid in a container. The surface of the liquid near the solid is curved if the solid-vapor surface tension is different from the solid-liquid surface tension.

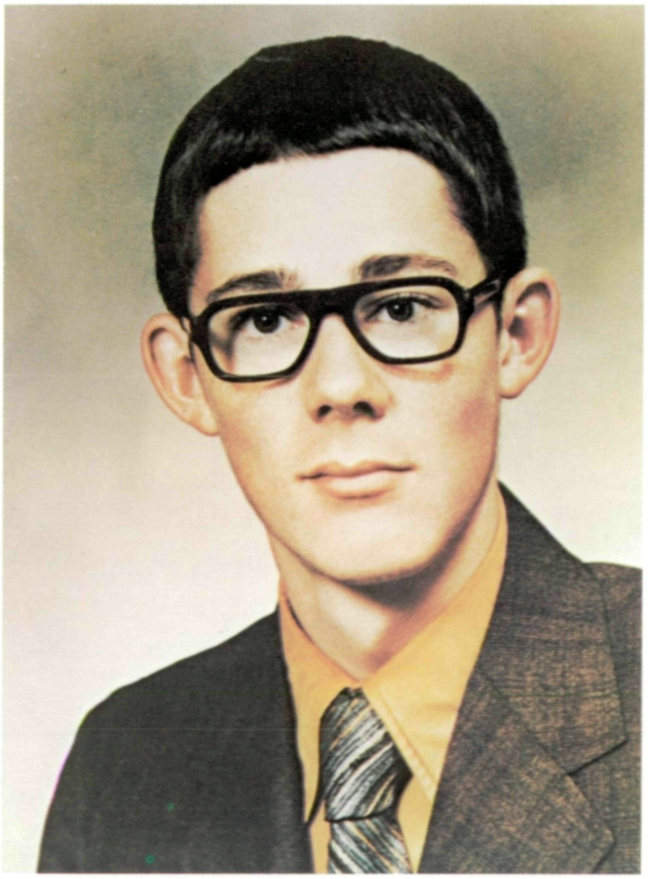
manufacturing systems, and crew comfort and health.

Skylab student investigators developed five experiments related to fluid behavior under conditions of weightlessness. These experiments concerned capillarity, liquid motion, the colloidal state of matter, Brownian motion, and very fine powder flow.

Capillary Study

The behavior of fluids, particularly their flow properties, in a low-gravity environment first became important when Robert H. Goddard launched his liquid-fueled rockets in the 1920's. He used gas-pressurized liquid flow as a substitute for gravity. In the more sophisticated space systems of today, it is sometimes necessary to design fluid-flow systems that will not only overcome the lack of gravity but also overcome or take advantage of the effects of surface tension. On Earth, capillary effects are observed when fluid adhesion to a solid surface produces a force that is sufficient to support the weight of the column of fluid. If the fluid wets the surface of a small capillary tube, it is drawn up until the weight of the column equals the adhesion force. Similarly, the fluid is depressed if it does not wet the surface of the tube.

Roger G. Johnston of Ramsey High School, St. Paul, Minn., theorized that in Skylab's zero gravity, the capillary rise might continue to infinity, since there would be no gravitational forces. His experiment consisted of two capillary tube units and a capillary-wick device. Each capillary tube unit contained identical sets of three tubes of graduated sizes. Each also had a fluid reservoir, one holding water and the other oil. The capillary-wick device had three columns of twill and mesh screen with a reservoir of a water solution that simulated the

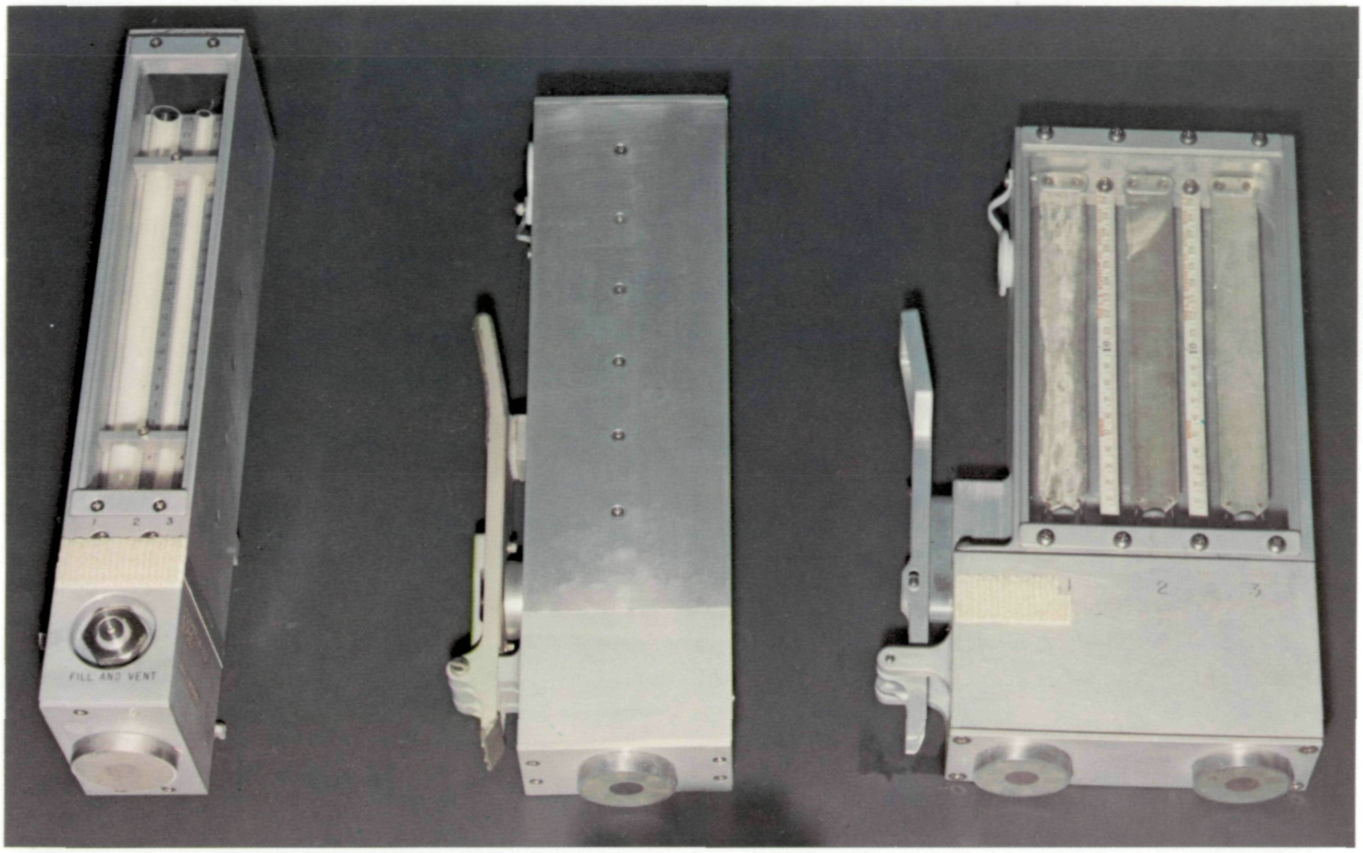


Roger G. Johnston theorized that a weightless column of fluid might rise to infinity in the zero gravity of Skylab. The experiment was later continued aboard the joint Soviet and American Apollo-Soyuz Mission in 1975. At right, he is shown discussing his experiment with Gene Vacca of NASA Headquarters.

properties of liquid hydrogen, a contemporary rocket fuel. During the experiment, the mouths of the capillary instruments were to be kept in contact with the reservoir fluid, but the capillary action was to be prohibited by a special valve until the experiment was activated by a Skylab crewman.

Astronaut Pogue initiated the capillary wicking device as specified, but there was little or no wicking action for more than 2½ hours. At that point, it was necessary to move it, and the resulting agitation apparently initiated some minor wicking action. Several days later, the capillary tube units were activated, but no capillary action occurred. In an effort to find the cause for such a lack of action, the crew discovered evidence of fluid leakage from the reservoirs that had occurred prior to the operation of the experiment. The loss could have been caused by vibrations of the Saturn during launch or by the excessive temperatures and reduced pressures during the early days of the near-abortive Skylab mission.

Not dismayed by this discouraging turn of events, Johnston completed a theoretical study of the capillary behavior in which he derived rise-time characteristics. He also analyzed films taken during the mission for the oscillation frequency of free-floating water globules, obtaining computed results within 2 percent of theoretical values estimated before the flight of Skylab.



Equipment used in Johnston's capillary action experiment. The two tube devices are shown left and center, while the wicking unit is on the right. Colored water and oil were used in the tube devices, but the wicking unit held only water to simulate liquid hydrogen, a common rocket fuel. The handles seen on the devices in the center and on the right operated special actuating valves.

Liquid Motion

A stone falling into a quiet pool produces concentric rings of disturbed water moving radially outward toward the shore. Lightning is seen as it occurs, but thunder is not heard for nearly 5 seconds. A newscast informs us that the city of Anchorage, Alaska, was severely damaged by an earthquake. Each of these events is an example of wave motion—water waves, light waves, sound waves, radio waves, and seismic or shock waves. All of these waves can be defined as physical disturbances transmitted from one point to another point in a fluid, solid, or vacuum. The disturbance may be a very simple one such as a rock falling into water, or it may be a very complex one like that caused by the seismic shock wave following an earthquake.

All waves have certain well-defined properties and are based on the concept of simple, harmonic motions. There are two basic types of waves, distinguished by the motion of the particles in the medium as the wave passes. In a transverse wave, the particles vibrate at right angles to the direction in which the wave propagates. In a longitudinal wave, they vibrate in the direction of travel. In either case, the wave is characterized by its amplitude, which is the displacement of the particles from the rest position, and its period, which is the time for one complete oscillation. The frequency of the wave is the reciprocal of the period, or the number of waves or cycles per unit of time (i.e., cycles per second). Waves that occur in nature frequently are combinations of transverse and longitudinal movement and have very complex shapes.

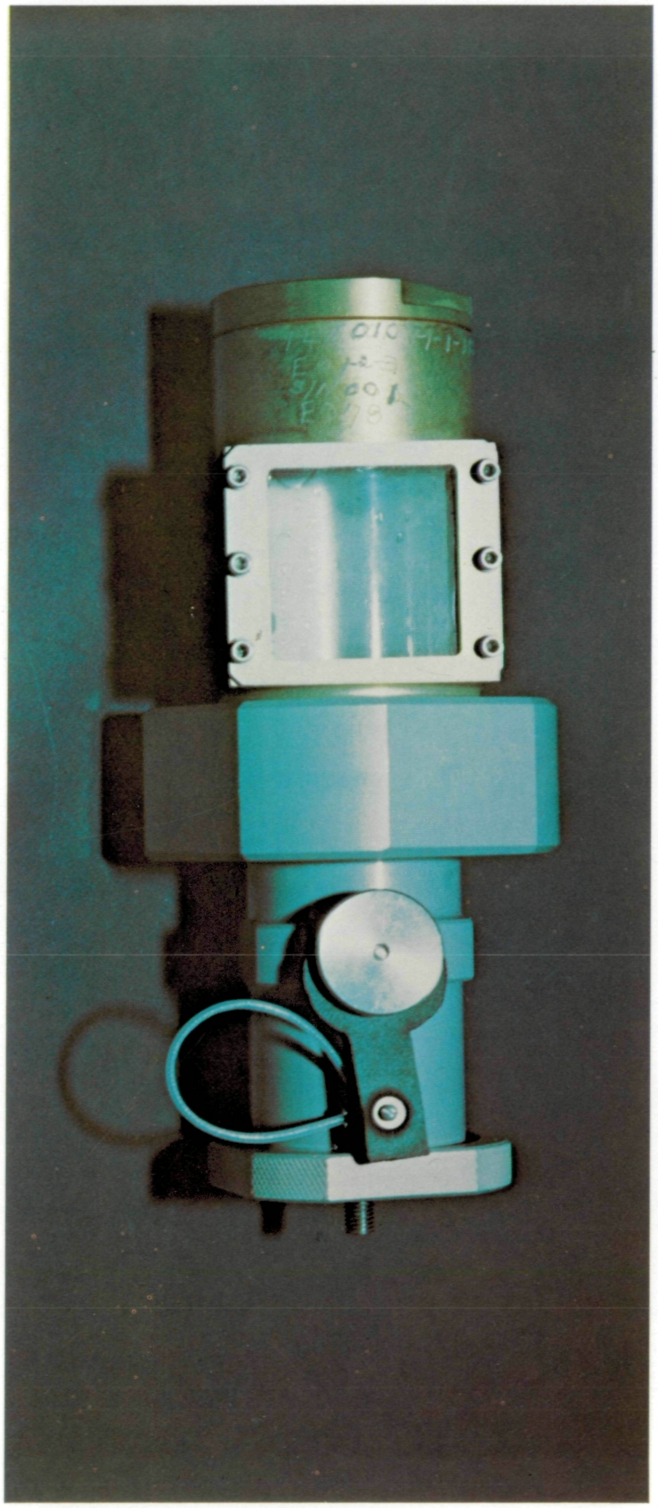
W. Brian Dunlap of Austintown Fitch High School in Youngstown, Ohio, proposed a study of wave motion in a liquid. He was particularly interested in comparing surface waves over a liquid in zero gravity with those occurring on Earth. In space, with the absence of gravity, a liquid does not necessarily take the shape of its container as it does on Earth. Adhesion forces may hold the liquid in contact with its container, but the liquid can also assume a free-floating condition. It was in this latter state that Dunlap wished to examine the behavior of surface waves.

The analysis of surface waves in water is an extremely complicated mathematical problem. Their motion is neither transverse, as in the case of electromagnetic waves (light, radio, etc.), nor is it longitudinal, as for sound. Although the water is, in general, standing still, it is alternately a crest or trough. Water is a basically incompressible fluid, and as a wave passes, a crest transforms to a trough. This causes the water particles near the surface to roll as a series of circles. Thus, the wave motion is a combination of longitudinal and transverse motions of particles. Progressively deeper beneath the surface, the particles produce ever smaller circles until their motion disappears completely.

Dunlap proposed containing water within a large, transparent, rectangular vessel, partially filled. His hypothesis was that the water would float freely within the vessel with virtually no contact with the sides of the container. He proposed using a vibrating crystal oscillator to produce waves in the water.

In analyzing the implementation of Dunlap's concept, two problems immediately arose. The first was how to insure in zero gravity that the water would truly float free of the sides of the container and at the same time maintain physical contact with the vibrator drive mechanism without having the water break into droplets. The second and more decisive problem was that the mass and

W. Brian Dunlap saw in Skylab a means of studying wave motion in a liquid that was free of the pull of gravity. He is shown below discussing the equipment used in performing his experiment with his science adviser Robert Head. After completing high school, he enrolled in engineering studies at Carnegie Mellon University.



A small cylinder containing water, an air bubble, and a window for photographing the waves on the fluid in zero gravity permitted Dunlap to achieve meaningful data from his Skylab experiment.

volume of the required experiment were excessive. Also, the time required to develop and test it was too great for the Skylab schedule.

However, since NASA considered the behavior of liquids to be of such great importance to future space programs, alternate procedures were developed. While not meeting Dunlap's objectives in their simplest form, a method of exciting oscillations in a small amount of water was developed. A small cylinder of water containing a trapped air bubble was utilized. An expandable membrane or diaphragm closed one end of the cylinder, and a clear window was provided to enable photography of the observed motion. The diaphragm was held in place by a piston which could be released and rapidly moved away. This action allowed the diaphragm to move, producing a sudden expansion of the gas bubble and creating waves at the surface of the water. The oscillations were photographed as they became smaller and gradually disappeared. Analysis of these waves would give insight into the behavior of the water in zero gravity.

The cylinder with entrapped air was filled at Earth's atmospheric pressure. When the experiment was to be performed, the trapped gas bubble could expand against the Skylab atmosphere at approximately 5 pounds per square inch (absolute), so that an expansive pressure of about 10 pounds per square inch was available to initiate the experiment.

The experiment was launched into orbit in the unmanned Skylab and exposed to high temperature and low pressure following the loss of the meteoroid shield. During the second manned period, Scientist Pilot Garriott tried to operate it, but release of the piston failed to impart any motion to the liquid-gas interface. Part of the diaphragm was reported to be protruding into the liquid. This indicated the possibility that some of the air and liquid could have leaked out, resulting in little or no differential pressure across the diaphragm. The exact cause of the malfunction could not be determined, since this equipment was not returned to Earth at the end of the mission.

Interest in such behavior prompted Scientist Pilot Kerwin during the first manned period and Garriott during the second manned period to demonstrate that small quantities of water could be easily handled in the form of free-floating globules. Consequently, a science demonstration was performed during the third manned period that showed oscillations on the surfaces of free-floating water globules and globules attached to a flat surface. Data were recorded on videotape and subsequently converted to 16-mm film. Dunlap analyzed these data to determine periods of oscillation of free-floating globules and found agreement with the theory to be much better than expected.

Colloidal State

The chemistry of colloidal materials is important to many disciplines of science and industry. This branch of chemistry deals primarily with the study of particulate materials of one phase of matter (i.e., solid, liquid, or gas) dispersed in another. It is important to the understanding of many ordinary materials, including glass, rubber, celluloid and other plastics, ore and minerals, beer, most foods, smoke, and pharmaceuticals.

Colloids are substances in a state of fine dispersion. They are, chemically speaking, mixtures as opposed to solutions. For example, maple sirup is a simple solution of sugar and water. The sugar dissolves in the water to form a homogeneous substance. In contrast, milk is a colloidal suspension of fat, protein, lactose, minerals, and vitamins in water.

Colloidal systems consist of submicroscopic particles which are distributed throughout another substance. The dispersed phase (usually of lesser relative concentration) is surrounded by the suspending solid, liquid, or gas called the dispersion medium or external phase. For the three phases of matter, there would obviously be nine possible types of dispersions, as shown in the accompanying table. However, only eight are colloidal, because "gas in gas" is considered to be a true solution.

Keith McGee of South Garland High School, Garland, Tex., conceived a series of investigations to study the colloidal state of matter. He proposed an experiment composed of four rectangular chambers, with transparent viewing and photography ports, heaters to control temperatures, power supply to establish electric fields, and the necessary controls. By this means he intended four specialized investigations in colloidal chemistry.

However, the time required to develop McGee's experiment was excessive. McGee then became associated with R. S. Snyder, the principal investigator for electrophoresis experiments in the Apollo program.

Dispersed phase	Dispersion medium		
	In solid	In liquid	In gas
Solid	*Solid sols* Alloys Paper Gem stones	*Suspension or sol* Paint Milk of magnesia Some inks	*Solid aerosol* Smoke Dust
Liquid	*Solid emulsion* Jellies Glue Gels	*Emulsions* Milk Protoplasm Butter	*Liquid aerosol* Mists Sprays Steam Fog
Gas	– Pumice Hydrogen in platinum metal	*Foams* Whipped cream	*Solution* Not a colloidal dispersion

Electrophoresis is an analytic technique used by chemists to separate the ingredients of a mixture, especially organic compounds, by means of an imposed electric field. An electrophoretic experiment was carried out aboard Apollo 16, the second mission to the Moon. The results showed that in the zero gravity of space, with reduced sedimentation and convective mixing, a much sharper separation of constituents could be obtained. A similar experiment was later performed on the Apollo-Soyuz Test Project in 1975. Such experiments suggest that it may be possible to produce extremely pure pharmaceuticals and other materials in space.

During the Skylab mission, a science demonstration utilizing a concept very similar to the one proposed by McGee was suggested by Milan Bier from the Veterans' Administration Hospital at Tucson, Ariz. This demonstration is described later. The conclusion drawn from the Skylab demonstrations of the electrophoretic process substantiated the earlier Apollo findings.

Brownian Motion

In 1827, Robert Brown, an English botanist, observed through a microscope that pollen grains suspended in water continuously vibrated. Brown

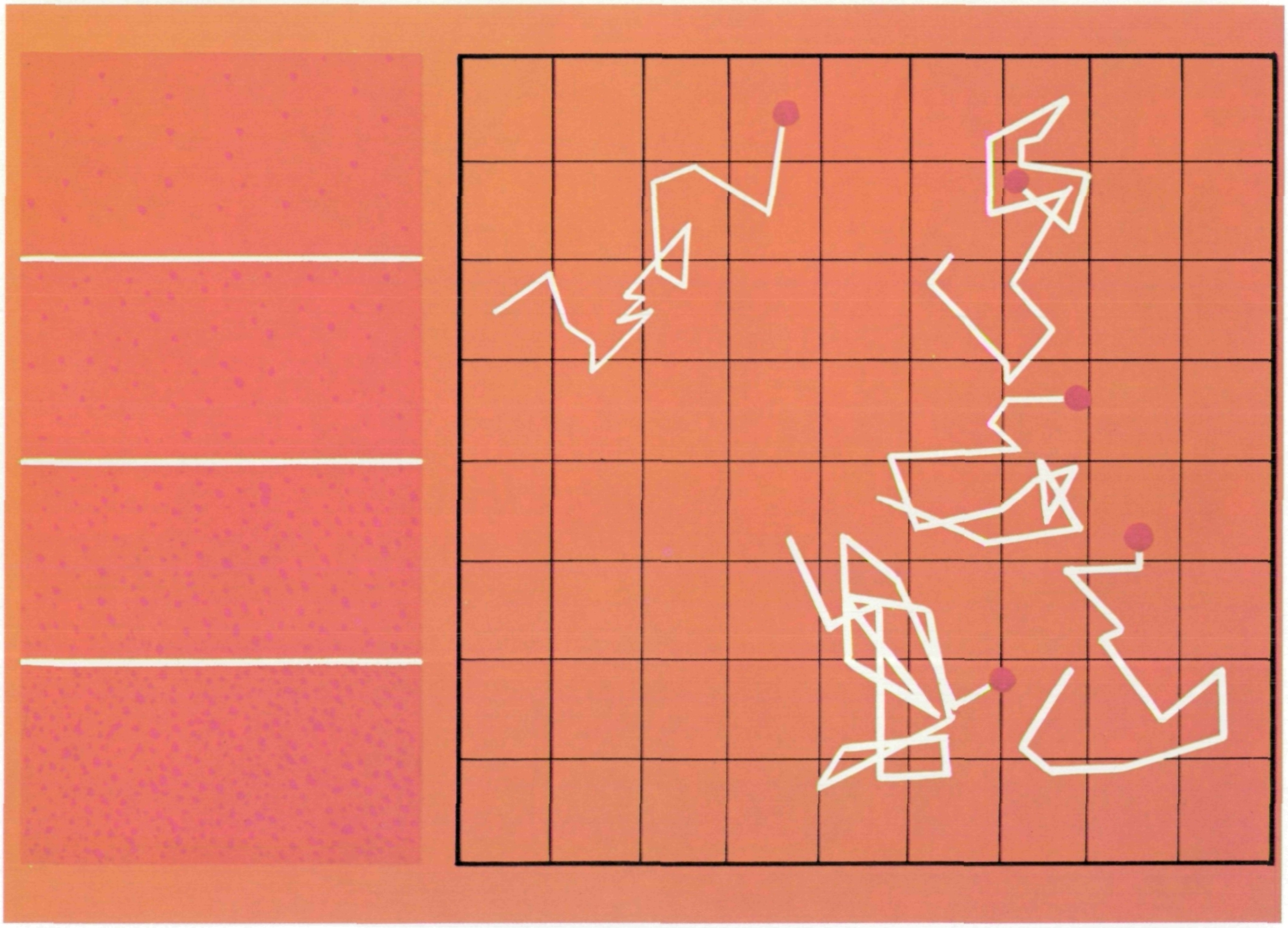
Keith McGee proposed an ambitious experiment in the field of colloidal chemistry, which proved unattainable within the time available for student experiments aboard Skylab. However, he became associated with a scientist who had important experiments in a related field in the Apollo program and the later Apollo-Soyuz project.

attributed this motion to the living matter. It was not until 1860, when the kinetic theory was proposed, that this hypothesis was disproved. It was then that nonliving particles in a similar suspended state were observed in the same type of motion. Today, it is well known that Brownian motion, named for its discoverer, is due to unbalanced molecular impacts on colloidal particles.

Gregory A. Merkel of Wilbraham and Monson Academy, Springfield, Mass., proposed a study of the effects of gravity on Brownian motion. His idea was to place a crystal of a colored salt in a graduated cylinder, held in place at the bottom of the cylinder. The cylinder would then be placed in a constant-temperature water bath. As the crystal dissolved, the solution near it would become colored. The apparatus, if left undisturbed, would allow the color to migrate throughout the cylinder in time due to the random Brownian motion of the solution's molecules.

Such an experiment is a classical high school demonstration of the kinetic theory of matter and

In 1909, the French physicist J. Perrin examined fine particles in a glass container. The sketch at the left shows what he saw after a time interval in which he expected that the particles would all have settled to the bottom. The zigzag lines on the right show the paths taken by five individual particles as recorded on movie film in less than 0.3 second during a later experiment.



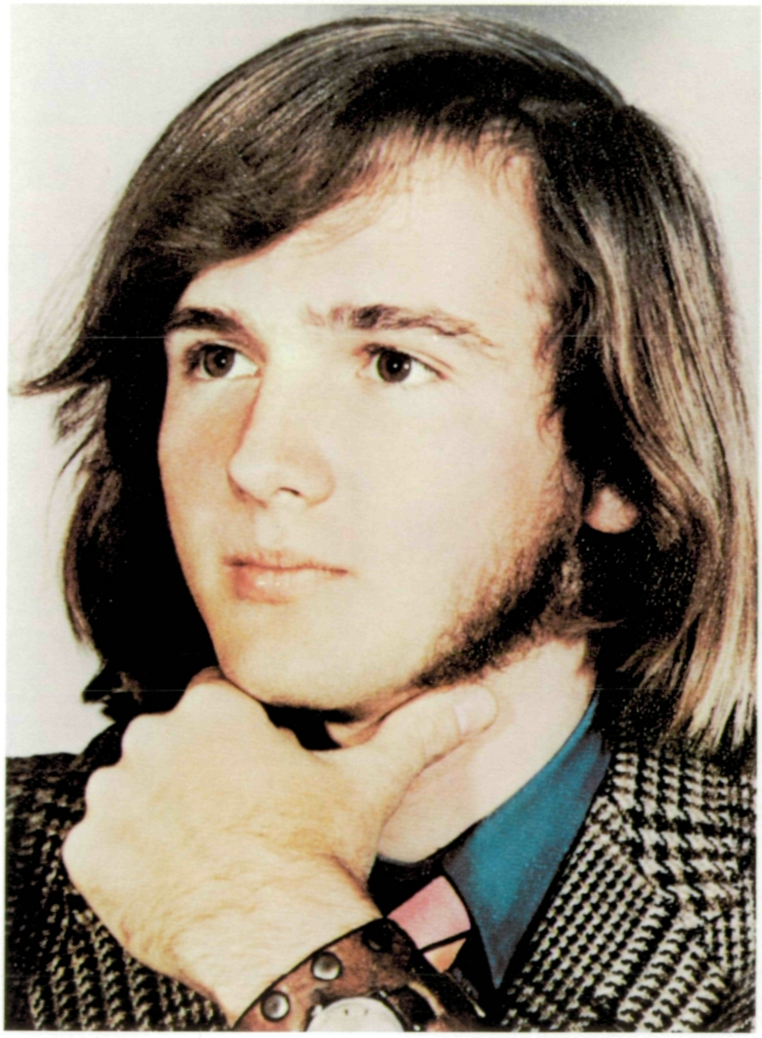
requires several weeks of observations for the solution to take on a uniform color. Skylab, however, did not provide a perfectly stable platform for such an experiment. Maneuvers to maintain or change the orientation of the vehicle and vibration due to pumps, fans, and other machinery all produced small accelerations that would have precluded the satisfactory performance of Merkel's experiment. However, during the second mission a demonstration of the diffusion of tea into water was performed by the astronauts and is described later.

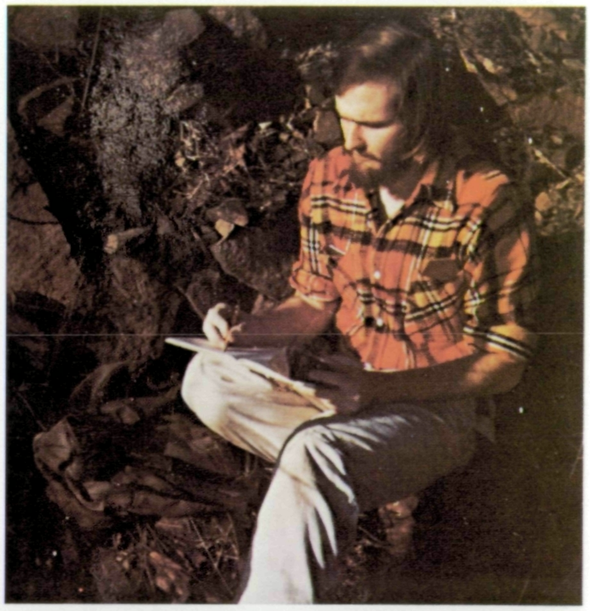
Powder Flow

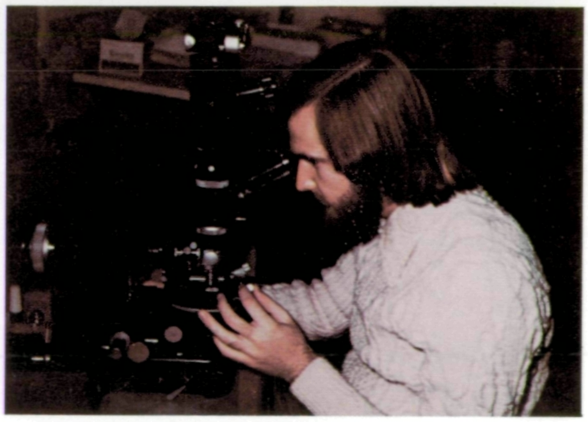
The transport of fluids in a space vehicle has been an area of study and experiment since the early development of liquid-propellant rocketry. Liquid fuels, liquid coolants, lubricants, and water all have presented problems of one kind or another in the space environment. Kirk M. Sherhart of Berkley High School, Berkley, Mich., suggested an experiment to study the flow of powdered solids as contrasted with liquids in zero-gravity environment.

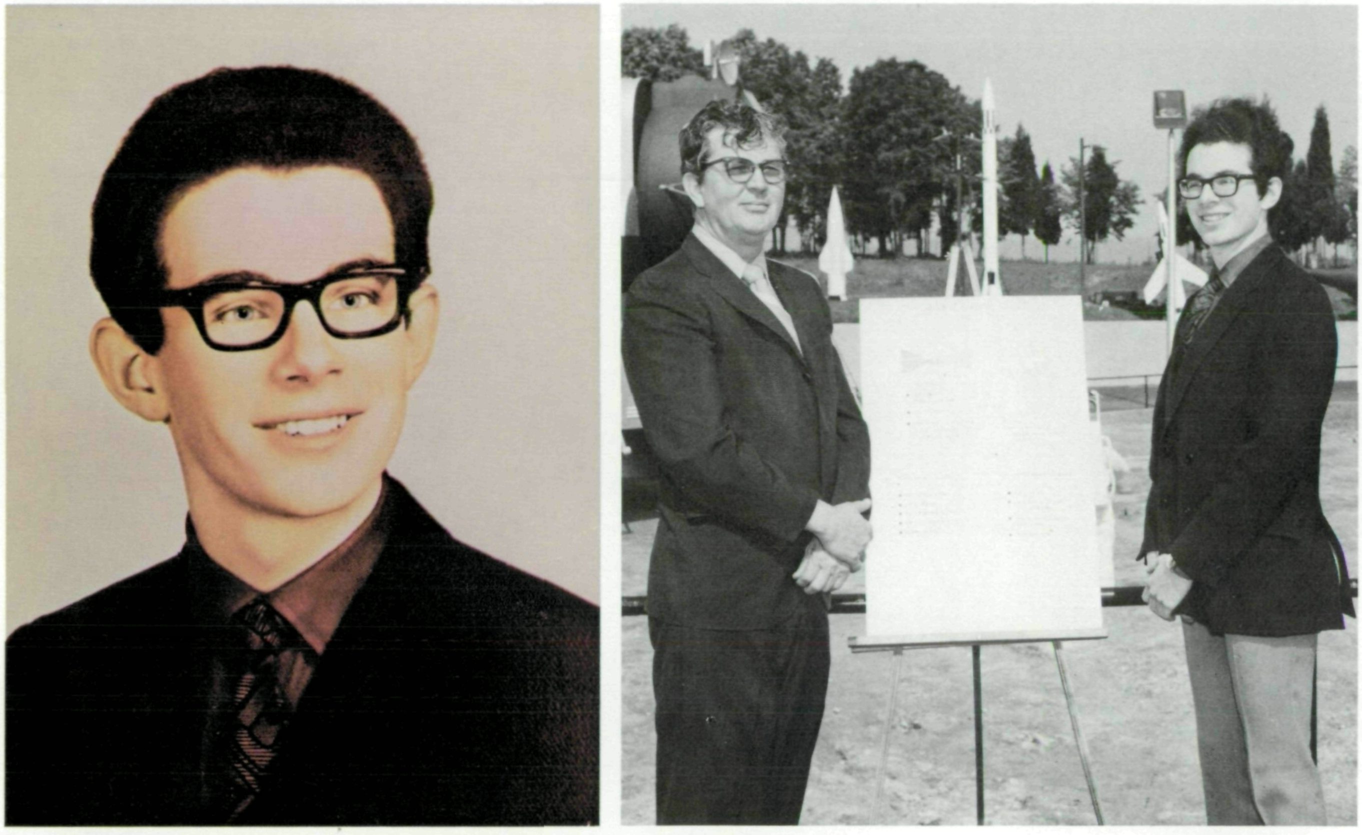
Several simple plastic models of various sizes

Gregory A. Merkel felt that the zero gravity of Skylab might significantly alter the movements of very small particles suspended in water, a phenomenon called *Brownian movement.*





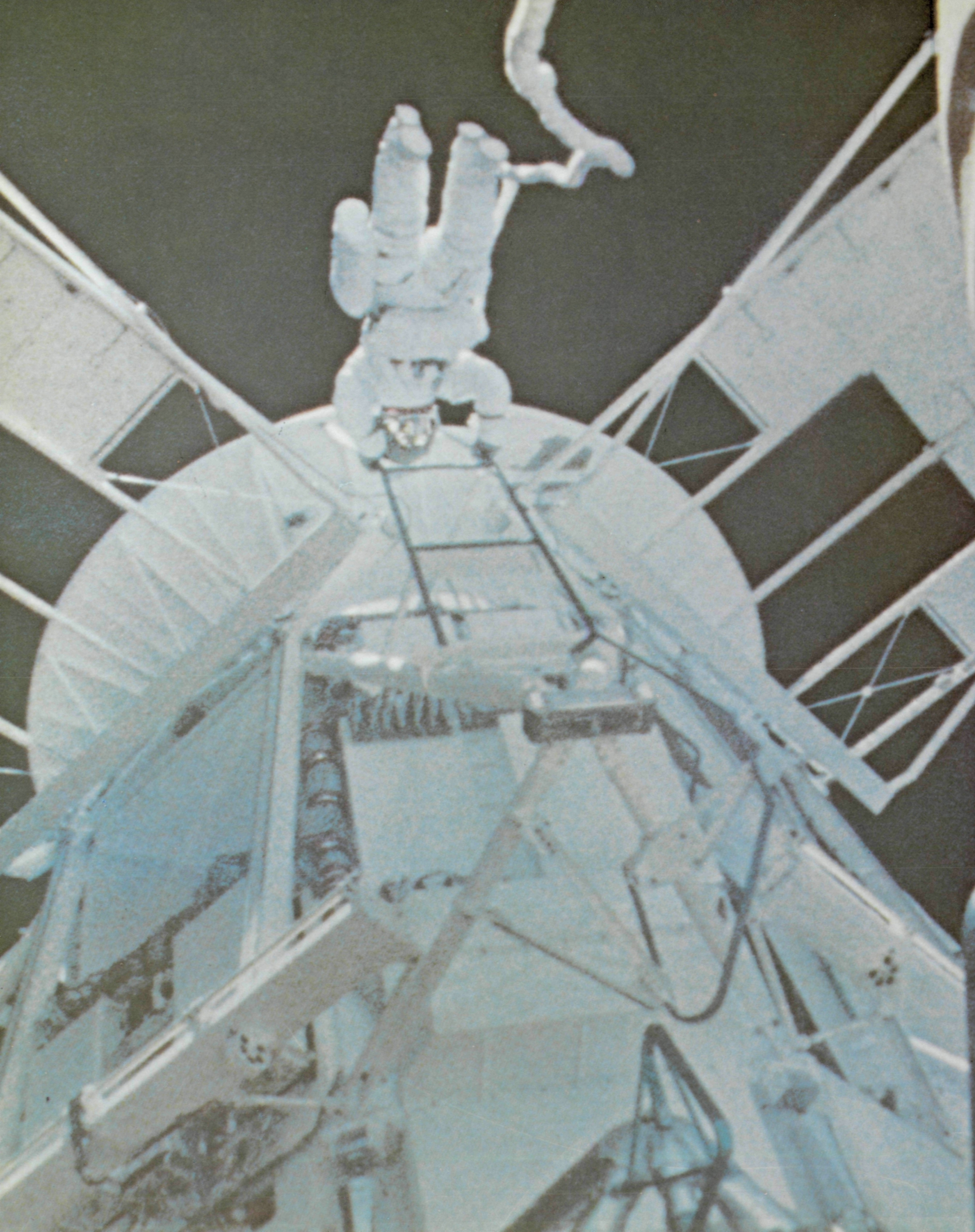




Kirk M. Sherhart suggested an experiment for Skylab that concerned the effects of weightlessness on the flow of very fine powders. Later, he became interested in computer engineering.

were constructed with mechanical pistons used to force steel marbles, small plastic beads, and a fine powder similar to talcum through sized openings. Preliminary tests revealed that the packing together of the spheres prevented their flow. The consensus of the researchers was that Sherhart's idea was worthy of investigation. However, there was not sufficient time to perform the necessary basic research toward development of an experiment that had a reasonable probability of success. As a result, even though Kirk's experiment did not fly, he was affiliated with the NASA researchers in the area of materials handling in space at the Goddard Space Flight Center.

The lack of gravitational force and very low accelerations in Skylab furnished a challenge to several students who saw how such a condition could be used to study the behavior of fluids. Again, their scientific curiosity and imagination prompted them to take advantage of weightlessness to propose experiments that were at once stimulating and fruitful.



8

Exploring the Stars and Planets

Astronomy is man's oldest science. What he learned from it influenced him in many ways. The length of the day, the phases of the Moon, and the seasons of the year are governed by the orbital mechanics of the solar system. Ancient man observed the heavens to determine the best time for planting crops. Nomads and seafarers learned to use the stars for navigation. Most early civilizations were so awed by the universe that religions, mythologies, and astrology were invoked to explain it.

Gradually the superstitions were dislodged, and man began to understand the universe for what it is: a physical entity, full of secrets, and a marvelous challenge for him to decipher. Piece by piece the foundations of the science were established. In 600 B.C., the Greek Thales suggested that Earth was round. About A.D. 140, the Greco-Egyptain astronomer Ptolemy defined a universe that revolved around a stationary Earth. Not until the mid-15th century did the Polish astronomer Nicolaus Copernicus properly place the Sun in the center of the solar system. In the following century, the German astronomer Johannes Kepler used data collected by his former teacher Tycho Brahe to define the elliptical orbits of the planets. The development of the telescope, about 1609, provided a closer view of the planets and gave strong evidence to support the Copernican system. Newton expanded upon Kepler's laws of motion to develop his universal law of gravitation, which marked a significant milestone in that it provided the means for the mathematical prediction of planetary orbits. In the 20th century, Albert Einstein's theory of relativity expanded the conceptual universe by relating energy to mass as well as establishing that measurement of motion and time is dependent upon their frame of reference. Furthermore, technological advances in astronomical instruments in the 20th century permitted Hubble and others to view far beyond the Milky Way. Today, with the knowledge of atomic structure, spectral analysis, and remote observational satellites, opportunities to acquire new information seem limitless.

Stellar observations have historically been performed in the visible region of the electromagnetic spectrum, but scientists have learned that a vast amount of information can be obtained from the other spectral regions. While other spectral regions cannot be seen with the human eye, they can be sensed by instruments and transformed either mechanically, electronically, or photographically into a meaningful form. A frustrating problem for astronomers is that energy from many of these spectral regions is absorbed by Earth's atmosphere before it can reach the surface. This is particularly true of certain X-ray and ultraviolet (UV) radiations. One of the specific objectives of Skylab's observation program was to take advantage of the space station's position above the atmosphere to enhance X-ray and UV astronomy.

A research technique exploited extensively by Skylab in its astronomy observations was that of spectroscopy. Spectroscopy is the interpretation of electromagnetic radiation to determine the chemical composition and temperature of a radiating source.

Spectroscopy is based upon the fact that excited atoms of individual elements radiate a characteristic pattern of wavelengths. By separating the light from a star into individual wavelengths, we can detect these patterns and determine what elements are contained in the star.

Four student experiments were concerned with stellar astronomy. Two used Skylab's UV stellar astronomy cameras to obtain photographs of emissions from pulsars and quasars. Two others used the X-ray spectrographic telescope of its solar observatory to photograph stars and the planet Jupiter in six X-ray wavelength bands.

UV From Quasars

Quasars are some of the most perplexing phenomena ever observed. Astronomers do not understand the mechanism involved and are not even certain just what or where quasars are.

Quasar is a shortened version of the term "quasi-stellar" radio source. Visually a quasar appears to be a rather ordinary, relatively faint star. But in the early 1960's these stars were identified as sources of electromagnetic emission in the radio wavelengths. Galaxies and nebulae had previously been recognized as radio sources, but never had such strong radio emission been associated with stars. Quasars then became a new classification of celestial bodies, objects that look like stars, but whose radio emissions do not fit the normal stellar pattern.

In 1963, astronomers at Mount Palomar in California succeeded in recording the line spectra from two quasars. To their amazement the wavelengths of their spectral lines did not coincide with any known elements. They appeared to be entirely composed of exotic substances never before observed. Physicists were certain that this was impossible, but they had no explanation.

Maarten Schmidt of the Hale Observatories offered the key to the quasar puzzle. He noticed that the emission pattern of the Balmer spectrum of hydrogen seemed to be present in their spectra, but it was displaced by a constant factor toward longer wavelengths toward the red end of the visible spectrum. In the case of the brightest known quasar, 3C 273 (number 273 in the Third Cambridge Catalogue of Radio Sources), the wavelengths are 1.158 times as long as the emissions of identical elements on Earth. This "red shift" is most often explained as a Doppler effect, meaning that the emission source is speeding away from Earth so fast that the wavelengths of its emitted energy appear to be stretched.

Hubble's law states that the distance to an object is proportional to its observed "red shift." This association is valid when considering distant galaxies and implies that some quasars are receding at 90 percent of the speed of light at a distance from Earth of some 10 billion light-years. Thus, these quasars would be the most distant objects of the known universe.

Another characteristic of quasars is their relatively large and rapid variation in brightness. Astronomers have known that the brightness of a celestial object does not significantly change faster than the time required for light to travel across it. Some quasars have been known to double their brightness in 1 week, in contrast to the 100 000 years required for light to traverse our galaxy. This fact suggests that quasars, for such small objects, are extremely powerful energy sources to be detectable at these enormous distances. Some quasars would have to produce hundreds of times more energy than the Milky Way. Yet their size is thousands of times smaller than the galaxy. No such powerful means of producing energy is known.

The alternative description of quasars is to accept them as stars within the Milky Way and attribute their "red shift" to something other than the Doppler effect. This resolves the energy dilemma; however, no accepted explanation for the "red shift" in this situation has yet been provided. A more thorough description of quasars is required before this controversy can be settled.

John C. Hamilton of Aiea High School in Aiea, Hawaii, suggested an experiment to photograph various quasars with the Skylab UV spectrometer. He hoped to identify further elements contained in quasars whose emission lines would shift from the far-UV or X-ray regions into the UV area.

Karl Henize, a NASA astronaut and astronomer at the University of Texas, was the principal scientist for one of Skylab's UV stellar astronomy experiments and had an instrument required for Hamilton's experiment. As a result of working with

John C. Hamilton worked with Dr. Henize on an experiment to detect quasars using Skylab instruments.

Henize, Hamilton decided to attend the University of Texas and major in astronomy and physics.

The list of prospective celestial objects for his experiment was expanded by Hamilton to include several Seyfert galaxies (small, intense galaxies that exhibit similar characteristics to quasars). He did so after a consultation with Henize revealed that the sensitivity of Henize's spectrometer was marginal for detecting distant quasars.

Photographic plates were exposed on June 17, 1973, in an attempt to observe several quasars and Seyfert galaxies. However, only quasar 3C 273 was identified. In order to maximize the spectrometer's sensitivity, its spectral separating prism was removed from Hamilton's experiment. Therefore, he changed his experiment to determine the apparent brightness of 3C 273 in the spectral region of wavelengths between 1250 and 5000 Angstroms (an Angstrom is 10^{-10} meter). Preliminary results indicate that the apparent ultraviolet magnitude of 3C 273 is 12.6 ±0.5 on the brightness scale used to compare stars. This value is very near the sensitivity limit of Skylab's UV instruments but corresponds favorably with apparent magnitudes of 3C 273 previously measured. The internal energy required to produce this magnitude is dependent upon the quasar's distance from Earth. Eventually, enough of these small additions to knowledge of quasars will lead to an overall understanding of their nature.

UV From Pulsars

In 1967, Jocelyn Bell, an astronomy student at Cambridge University was investigating fluctuations in the strength of radio waves emitted by distant galaxies. Unexpectedly, she discovered several celestial areas emitting short, rapid signals at short intervals. None of them lasted longer than one-hundredth of a second. The intervals between the signals were extremely constant, as precise as a clock that would vary only 1 second or less in a year. The discovery was so surprising that at first the results were not announced.

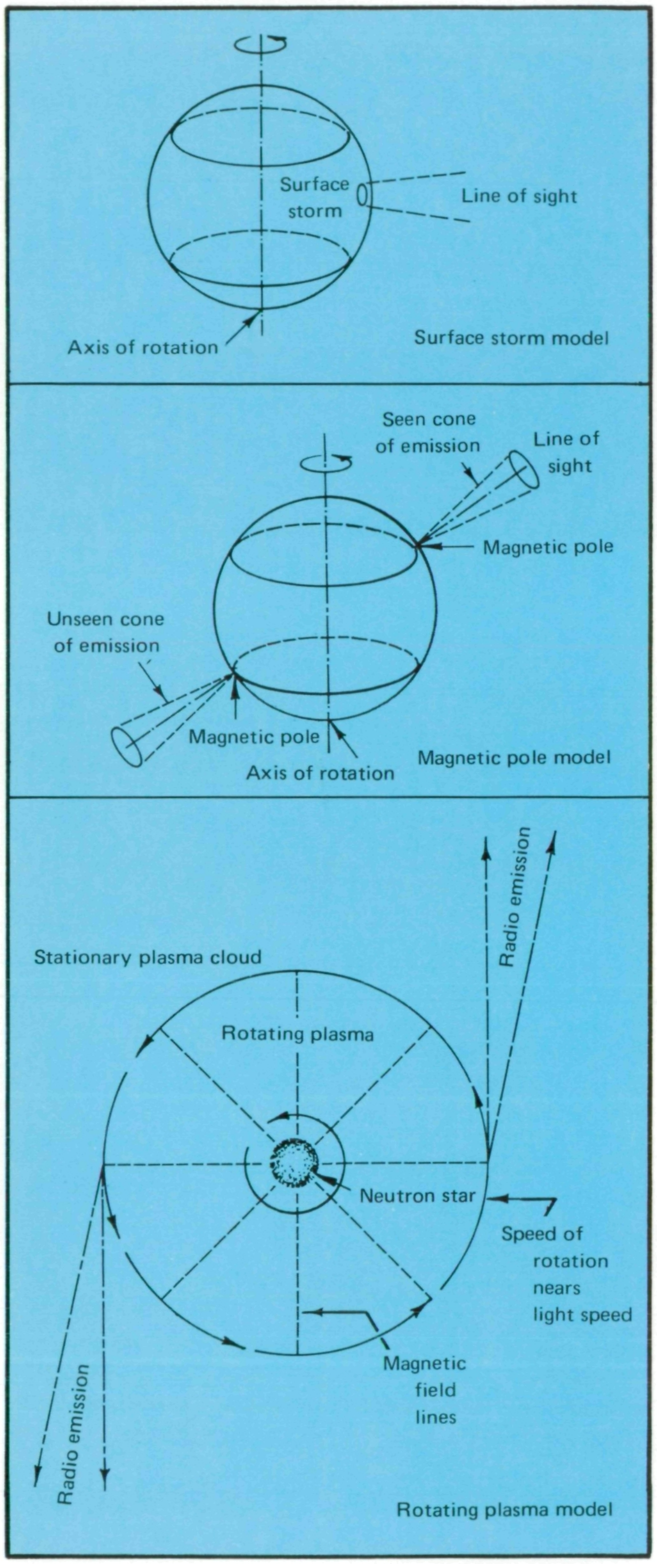
The first thought of some astronomers (and many science fiction fans) was that intelligent beings from other galaxies were beaming messages to Earth. But soon too many such sources were discovered for this idea to be realistic; the signals simply covered too broad a band of frequencies for efficient transmission. The radio pulses had to be natural phenomenon, and their sources became known as *pulsars,* a contraction for pulsating stars.

Another confusing thing about pulsars was that at first no visual objects were found to correspond with the sources of the radio emission. A clue to the solution of this mystery lay in the sharpness of the pulses. When a burst of radio energy is emitted from a large source, the radio waves from different portions of the object arrive at different times, blurring the signal. The smaller the object, the shorter and more precise the pulse. Knowing this, astronomers calculated that pulsars could be no more than 10 miles in radius. Until this discovery, the smallest, most dense stars in the universe were thought to be about 10 000 miles in radius.

Consideration also had to be given to a prediction made several decades previously. Theoretical astronomers had described the forces involved in the collapse of a large, dying star to be so great that individual atomic nuclei at the star's center touch each other and electrons are forced to combine with protons to form a core of solid neutrons. A supernova explosion blasts off the star's bright shell, leaving behind the core of neutrons. This hypothetical ball of neutrons became known as a neutron star, the most compact, most dense form of matter thought possible.

In 1968, a pulsar was discovered in the center of the Crab Nebula, at precisely the location where scientists had searched for a neutron star, the remnant of the supernova explosion that created the Crab. Indeed, pulsars seem to be neutron stars. Neutron stars would rotate rapidly enough to produce the precise radio bursts of a pulsar. The Crab pulsar "beeps" at a rate of 30 times per second.

Several theories have been proposed as the mechanism for production of these radio bursts. The most popular explanations are: a surface storm on the pulsar that emits a beacon of radio waves throughout its revolution, but is only seen when pointed toward the Earth; the poles of a strong magnetic field of the pulsar are set from its axis of rotation and are focusing ejected particles and their radiation into emission beams; or a plasma held in position by a strong magnetic field surrounds the pulsar and rotates with it. At a certain radius, the rotational speed of the plasma will approach the speed of light, causing a portion of it to break away from the magnetic field and release a pulse of electromagnetic energy.



Three theories have been advanced to explain how pulsars produce their radio-wavelength emissions.

Neal W. Shannon, a high school student working at the Fernbank Science Center, Atlanta, Ga., proposed the observation of several pulsars with Skylab's UV spectrometer to determine their intensities in that portion of their spectra. A more detailed description of a pulsar's electromagnetic emission profile would be expected to further define means by which its energy is released.

Unfortunately, upon examination of the photographic plates containing the data from Shannon's experiment, it was found that an alinement error of the spectrometer had prevented the detection of any of the pulsars. Thus, the mystery of pulsars remains.

X-Ray Stellar Classes

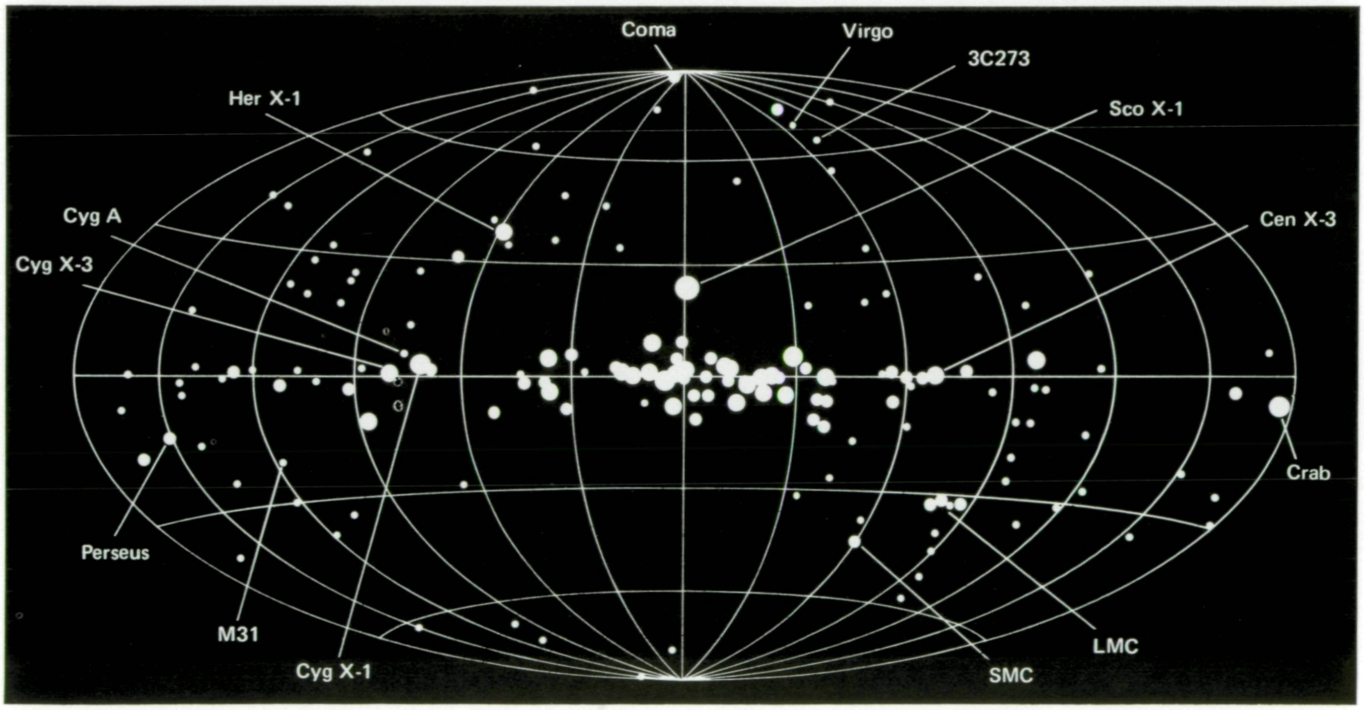
X-ray astronomy is one of the younger branches of an ancient science, only recently made possible with the advent of space technology. With the development of reliable spacecraft, new regions of the electromagnetic spectrum became accessible to astronomers for investigation.

By 1962, X-ray emission from the Sun had been detected and mapped in some detail. But if X-rays were produced by other stars in strengths comparable to those released by the Sun, such sources would be too weak to be detectable at their great distances from Earth. It was thus a major surprise when strong sources of X-rays were observed by instruments in sounding rockets throughout the heavens, many of which appear to have no visible counterpart. Uhuru, the first X-ray satellite, was launched in 1970 from a platform off the coast of Kenya. It scanned the sky for 3 years and detected additional new X-ray sources, some point sources, some large regions of radiation, and a diffuse, uniform, background glow.

This intriguing new science inspired Joe W. Reihs of Tara High School, Baton Rouge, La., to propose X-ray observation from Skylab of several stars in each spectral classification to determine if there might be a direct relationship between the magnitude of a star's X-ray emission and its age, or stage of stellar evolution.

Reihs' experiment was associated with Skylab's solar observatory X-ray spectrographic telescope, which could be pointed at specific star fields and record X-rays. However, it was determined that the X-ray telescope designed for solar studies did not have sufficient sensitivity to detect any stellar

Neal W. Shannon, shown above right with science adviser John Humphreys, proposed an experiment for Skylab that would investigate the ultraviolet properties of pulsars.



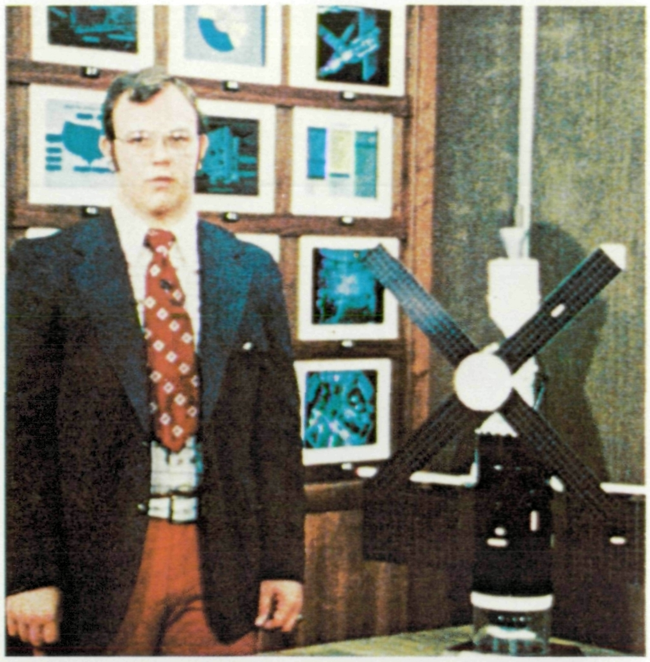
The Uhuru satellite, launched in 1970, gathered data for this X-ray map of the Milky Way. Note that sources are concentrated along the Equator.

X-ray sources and was thus unable to acquire data for Reihs.

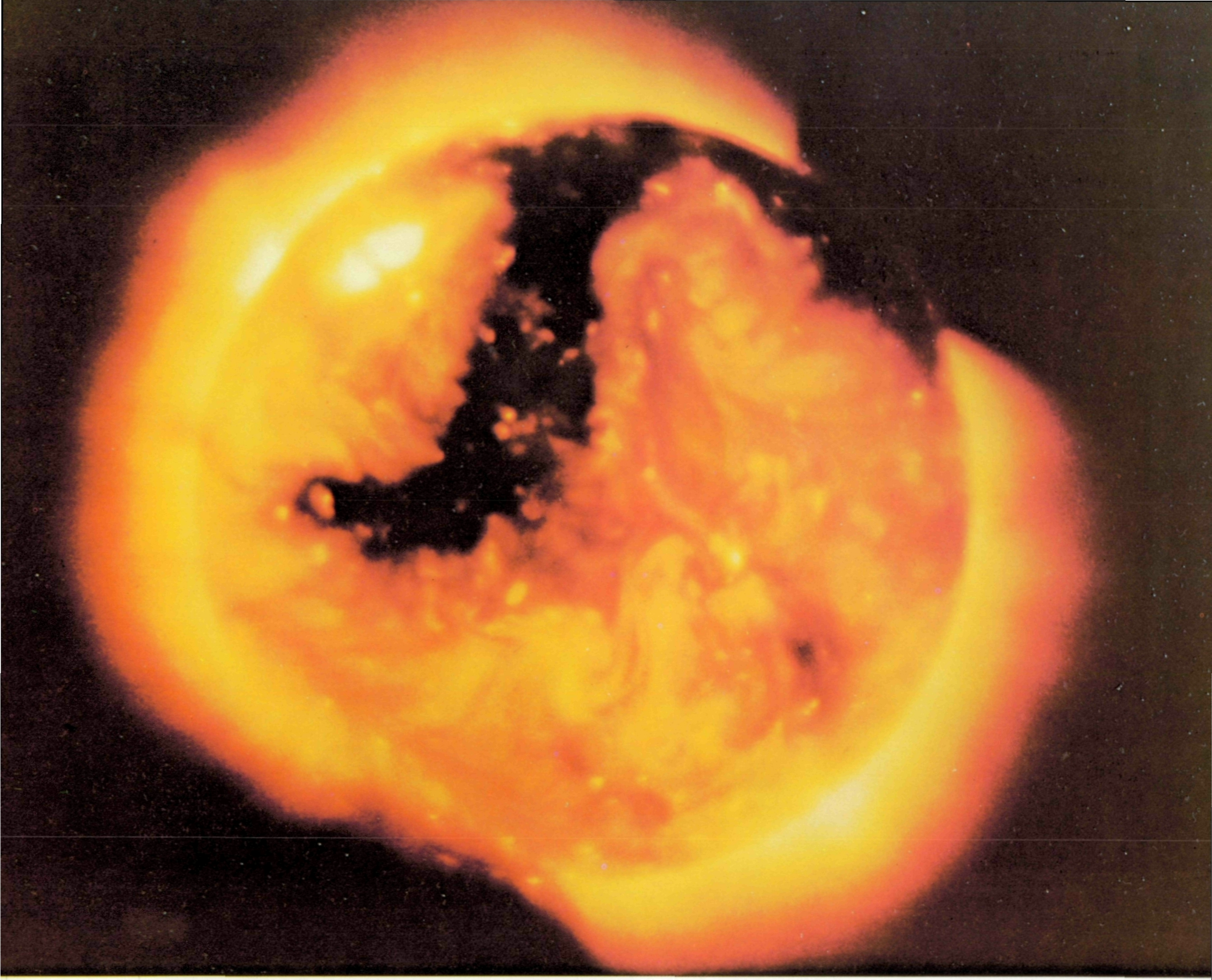
However, he did benefit from his experiment in that it provided him the opportunity to work for American Science Engineering, Inc., both in Boston and Houston, for most of 1973, as the company reviewed the performance of its X-ray telescope.

X-Rays From Jupiter

The ancient Greeks first identified Jupiter as a planet or a "wanderer" different from the fixed



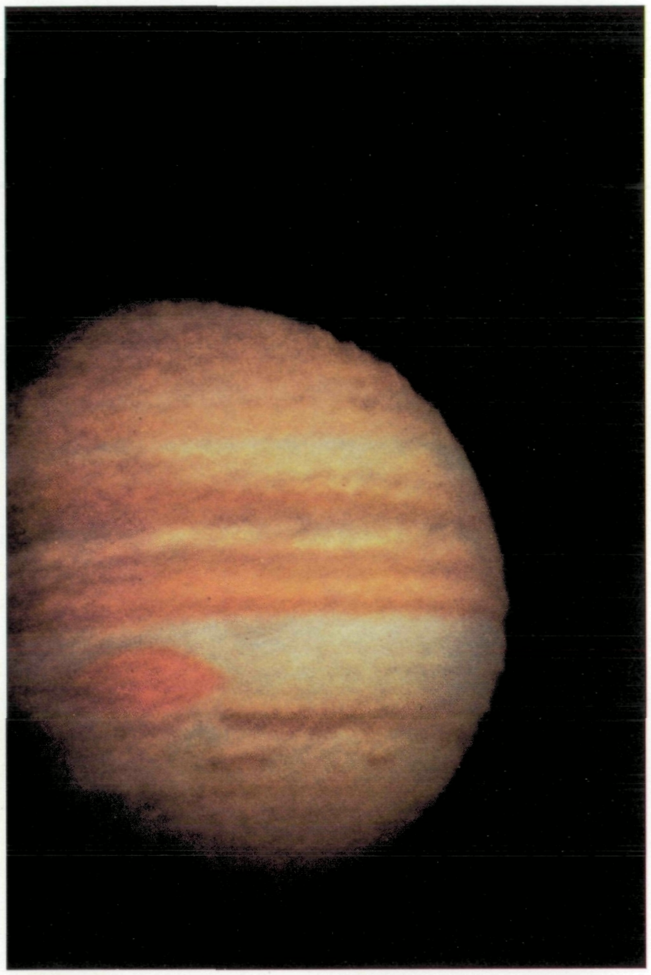
Joe W. Reihs suggested an experiment for observing X-ray emissions of certain stars as a possible index of their age or stage in evolution. Below right, he is greeted by Astronauts Russell Schweickart and Owen Garriott; Leland Belew, Skylab Program Manager; and David Newby, Marshall Space Flight Center Director of Administration and Technical Services.



Skylab's X-ray spectrographic telescope took this picture of the Sun on August 19, 1973. The large bright areas are X-ray emissions that represent gases in the corona at temperatures greater than 3 600 000°F. The great number of small, bright points shown had not been suspected prior to Skylab.

stars. In 1610, Galileo identified four of the moons (nine more have since been observed). It was, in fact, observations of Jupiter's "miniature solar system" that encouraged acceptance of the Copernican model of planets orbiting the Sun.

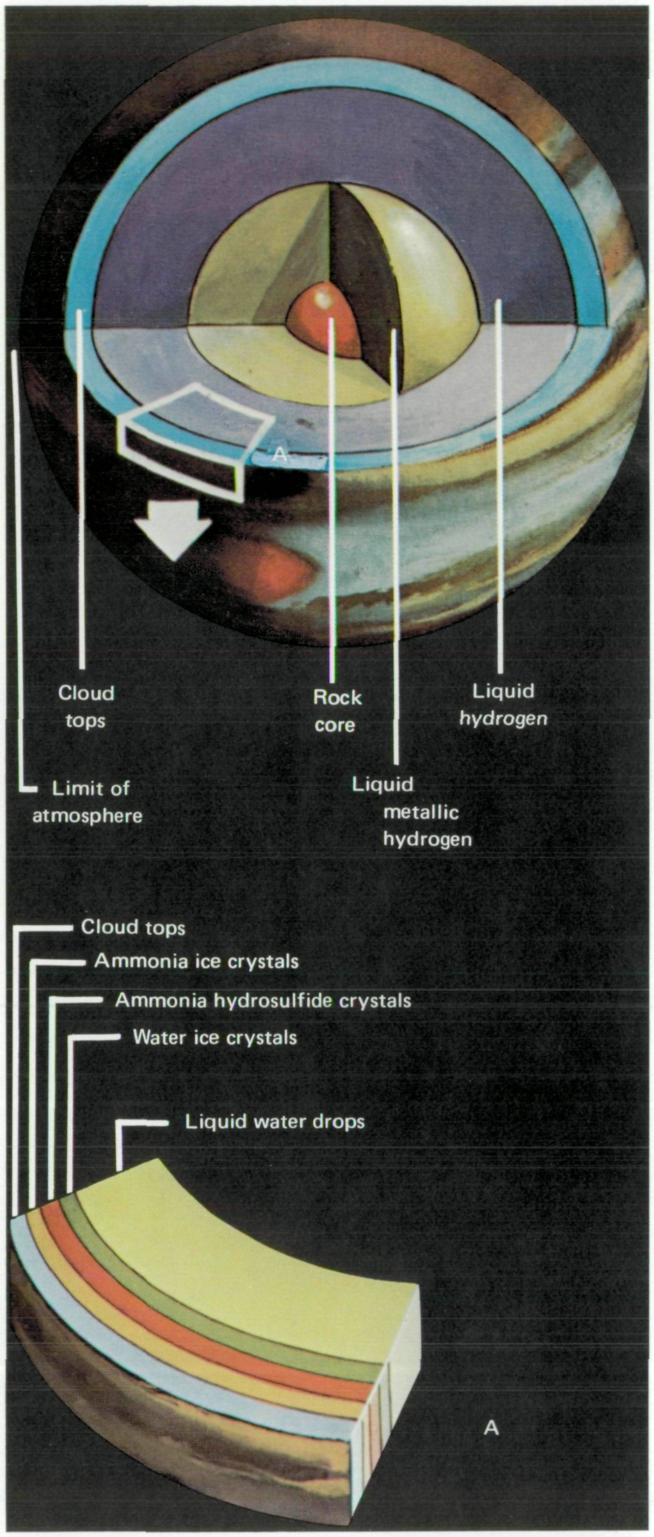
Jupiter is quite unlike Earth. Its diameter is approximately 11 times as large, and its mass is 317.8 times greater. More significantly, Jupiter has no surface such as Earth's. There are no oceans and continents. It has no distinct boundary between its surface and its atmosphere. The greater part of its innermost regions is solid hydrogen. The huge planet may have a very small metallic core, which is covered by a sea of liquid hydrogen that blends



The Great Red Spot on Jupiter has been seen from Earth for some 300 years. This picture, made from the space probe Pioneer 10, indicates that the spot may be a huge storm within the planet's atmosphere.

into a mixture of gases such as hydrogen and helium. Above it are turbulent clouds of ammonia ice crystals, the tops of which can be seen from Earth with the larger telescopes. Beneath this topmost layer probably lie regions of ammonium hydrosulfate crystals, and perhaps, still lower, water ice crystals.

Some astronomers feel that X-ray emissions from Jupiter may be produced by a nonthermal process within Jupiter's atmosphere or the *bremsstrahlung* method as electrons carried by the solar wind interact with Jupiter's magnetosphere following an increased period of solar activity. *Bremsstrahlung* (German for "braking radiation") is the



Jupiter consists almost entirely of hydrogen in some state; however, it may have a small, rocklike core.

form of energy release caused by a rapid deceleration of charged particles such as electrons. X-ray emission has never been detected from Jupiter, but the effect has been detected in the upper limits of Earth's magnetosphere. Photographs of X-ray emission from Jupiter would reveal new information about the conformation and mechanism of Jupiter's magnetosphere and magnetospheres in general.

Jeanne L. Leventhal of Berkeley High School, Berkeley, Calif., proposed using the Skylab solar observatory's X-ray telescope to observe Jupiter. The experiment was scheduled for the second Skylab mission, but the space vehicle experienced problems with its power supply during the most probable time for observing Jupiter. The normal orientation for the solar cell arrays, Skylab's power generating system, was toward the Sun. Reorientation of the solar observatory in order to view Jupiter would have required a relatively complex maneuver which could not be accommodated in the minimal power situation. Thus, it became obvious to Ms. Leventhal, a working member of

Jeanne L. Leventhal proposed examining Jupiter with Skylab's solar X-ray telescope.

the American Science Engineering, Inc., X-ray telescope support team at the JSC Mission Control Center at the time, that the Jupiter observation would not be performed. She therefore proposed an alternative target, the Cygnus Loop or Veil Nebula, which required a smaller spacecraft maneuver angle for observation.

The Veil Nebula had been identified as a source of X-ray emission in 1968. Improved instruments launched in 1971 showed that the X-rays are primarily produced in the outer edges of the filamentary structure of the nebula. In 1973, an X-ray "hot spot" was observed near the center of the Veil Nebula that apparently possessed the size, luminosity, and temperature characteristics of a neutron star. Confirmation of this "point" source of X-rays would add support to the theory of supernovas.

Ms. Leventhal then proposed using Skylab's X-ray telescope to further define the X-ray source near the center of the Veil Nebula. The observation was planned for the third Skylab mission. Concurrent with preparation for the Veil Nebula observation, data from the second Skylab visit were being analyzed. Close examination of the returned film from the solar observatory revealed that the sensitivity of the solar X-ray telescope, in combination with Skylab pointing uncertainty, had prevented the detection of an X-ray target within the Scorpius constellation (the brightest stellar X-ray source in the sky). This failure suggested that attempts to detect the Veil Nebula would be similarly unsuccessful, so the Skylab experiment was terminated in order to utilize the solar X-ray telescope for the higher priority observations of the Sun.

9

Celestial Objects in Space

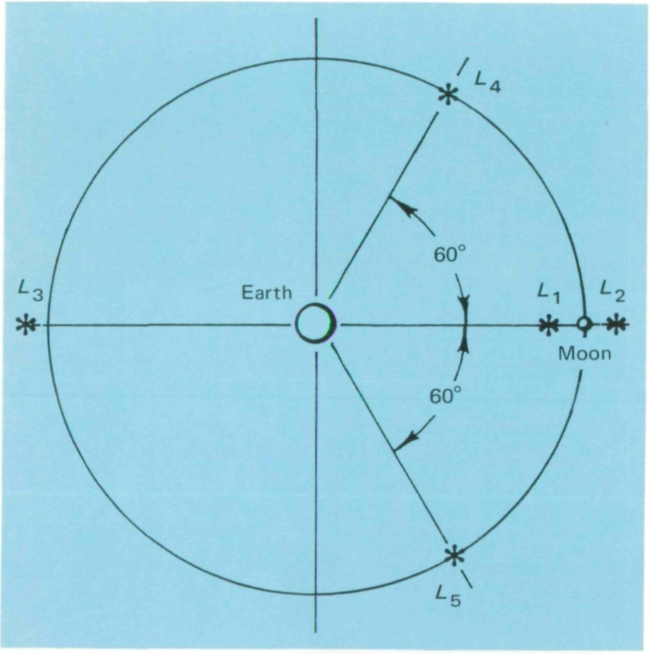
In the 18th century, Joseph Lagrange, the French astronomer, theorized that in a three-body system of celestial objects there exist points at which all gravitational forces on the third body cancel out. These Lagrangian or libration points, then, offer locations in which interplanetary matter might be found.

Two Skylab student investigators were interested in exploring the possibilities of observing such locations. One student wanted to search for the existence of matter which might accumulate in the stable Lagrangian points of the Earth-Moon system. Another sought to verify or disprove the theory that there is a planetary body orbiting the Sun closer than the planet Mercury.

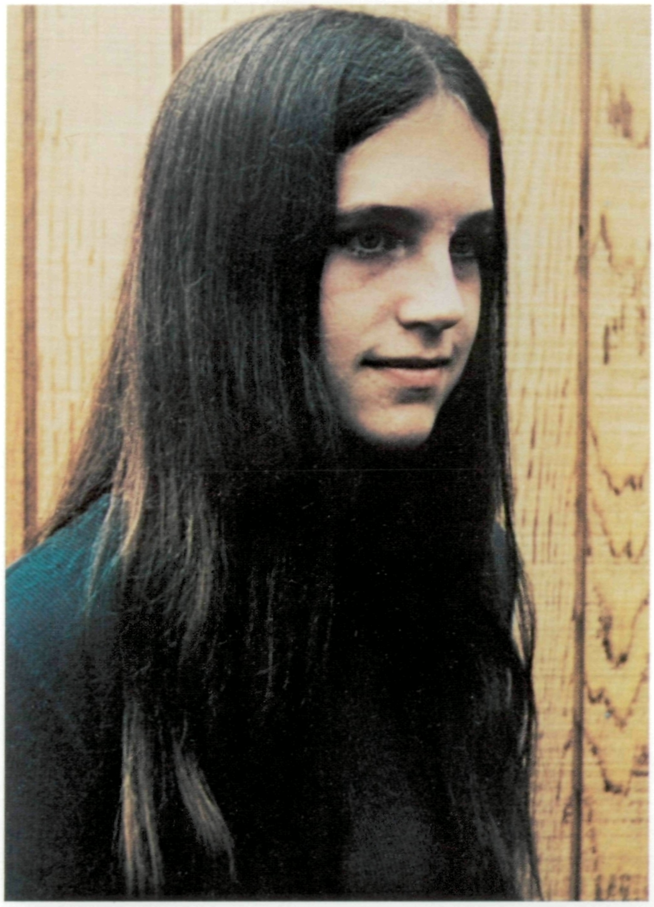
Lunar Libration Clouds

Lagrange had shown that small particles could be placed at five points where gravitational and centrifugal forces acting on the particles would balance almost exactly in the Earth-Moon system. While forces at three of these points are not stable, balanced forces acting at the other two points could trap any small particles. An accumulation of these small particles in these regions is called a "libration cloud."

Alison Hopfield of Princeton Day School, Princeton, N.J., proposed an observation of the region of Lagrange points L_4 and L_5 of the Earth-Moon system by photographing them with the aid of Skylab solar observatory's white-light coronagraph. This instrument was designed to produce artificial eclipses of the Sun by means of circular disks centered on the instrument line of sight and blocking the bright Sun. The region thus seen by the coronagraph was the outer edges of the Sun's total atmosphere or corona. She felt that any particles in the libration points would be identi-



There are five points where gravitational forces balance each other in the Earth-Moon system.

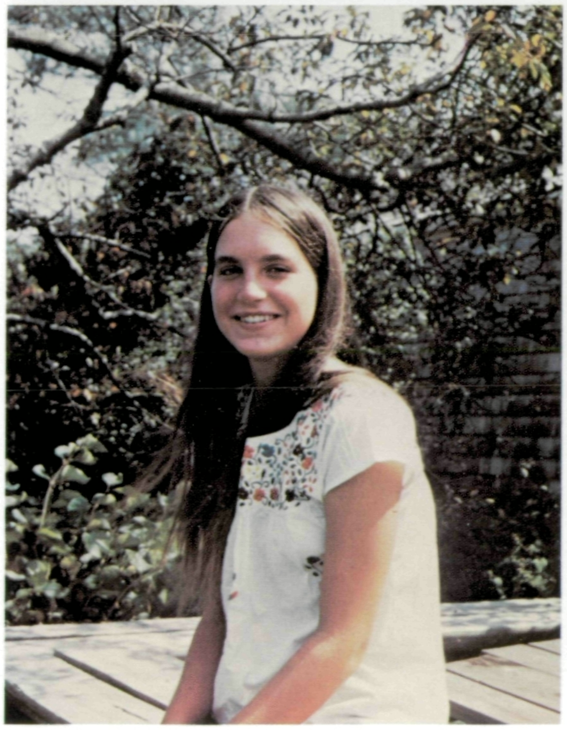


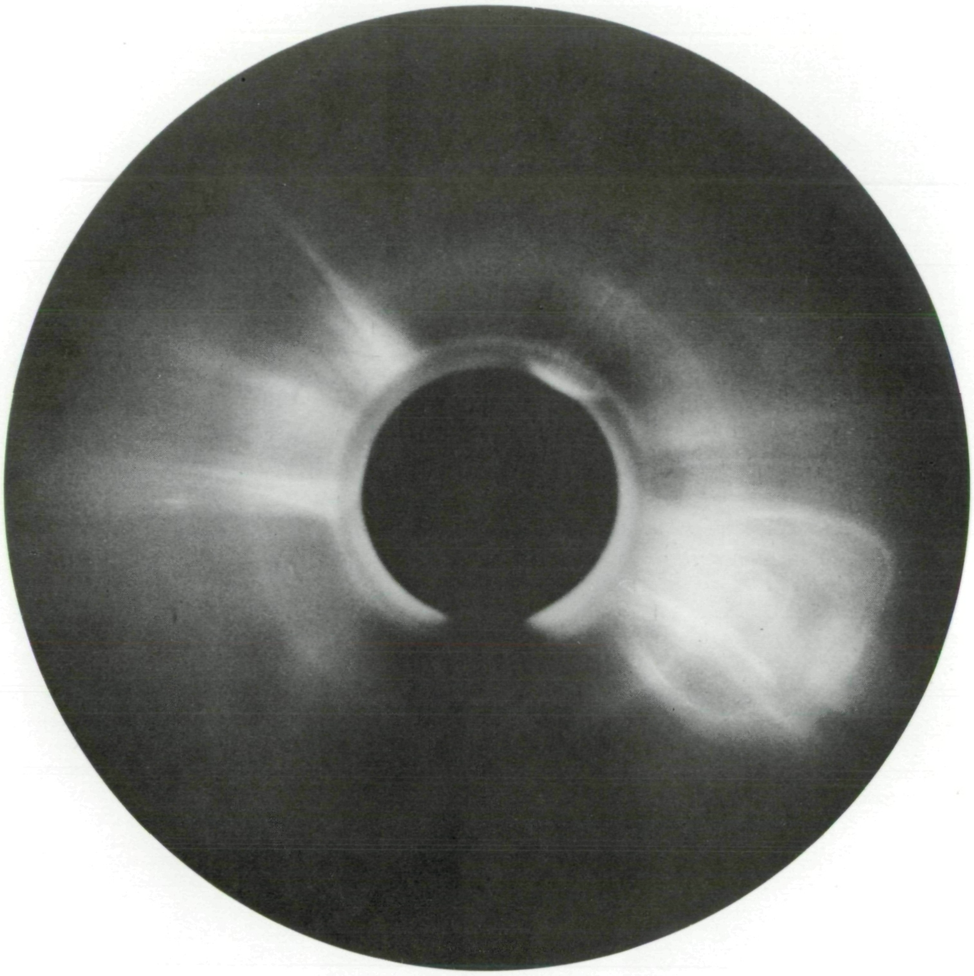
fiable only by the scattering of sunlight striking them.

The Skylab investigators with whom Ms. Hopfield was affiliated utilized the forward scattered light from material in the libration regions, since they observed the regions when they were near the Sun. At smaller scattering angles, the brightness from any small particulate clouds in these regions would be enhanced over that seen at the large angle.

The observations of the libration clouds reported by the OSO-6 satellite indicated that the clouds are of an angular size of approximately 6 degrees (compared to the 3.2-degree field of view of the Skylab instrument). The coronagraph's field of view was such that the predicted location of the libration points could not be included. The areas investigated were generally 1 to 3 degrees away from the libration points, although in at least one observation the coverage was within 1 degree of

Alison Hopfield, seen below right with science adviser Harry Coons, felt that interplanetary dust might be detected as clouds reflecting sunlight at Lagrangian points 4 and 5. She suggested that photographs from Skylab might reveal them.





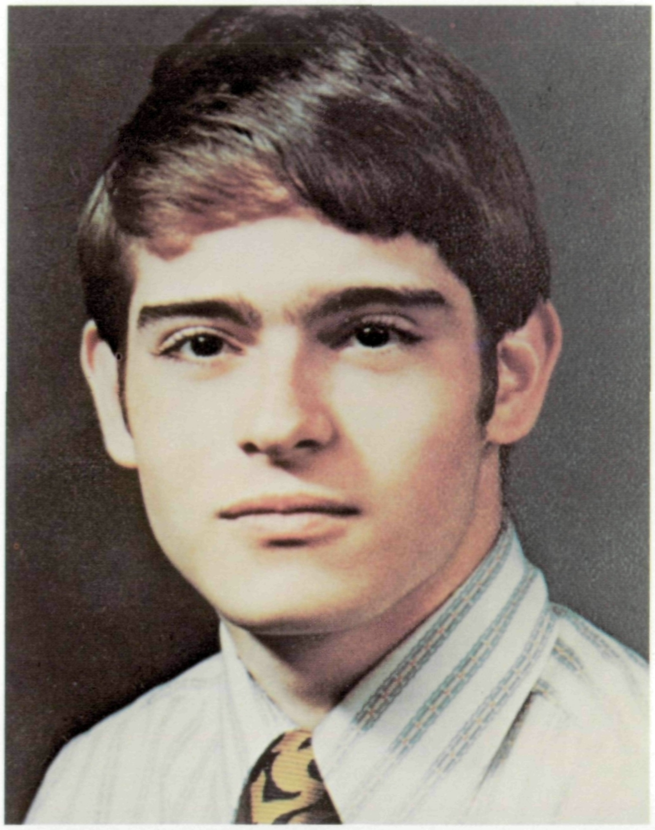
Pictures such as this one made from Skylab were analyzed by Alison Hopfield to see if libration clouds were present; none were.

the position predicted from the OSO-6 observations.

Ms. Hopfield spent the summer of 1974 at the High Altitude Observatory, in Boulder, Colo., helping analyze the coronagraph photographs. No dust clouds could be distinguished against the solar coronal background. An upper limit to the libration cloud radiance of 2.5×10^{-11} of the mean radiance of the solar disk was determined. When this upper limit was combined with past measurements of the libration region backscattered radiance, certain candidates for the nature of the interplanetary dust could be eliminated. It was calculated that the radiance contrast of a possible libration cloud composed of remaining candidate materials to the background zodiacal light would be maximized at about 30 degrees from the Sun (which was not within the field of view of the coronagraph). Thus, the observations serve as a guide for future ground or spaceborne instruments which will examine the nature of the libration regions.

Objects Within Mercury's Orbit

By the mid-19th century astronomers understood the motion of the planets of the solar system well enough that any pertubations between observed orbits and calculated ones had to be caused by some gravitational force. Such perturbations in the orbit of Mercury caused many astronomers, notably Jean Joseph Laverrier, in Paris, to assume

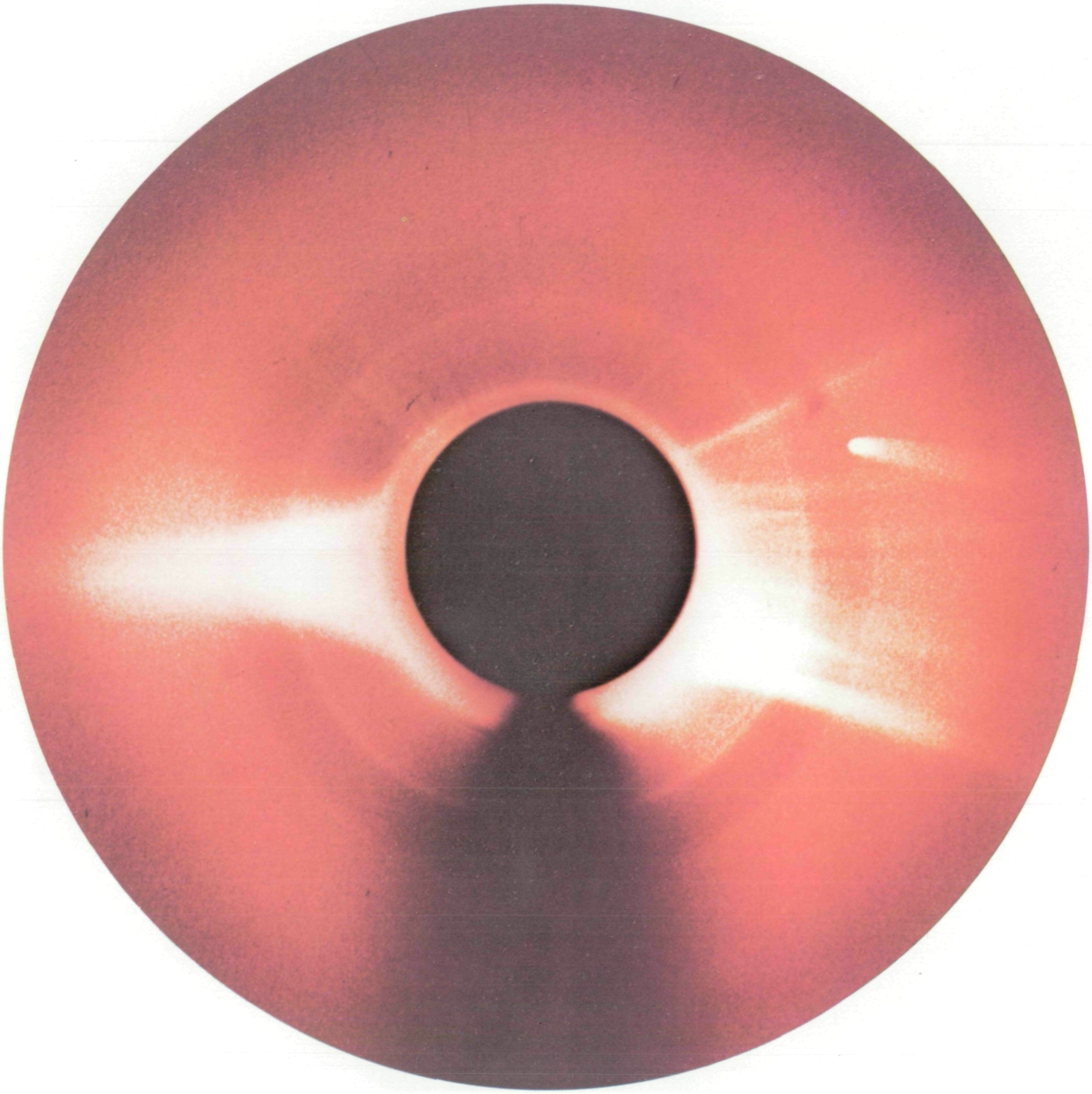


that there must be another planet (or asteroid belt) between it and the Sun. He even proposed the name "Vulcan" for the planet. For many years the search for Vulcan went on, but there was never any positive observational proof of its existence.

A Skylab experiment to look for possible bodies in orbit between Mercury and the Sun was proposed by Daniel C. Bochsler of Silverton Union High School, Silverton, Oreg. The Skylab white-light coronagraph provided the capability, and it took thousands of frames of film of the near-Sun region. Analysis of these photographs revealed no new objects other than Comet Kohoutek (1973f). It is theoretically possible that one or more extremely small objects could be orbiting very near the Sun but were too dim for the coronagraph to detect.

While Bochsler's experiment was not conclusive,

Daniel C. Bochsler felt that pictures from Skylab might answer the centuries-old question of whether there is an object in orbit between Mercury and the Sun. Below, he discusses the Skylab program with science adviser John Humphreys.



This Skylab photograph shows Comet Kohoutek visible to the right of the occulted Sun.

his results strongly suggest that Vulcan does not exist, since the proposed planet should have been easily visible several times during the Skylab mission. Indeed, the results indicate that no object larger than 104 miles in diameter is orbiting the Sun inside Mercury's orbit.

10

Particle Physics in Space

Man has been probing the nature of matter since the ancient Greeks hypothesized that everything is made of four elements: fire, air, water, and earth. The medieval alchemist believed that all kinds of matter had a common origin, that they possessed one permanent "soul" housed in a variety of temporary bodies, and that these bodies could be transmuted, i.e., converted from one element to another.

The sciences of chemistry and physics, evolving over the years, have established a remarkable similarity to these primitive concepts. Some of the earliest systematic investigations into the nature of matter were made by Robert Boyle in 1661. He proposed the idea of *elements,* which he described as being "certain primitive and simple or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the ingredients of which all those called perfectly mixed bodies are immediately compounded, and into which they are ultimately resolved."

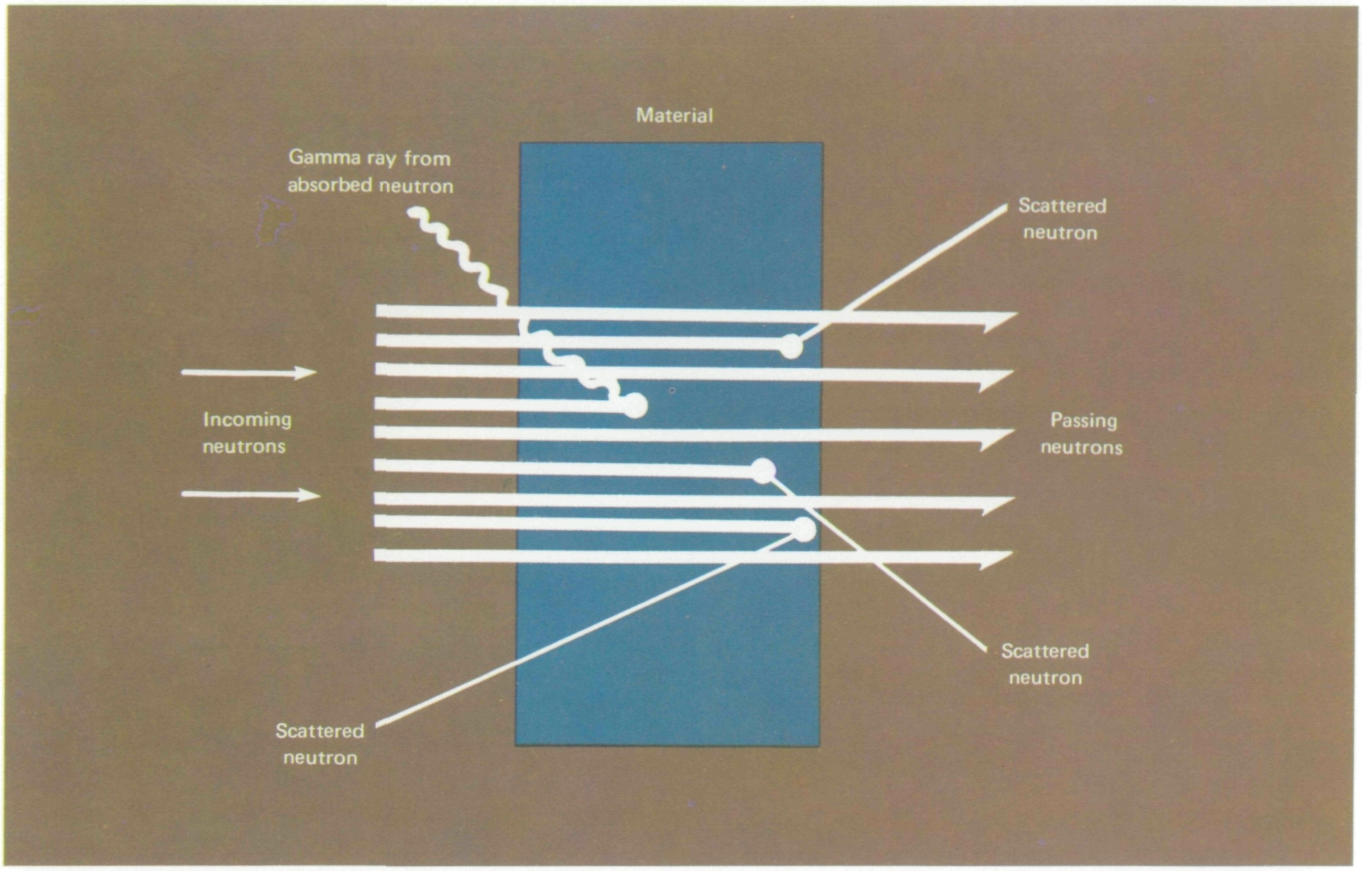
By 1789, the French chemist Lavoisier had listed 23 known elements. It was the Englishman John Dalton, however, who put the concept of an element on a firm foundation. In 1808, he theorized that elements are composed of atoms. All atoms of a given element have the same mass but differ in mass from atoms of other elements. An atom's mass, therefore, is a characteristic of an element. In 1868, Mendeleev, a Russian, prepared a chart of the then known elements, classifying them in the order of increasing atomic masses. It is now called the *periodic chart* or *table.*

Early in the 20th century, it was shown that the nucleus of an atom contains the vast majority of its mass. The nucleus consists of protons and neutrons and carries a positive electrical charge balancing the negative charge of the electrons surrounding the nucleus. Thus, atoms differ from one another in their mass according to the number of protons and neutrons in their nuclei.

Matter is fundamentally molecular rather than atomic, but the molecules are made up of atoms. It is the manner in which atoms stick together that determines the structure of the molecules. The force which binds atoms together into molecules is electrical, as is the force that holds the atom's electrons in orbit about the nucleus. The question then arises, "What is the force that holds the particles of the nucleus together?" This force has been the subject of investigation by modern physicists since Carl Anderson discovered the positron in 1932. He also revealed the existence of the meson in 1936. Since then some 200 "particles" have been found to originate in the nucleus!

Some subatomic particles exist in a free form in outer space. Among these are electrons, protons, neutrons, alphas, and higher mass particles resulting from the processes that take place in the Sun and stars. Some subatomic particles result from natural radioactivity when atoms with relatively unstable nuclei spontaneously radiate energy or matter.

One of the more subtle of the nuclear particles, and one of the more difficult to detect, is the neutron. Space radiation in the form of galactic



A beam of neutrons is attenuated while passing through material because the particles are either scattered or absorbed.

and solar cosmic rays, X-rays, and gamma rays as well as the alpha particles, protons, and electrons in the Van Allen belts are relatively well known. However, neutron radiation is not nearly so well understood, largely due to the fact that neutrons have no electrical charge. They are classified according to their energies as cold, thermal, slow, intermediate, and fast neutrons.

Since neutrons have no charge, they do not interact with atomic electrons. They lose no energy through ionization or atomic excitation and are able to penetrate matter much more easily than charged particles with the same energy. The detection of energetic neutrons is quite difficult because of the small likelihood of their interaction with most all substances except those rich in hydrogen. As a result, most neutron detection methods rely on detecting a "secondary" effect caused by the passage of a neutron–as in the recoil of protons from hydrogen nuclei in emulsions, induced fission, or induced radioactivity in foils. The effective target area presented by a nucleus to an incident neutron, expressing the probability that an interaction of a given kind will take place, is known as the *neutron cross section* of the material.

Neutron Analysis

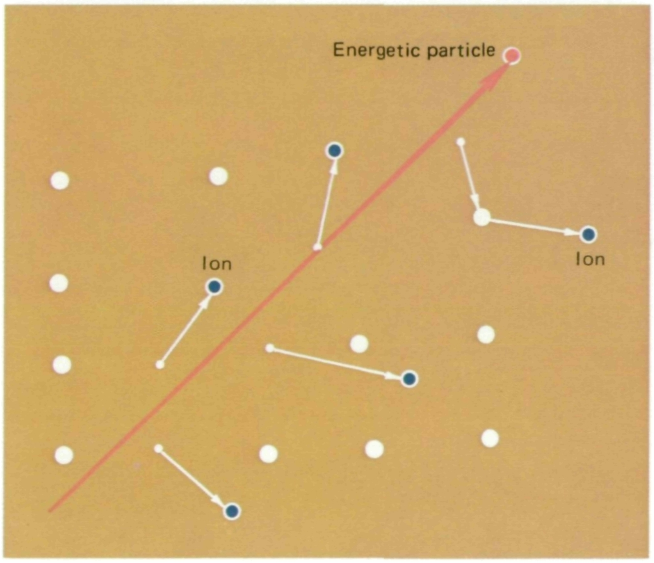
The rate of neutron flow is commonly referred to as a "flux." The measurement of neutron fluxes in Skylab was the subject of a proposal by Terry Quist of Thomas Jefferson High School, San Antonio, Tex. These measurements were considered important not only by NASA but also by

Terry Quist's experiment aboard Skylab consisted of measuring neutron fluxes. He is shown, top, with his science adviser Harry Coons.

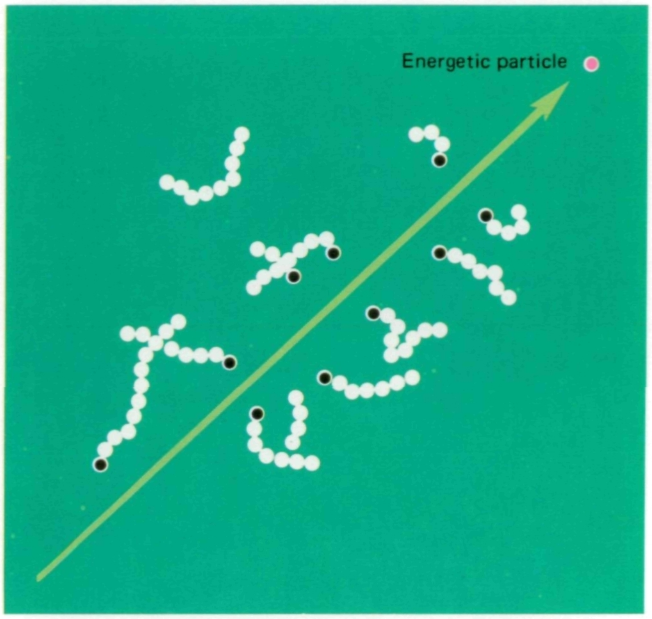
the scientific community for four reasons. High-energy neutrons can be harmful to human tissue if they are present in significant quantities. Fluxes of neutrons can damage film and other sensitive experimental equipment in a manner similar to that produced by X-rays or other radiations. Furthermore, neutron fluxes can be used as a calibration source for other space-oriented particle physics experiments. Finally, neutron fluxes can affect sensitive X-ray and gamma-ray astronomy observations.

Quist had long been interested in radiation physics, and he had prepared several science fair exhibits on the subject over a 5-year period. Drawing upon his experience and knowledge of the literature, he proposed an experiment for the Skylab student program. While he had been able to find a reasonable amount of material in the literature regarding proton and cosmic ray fluxes in space, he could find little on neutron flux.

Thus, he proposed the measurement of neutron fluxes using a "solid-state track recorder." This technique utilizes a foil of metal that has a relatively large neutron cross section and is capable of nuclear fission or induced radioactivity when impacted by a neutron. When such a particle strikes the nucleus of an atom in a metallic foil or detector, fission fragments are ejected as secondary emission or induced radioactivity occurs. A second foil or film, in contact with the detector, made of a dielectric material such as muscovite mica or polycarbonate materials like lexan or cellulose triacetate, is then struck by these fission fragments or decay particles. These projectiles either disrupt the polymer chains in plastics or disturb the crystal lattice of mica in a way that the submicroscopic paths or tracks so produced can be chemically etched. Etching makes the paths visible under a microscope, so they can be counted. Calibration of such a detection scheme is carried out using a known neutron flux from a nuclear reactor or particle accelerator.



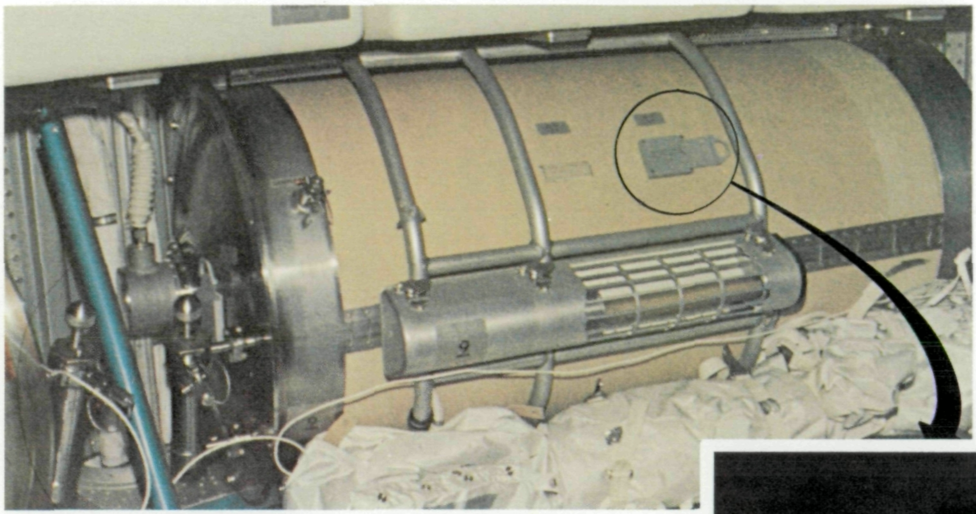
A highly energetic particle passing through a crystalline solid such as mica knocks electrons off atoms in its path and thus ionizes them. The path along which the particle passed is made visible by etching the material.

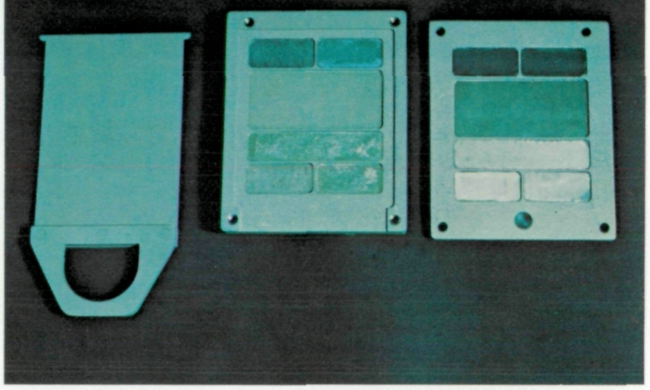


When an energetic particle passes through an organic polymer such as cellulose triacetate, it excites and ionizes molecules of the material. Etching the material makes the path of the passing particle apparent.

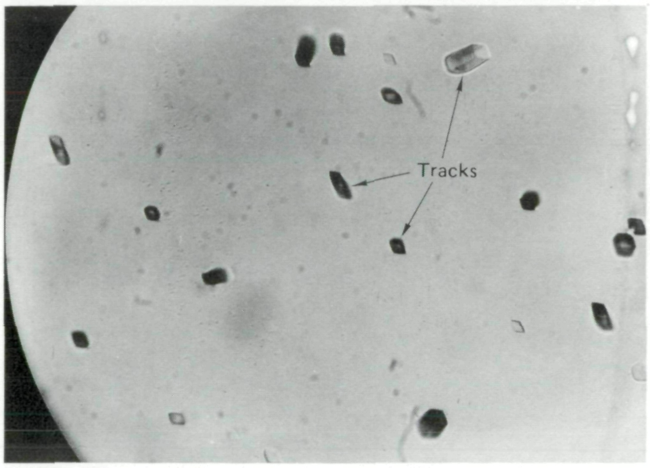
Quist's objectives were to measure the neutron fluxes present in Skylab and, with the assistance of NASA and other physicists, to attempt determination of their origin as well as their energy range or spectrum. Quist's plan called for 10 identical detectors containing boron, bismuth, thorium, and uranium foils, with cellulose triacetate and muscovite mica as recording media, housed in an aluminum container. This unit enabled detection of thermal (slow), intermediate, and fast neutrons.

When the Skylab was in orbit, these detectors were deployed at various points throughout the space station by its first crew. Each was activated in orbit by removal of an aluminum shield between the metallic foil and the dielectric and deactivated for return to Earth by reinserting the shield. Four of the detectors were returned by the crew of the first mission and delivered to Quist. Under the supervision and assistance of Donald Burnett of the California Institute of Technology, Quist etched each of the 24 dielectric films and counted the tracks. Preliminary analysis indicated that the neutron flux was higher than had been expected.





One of the Quist's detectors was attached to a water tank in the Skylab workshop. It consisted of metallic foils, cellulose triacetate and mica sheets, and a protective cover.



Typical neutron tracks found in a sample of muscovite mica after being etched on return to Earth from Skylab.

As a result, a request was initiated to refurbish one of the four returned detectors for launch and deployment by the third crew.

The seven detectors on board (six remaining from the first visit and one carried up by the third crew) were returned to Earth. Thus, four detectors had been exposed to the Skylab environment for 24 days, six for 251 days, and one for 81 days.

After very careful analysis of the data obtained, it was concluded that the track-density count was much higher than could possibly be expected from the identified neutron sources, i.e., the Sun, Earth's neutron albedo (escaped secondary atmospheric neutrons), and cosmic ray interactions. The high count was attributed to the impact on the materials of the space station by charged particles (mostly protons) trapped in the Van Allen belts. These, in turn, produced secondary neutrons. This is the best explanation Quist and Dr. Burnett can provide to explain their results. Their work has stimulated interest in further studies of neutron phenomena in space.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11

Observing Earth From Space

Observations of certain physical characteristics of Earth and its atmosphere were the objectives of two of the Skylab student investigators. One devised a method of predicting volcanic activity from space, while the other developed a technique for measuring air pollution and its effects.

Remote sensing of Earth's characteristics, whether by electronic scanners or photography, is based on the energy radiated and reflected by it. Every object radiates and absorbs a characteristic spectrum of energy typical of the object's composition and temperature. During daylight hours, the solar energy absorbed and reradiated from the surface masks the thermal energy generated by and emitted from Earth itself.

Skylab was equipped with sensors capable of measuring the energy, both emitted and reflected, from a relatively small area of Earth's surface. The spectral bands for which these sensors could detect this energy lay in the radar, infrared, visible, and ultraviolet regions.

Infrared energy (the region of primary interest) is electromagnetic radiation of wavelengths longer than visible light, but shorter than radar wavelengths. The measurement of infrared energy radiated and reflected from crop lands, forests, and oceans is very useful in assessing the condition of vegetation, ocean temperatures, and other characteristics of Earth. It is possible to determine the temperature of a body from an analysis of the thermal infrared energy that it radiates in the band of wavelengths from 10.2 to 12.5 micrometers.

Volcanic Study

Since the 16th century, volcanic eruptions have caused over 200 000 known deaths and destroyed much valuable vegetation. One reason for this catastrophic loss of life is that volcanic activity is not predictable. As a possible method of predicting when volcanic eruptions might occur, Troy A. Crites of Kent Junior High School, Kent, Wash.,

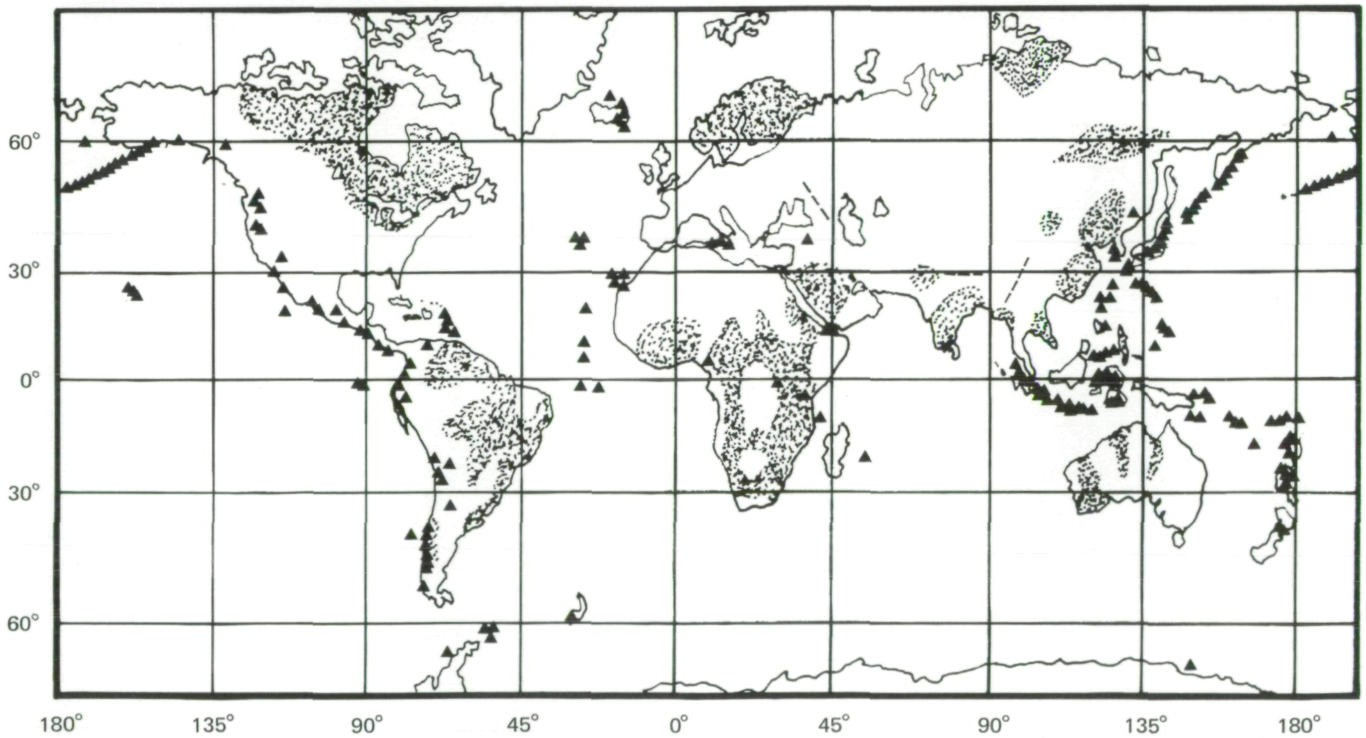
Mount Rainier, in Washington, is a dormant volcano that helped spark the interest of Troy Crites in studying such geographical features of Earth from Skylab. (Courtesy Dr. C. H. Murrish)

Troy Crites proposed monitoring volcanoes by measuring their infrared energy as Skylab orbited over them. He is shown, above, at the Marshall Space Flight Center greeting Astronauts Russell Schweickart and Owen Garriott; Leland Belew, Manager of Marshall Space Flight Center's Skylab Program; and David Newby, Director of Administration and Technical Services.

proposed the use of infrared sensors on Skylab to detect changes in the heat emitted from known volcanoes.

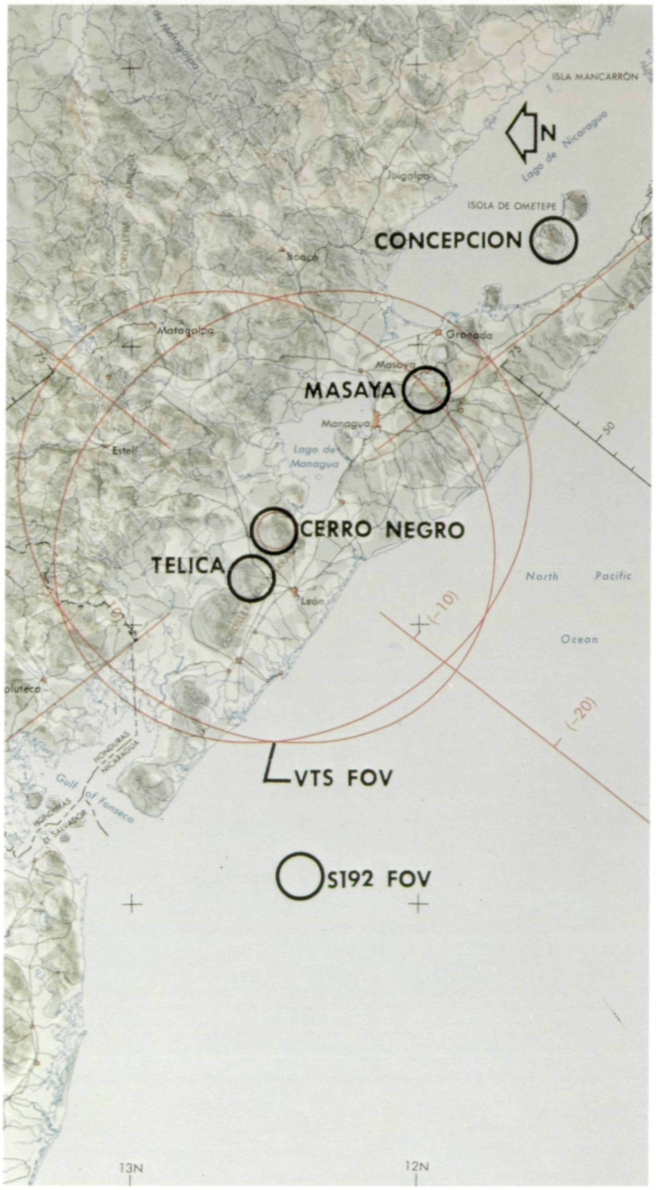
Some progress has been made in predicting impending volcanic activity. Warnings are sometimes provided by the melting of ice caps, the disappearance of crater lakes, the drying up of springs and wells, the death of surrounding vegetation, or an unexplained evacuation of wildlife. Other attempts to predict volcanic eruptions have generally relied upon direct measurements. Temperatures have been measured at or near the surface of volcanic mountains, and the shape of volcano slopes has been measured in the hope that detection of an increase in temperature or an actual swelling of the mountain caused by an upward movement of lava would indicate an impending eruption. An increase in frequency and strength of Earth tremors detected by seismographs can also indicate that the lava under volcanoes is welling up and that an eruption may occur. Recently, data from tiltmeters, seismographs, and other instruments have been collected by satellites from sensors located on remote volcanoes and transmitted to laboratories where scientists can study them.

Crites' experiment was intended to determine whether or not infrared sensors in a satellite would be able to detect the heat flow from individual volcanoes. If so, heat radiating from active volcanoes could be periodically measured by the orbiting sensors and their normal heat-emission rate established. An observed increase in the rate might then be used to predict an eruption. He proposed to use data from Skylab instruments that recorded thermal radiation in the infrared region. These instruments and cameras were part of Skylab's Earth observation experiments. Data were obtained from Mount Etna and a volcanic region in Nicaragua during the mission. Information in the form of computer printouts was obtained at 6.2, 10.2, 12.5, and 15.5-micrometer wavelengths.



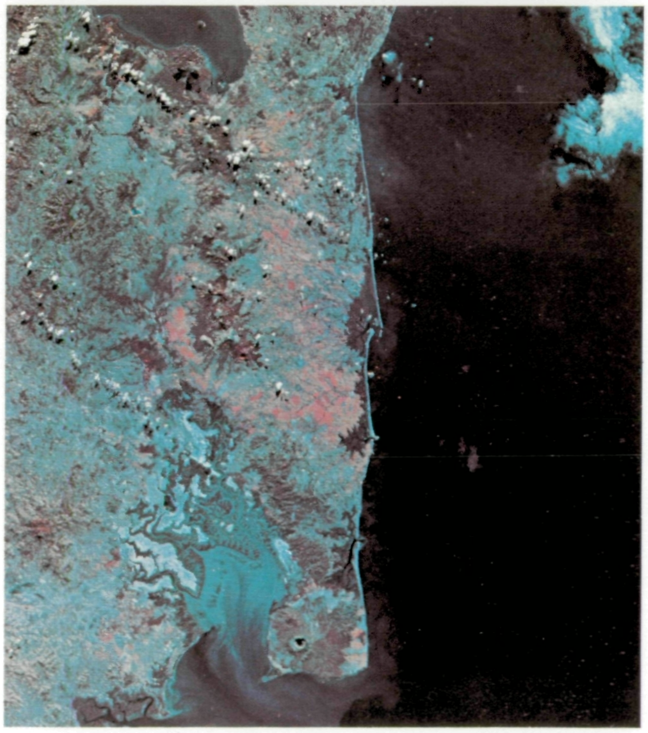
Volcanoes active, dormant, and extinct are scattered throughout the world, and the Pacific Ocean is sometimes said to have a "rim of fire." (*Introduction to Geophysics,* **by B. F. Howell. Used by permission of McGraw-Hill Book Co.)**

As of this printing, Crites had not completed his analysis of the voluminous data from Skylab, so definite conclusions could not be reached. Based on the observations of scientists who have performed ground-based thermal infrared surveys of volcanoes, however, it appears that Crites' experiment could establish the feasibility of monitoring thermal activities of volcanoes from space. It is also believed that such monitoring from space can lead to more accurate predictions of volcanic eruptions.



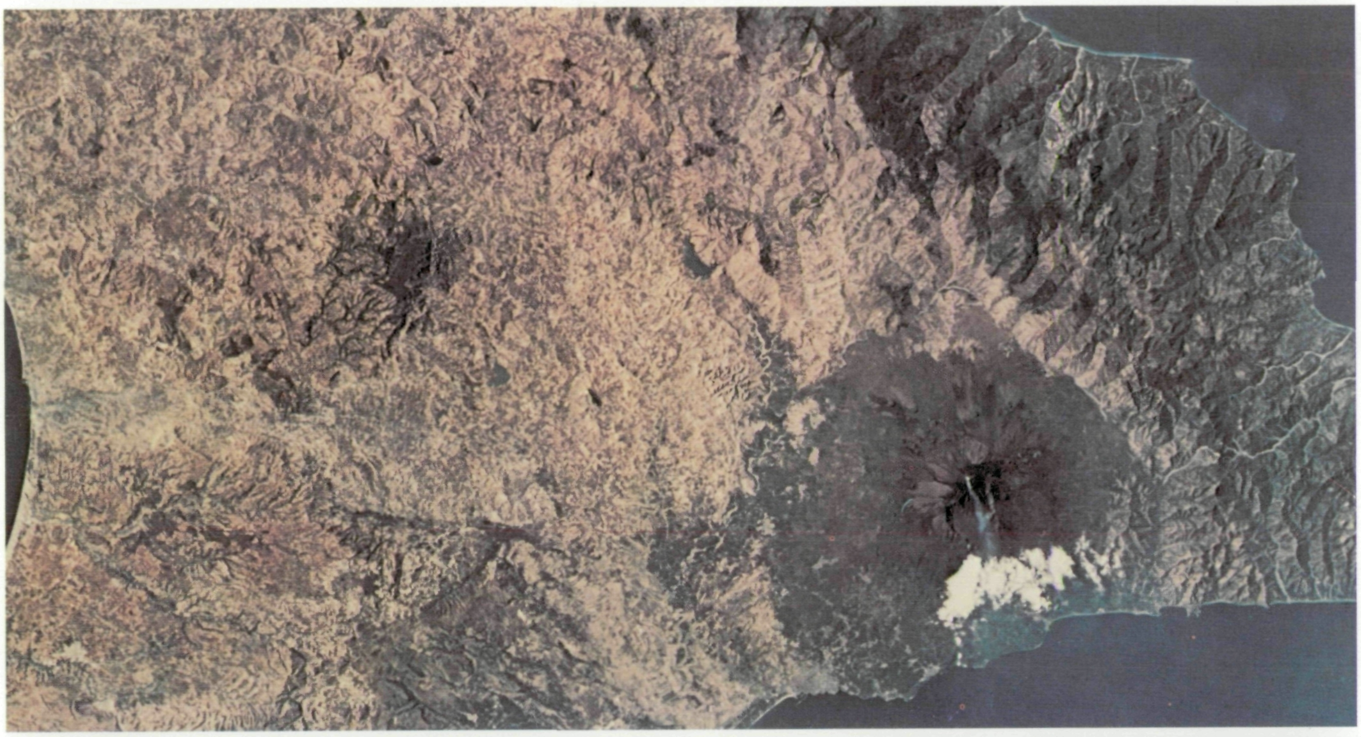
Crites proposed measuring the heat energy radiated from Telica and Cerro Negro, two volcanoes in Nicaragua.

Volcanoes Telica and Cerro Negro were photographed in true color from Skylab.

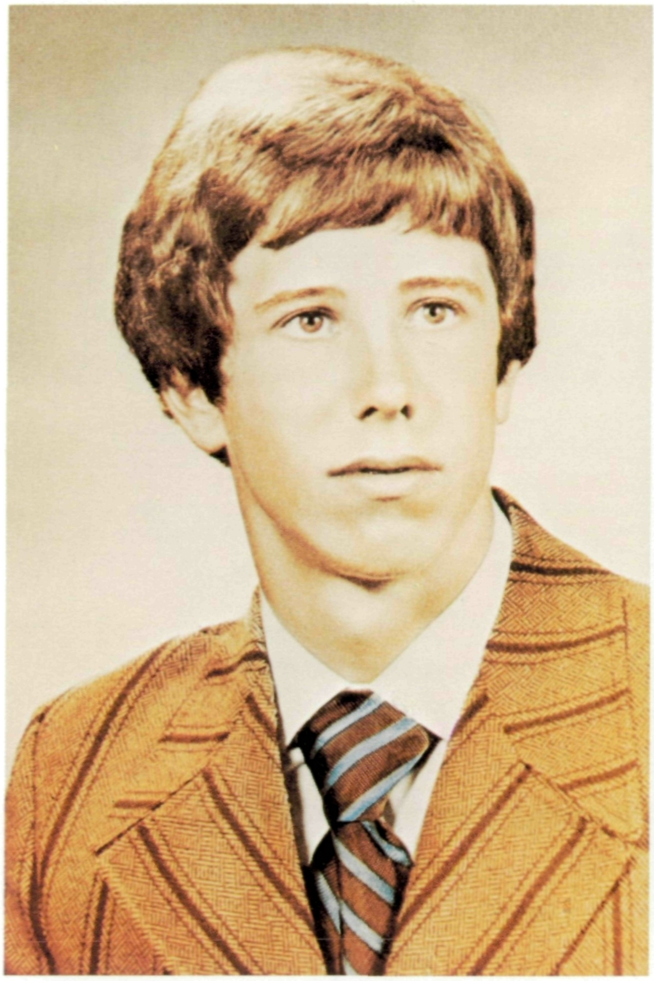


The same two volcanoes were photographed in color infrared from the space station.

Mount Etna, on the island of Sicily, was photographed in true color from Skylab just 3 months before an eruption. It is in the lower right corner of the picture.



A fuming Mount Etna was also photographed by the crew of the second Skylab mission in color infrared.



Joe B. Zmolek, who proposed a Skylab experiment for measuring pollution in the atmosphere, went to Notre Dame University, where he majored in premedicine. Above right, he is greeted by Astronauts Russell Schweickart and Owen Garriott; Leland Belew; and David Newby at the Marshall Space Flight Center.

Atmospheric Attenuation of Energy

Atmospheric pollution has become one of the major problems for people in industrialized countries. Little fundamental information is available from which to judge the long-range effects of such pollution. Joe B. Zmolek of Lourdes High School, Oshkosh, Wis., proposed investigating the feasibility of measuring the amount of energy absorbed and dispersed by the atmosphere. Such measurements would establish a data base to support future investigations of atmospheric changes, particularly those brought about by man's pollution.

Several of Skylab's Earth observation instruments were used in conjunction with ground-based instruments to measure the attenuation, or reduction, of solar-energy radiation in the visible and near-infrared regions of the spectrum as the energy passed through the atmosphere. The degree of attenuation was to be determined by comparing the energy received at Earth's surface with the energy entering Earth's atmosphere. Attenuation of energy reflected through the atmosphere from Earth was to be determined by comparing energy measurements made just above its surface with simultaneous measurements made from Skylab.

Data were to be collected over sparsely and densely populated regions to permit evaluation of both natural and man-induced atmospheric conditions.

Ground data were obtained by NASA personnel at selected sites in the United States, using a spectral pyranometer. This is an instrument that measures radiant energy at selected wavelengths. The pyranometer was first pointed upward to measure the energy coming from the Sun to provide a comparison with previously recorded data. It was then inverted to measure the radiation reflected from Earth at the same time that Skylab was passing overhead and also measuring radiation from the site.

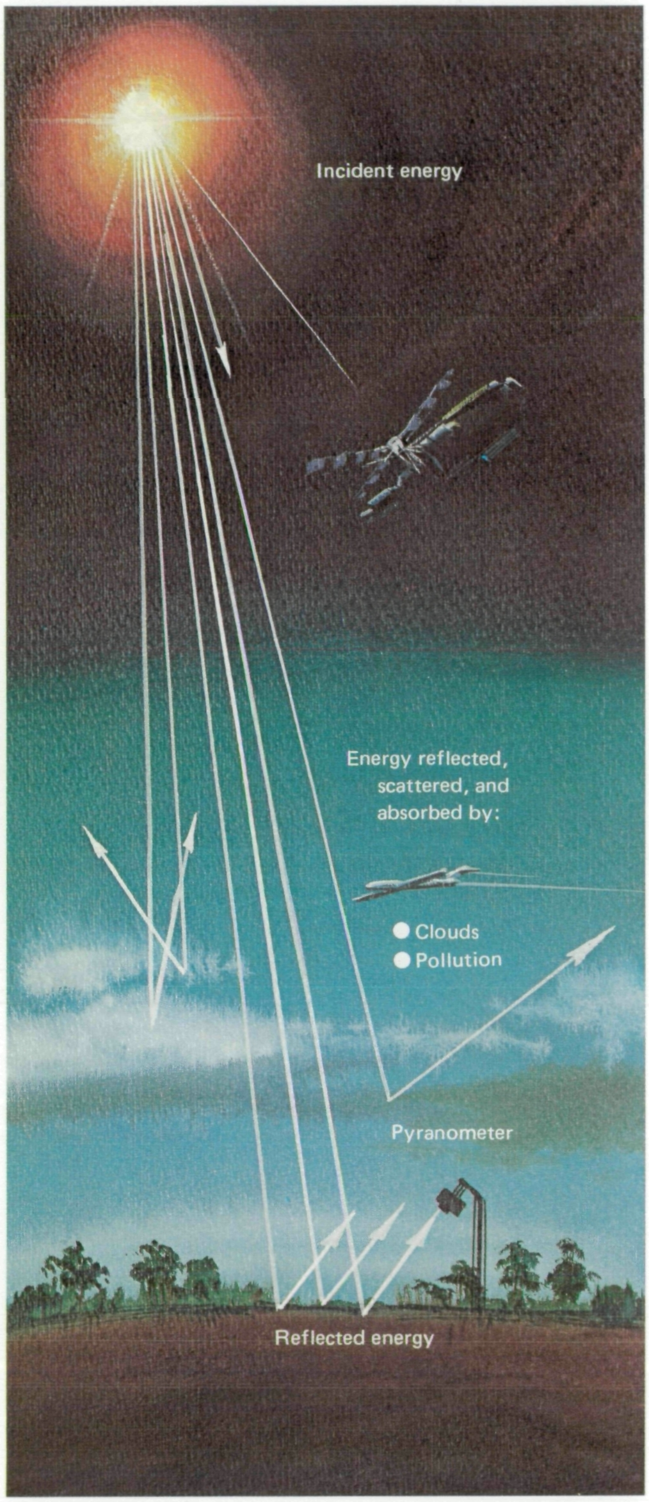
Skylab data were obtained by six cameras using visible light and infrared film and filter combinations and by electronic instruments that measured energy levels in spectral bands from 0.4 to 2.4 micrometers. The cameras took pictures simultaneously, each covering a different portion of the visible and infrared spectra.

On June 5, 1973 (during the first manned period), Zmolek was in Texas at the Houston Area Test Site, one of the ground sites assigned for his experiment. He acquired the necessary ground data but, unfortunately, the clouds over the site prevented Skylab from collecting data at the same time. However, the space station made a marginal data pass over the White Sands, N. Mex., site on June 14.

During the second manned mission, an experiment was conducted over Phoenix, Ariz., on September 6. On that occasion, data were gathered not only by Skylab instruments but also by six similarly instrumented aircraft over the site. Data were acquired at test sites upwind and downwind of Phoenix, providing, in effect, information from a relatively pollution-free atmosphere as well as from a polluted atmosphere.

During the third mission, data were gathered once at Houston and twice at White Sands. However, neither ground nor aircraft data were obtained.

Zmolek's experiment produced a large volume of data that has not yet been completely analyzed. Since the study of atmospheric conditions has been a subject of intensified interest to scientists and engineers for at least the past 50 years, the experiment may give added impetus to this area of investigation. The continual measurement from a satellite of the attenuation of solar energy could



Using a pyranometer, Joe Zmolek measured the energy received from the Sun as well as that reflected by the Earth. Simultaneous measurements were made from Skylab and aircraft. Such studies could help determine the effects of atmospheric pollution on Earth's heat-energy balance.

Data for Zmolek's experiment were to have been gathered from areas near Houston, Phoenix, and White Sands, N. Mex. However, clouds often obscured the view. The second crew of Skylab managed to take this picture of Phoenix on an exceptionally clear day.

assist in the prediction of weather conditions and aid in determination of the overall effect of pollutants in the air.

Thus, the combination of instruments aboard Skylab and the scientific curiosity and imagination of two high school students produced information about one of the most awesome and potentially destructive geological features of Earth and helped open the way to measuring on a large scale the pollution of its atmosphere.

The same view of Phoenix was also made in color infrared, showing such natural features as Salt River joining Gila River just downstream from the confluence of the Gila and the Agua Fria Rivers.

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Part III

Science Demonstrations

In keeping with the charge that NASA's space activities shall contribute to the knowledge of phenomena in space, a series of science demonstrations, enhanced by Skylab's weightless environment, was scheduled to illustrate certain scientific principles. They ranged from the mere satisfaction of curiosity to providing significant scientific results.

The demonstrations utilized either onboard equipment or extremely simple implements that could be easily taken into orbit aboard the space station. Small kits were launched for the second and third visits to supply the few items not originally on board.

However, it was really the interest and ingenuity of the crew, and their desire to contribute time designated for rest and recreation that made them possible. Fifteen science demonstrations were devised for the second crew to perform. Two of these were added after the crew, at midmission, requested additional activities. Twenty-one demonstrations were provided for the third crew, but not all were performed, since the science demonstrations could be done only on a "time available" basis.

The demonstrations involved mechanics, magnetic effects, particle physics, fluid phenomena, crystal growth, and life sciences. All the demonstrations were recorded on the videotape; photographs were later made from conversion of the tapes to film. Because of this, the photographs were not always of the best quality. (For available instructional material based on these demonstrations, see p. 178.)

12

Fluid Behavior in Zero Gravity

On Earth, gravity has a strong influence on the behavior of liquids. Because of this force, a liquid settles in the bottom of its container. Another force acts upon any liquid that has surface exposed to a gas. The mutual attraction of the liquid molecules at the surface produces a tension force that causes the surface to behave as if it were covered with an elastic membrane. Gravity usually dominates the surface tension force on Earth, flattening the "membrane" so the presence of the force is not readily detected. However, in a small volume of free-falling water, surface tension can be observed to form the water into a uniform, nearly spherical shape, as it does in a raindrop.

In Skylab, the effect of gravity was negated and surface tension became the dominant force acting upon a liquid. Because of surface tension, the behavior of a liquid was considerably different in zero gravity.

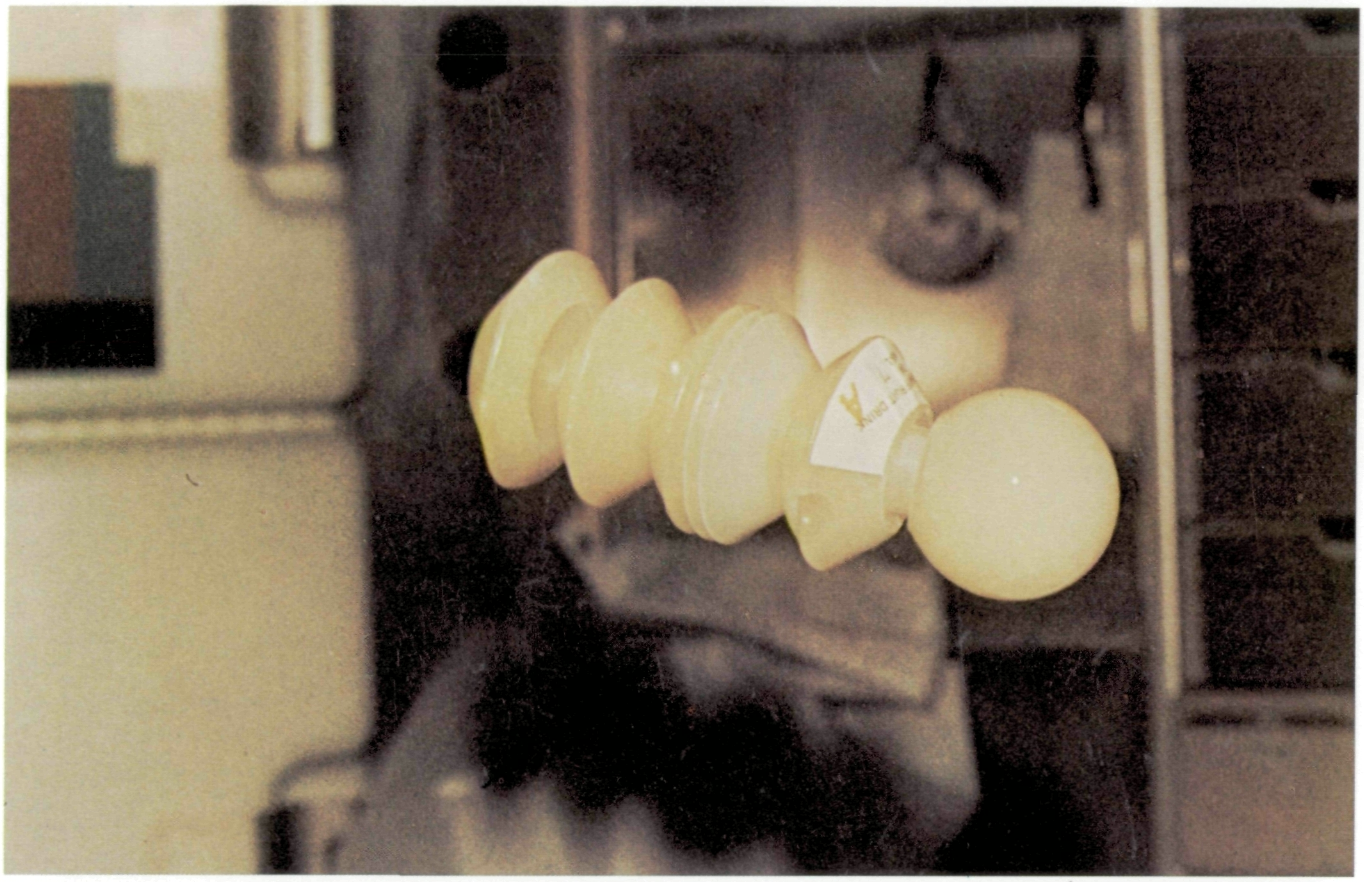
A number of fluid-mechanics experiments were performed in Skylab to demonstrate and to evaluate the behavior of liquids under conditions where surface tension forces dominated. In certain cases, phenomena were demonstrated that are not possible on Earth; in others a comparison between the phenomena in space and on Earth was possible.

A knowledge of zero-gravity fluid mechanics is essential to the design of any fluid system that operates in space, from rockets with liquid propellants to the water used in a life-support system. In the future, space may become the best place for processing of materials and pharmaceuticals, thus eliminating detrimental convection and sedimentation effects caused by gravity, and permitting containerless handling of fluids where contamination from the container occurs. In order to perform such processes, the basic fluid phenomena must be understood. Even Earth-based phenomena, such as the falling raindrop mentioned above, can be studied in a more basic form when the effect of gravity is eliminated.

Surface Shape

A number of free-floating water globules were formed as part of the Skylab fluid-mechanics experiments. An undisturbed drop of liquid assumes a spherical shape in zero gravity. The "membrane" effect of surface tension causes the liquid to be drawn into a shape that has a uniform pressure over its entire surface, i.e., a sphere.

The interaction of a free-floating drop with various solid surfaces was also demonstrated. A drop was placed on a string to prevent it from drifting out of the view of the camera. The "membrane" of surface tension must attach itself to any solid surface that the liquid contacts. Surface tension caused the drop to be strongly centered on the string. In this position, the pressures on the drop were in equilibrium. Since the "membrane" was distorted by the string, the shape of the drop was elongated in the direction of the string. As the size of the solid surface contacting the drop was increased, the distortion of the



Demonstrations of liquid behavior in zero gravity were performed by Scientist Pilot Kerwin using fluids from Skylab beverage containers.

surface was increased. While the string produced nearly imperceptible distortions, a drop on a straw was noticeably distorted.

A drop of water placed on a flat plastic surface had a hemispherical shape. In this demonstration the liquid surface was perpendicular to the solid surface at their intersection. In maneuvering the drops of water for the experiments, the astronauts found that wires or strings were the most effective instruments for applying small forces to the floating water globules. If objects with a larger surface were used, such as a straw, the drop merely stuck to the object and was difficult to detach.

The nature of the surface also influenced the shape of a drop on the surface, a fact that was demonstrated by placing water on each of three materials: plastic, metal, and paper. How readily a liquid wets a surface depends upon their relative energies. Surface energy is a quantitative measure of the energy that produces the forces of adhesion and surface tension. Metals have high surface energies in comparison to liquids, so the liquids readily spread over them. Plastics have lower surface energies than metals, so water did not wet plastic as it did metal. Some of the water was absorbed into paper, influencing wetting.

Free-floating drops of liquid were rotated to demonstrate the effect of centrifugal force on their shape. Centrifugal forces and surface tension forces balanced one another to establish the equilibrium shape. Strings were used to apply a force on the edge of a drop, causing it to rotate. Beyond a certain rotation rate, the drop assumed the shape of a peanut. As the rotation rate increased, the neck of the center of the drop became thinner. At some higher rotation rate, surface tension could no

Free-floating drops were rotated by applying a force to them with a string. Centrifugal forces within them caused a shape like a peanut. When the angular momentum reached a certain value, the "peanut" drop broke into two smaller but equal drops.

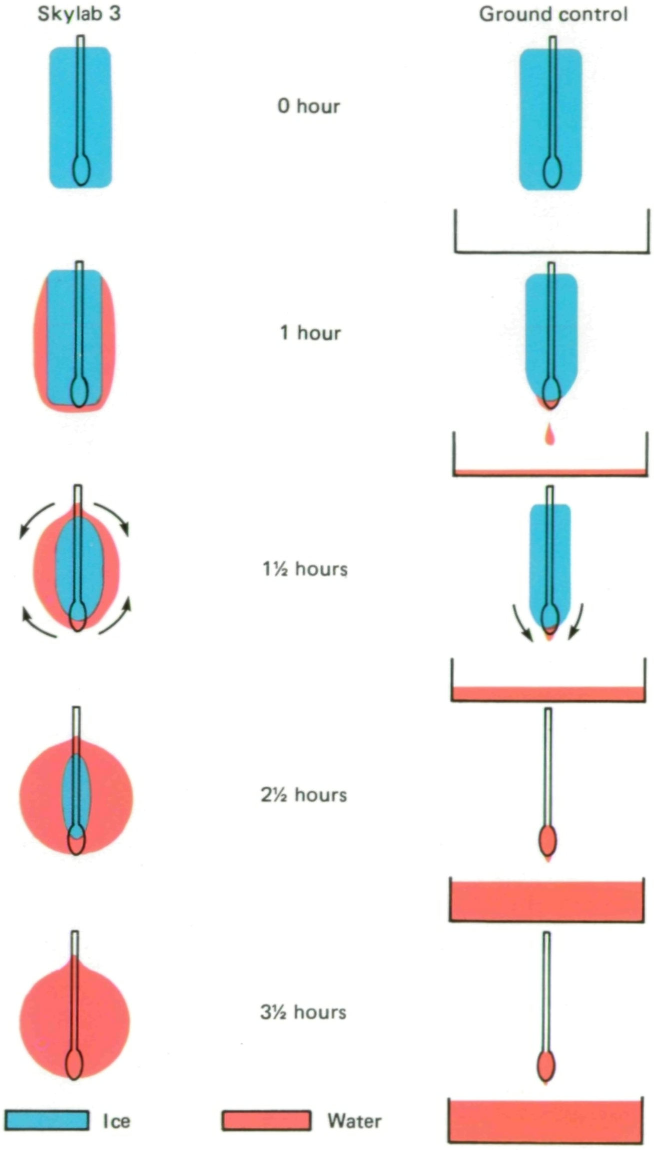
longer hold the drop together, and it separated into two drops of equal size. Raindrops are believed to break up within clouds in this manner.

Another interesting demonstration of the influence of the liquid surface in zero gravity was the melting of ordinary ice. An ice cylinder was photographed as it melted. As water formed, it collected on the ice cylinder to give the ice/water combination a more spherical shape. On Earth, gravity would drain the liquid away from the ice. The time required for the ice to melt is increased in zero gravity because the layer of liquid insulates the ice from the surrounding warm air. It took approximately 190 minutes for the ice to melt in Skylab and only 130 minutes for it to melt in a duplicate experiment on Earth. The melting of ice simulated some of the fluid aspects of processing metals in zero gravity.

Oscillation of Liquid Drops

Free-floating drops of water were caused to oscillate by stretching and releasing them. Oscillations were induced by placing the flat ends of plungers removed from syringes against opposite sides of the drop, and then rapidly pulling them away from the drop. The surface of the drop was stretched until it broke away from the plungers and the drop oscillated at a constant frequency. Surface tension pulled the distorted drop back to the spherical shape, but the inertia of the liquid mass continued the motion of the liquid beyond the equilibrium spherical shape, and the drop distorted in a direction perpendicular to the initial perturbation. Again, surface tension opposed the distortion. The shape passed through the equilibrium condition again and then distorted along the axis of the initial disturbance. Oscillation occurred at the harmonic frequency of the drop. Since water is viscous, energy was dissipated with each oscillation cycle, and the drop eventually came to rest in a spherical shape. A water drop on a flat surface was also oscillated and behaved in a similar manner.

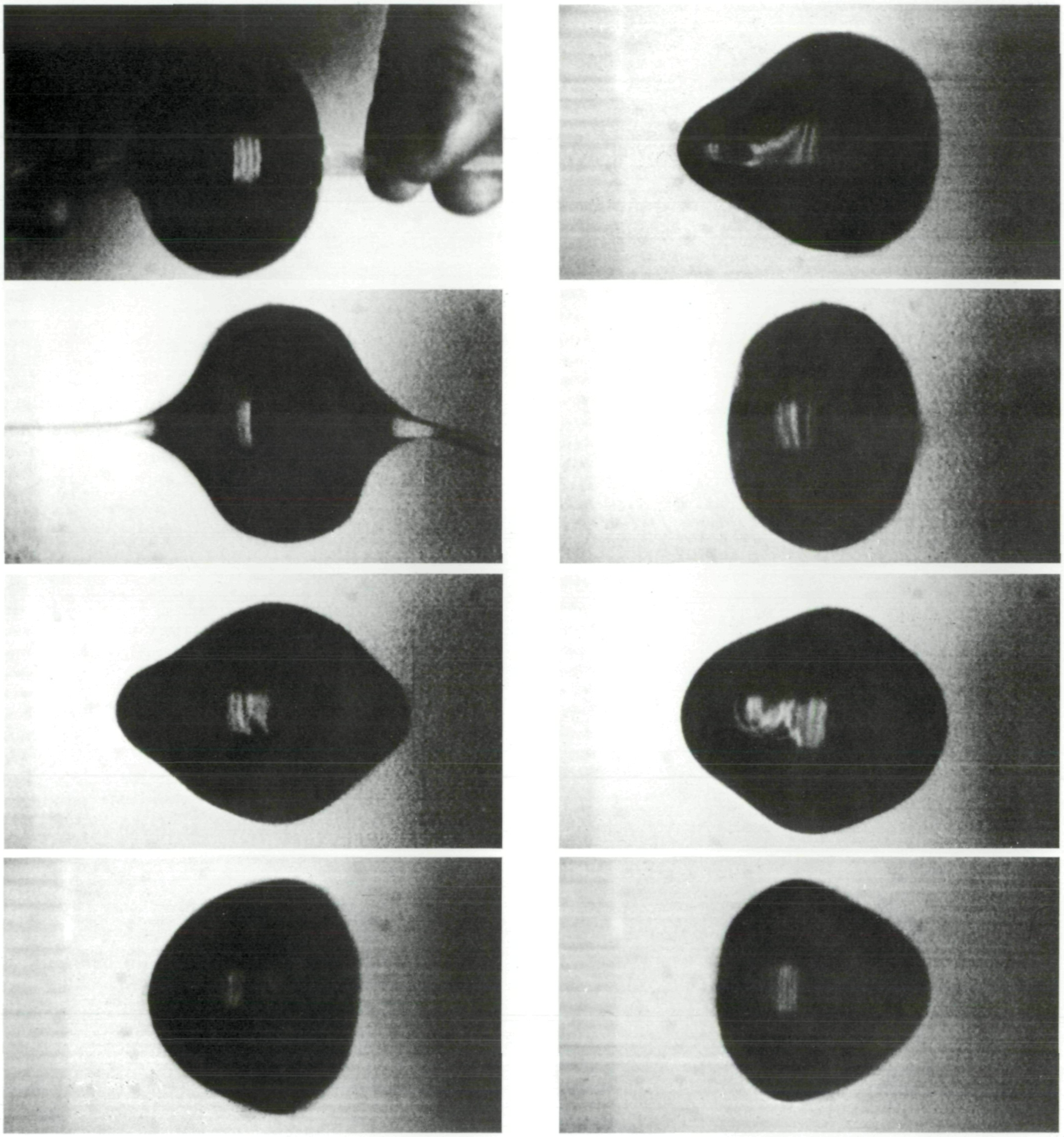
The demonstrations were significant because they were the largest drops (6 cubic inches) that have ever been observed in oscillation. Their size allowed detailed observation of the oscillations.



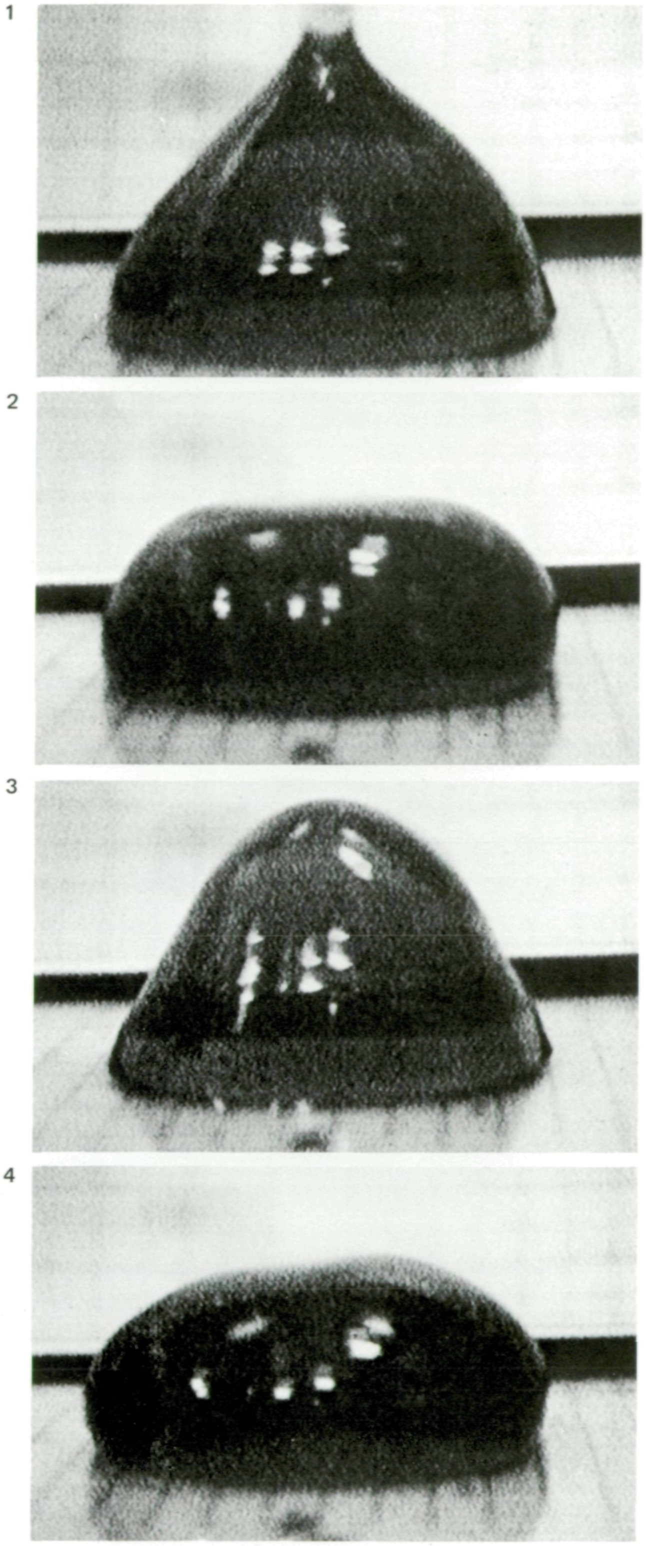
An ice cube melting in zero gravity did not behave as it did on Earth. It formed into a sphere, as shown on the left, and adhered to cotton swab which was frozen within it. The same demonstration on Earth produced different results, as shown on the right.

Coalescence

Drops of water were also impacted with one another to observe their coalescence. The sizes of the drops impacting and being impacted and their relative speed and angle of impact were varied. The initial joining of the drops was dependent upon the rate at which the air between the drops was moved out of the way. It is possible, and this was demonstrated in Skylab, for two drops to bounce off one another if a film of air remained between the drops. After the drops combined, it was also



Freely floating drops of liquid were made to oscillate by stretching them and then releasing them. Surface tension pulled the elongated shapes back into a sphere, but momentum of the fluid overcame it. Thus, the drops continued to move for almost 30 minutes before resuming a spherical shape.



Oscillations induced into a drop on a surface acted in a manner similar to those in a freely floating drop.

possible for them to separate again. If their momentum before impact was sufficiently large, surface tension could not hold the combined drop together. Coalescence occurred at relatively low velocities in the Skylab demonstrations, so that the resulting drop formed from the impacting drops remained intact. Coalescence is another phenomenon important in the formation of raindrops.

Immiscible Liquids

Two liquids that will not mix, such as oil and water, are said to be immiscible. When vigorously shaken, the two liquids can become intermingled, but one does not dissolve in the other. Eventually, the force of gravity will cause the heavier liquid to separate from the lighter, producing two distinct layers. Experiments were made in Skylab to determine what happens when immiscible liquids are mixed in zero gravity.

Oil and water were placed in transparent plastic vials. By swinging the vials on the end of a string, the two liquids were separated by centrifugal force. The vials were then shaken to disperse the liquids and observed to see whether separation took place. While a gravity force was not present to separate the liquids, some separation by coalescence was possible. Small drops of the same liquid joined as they came into contact, eventually into significant amounts.

On Earth, a dispersion of the two liquids separated completely in 10 seconds. In Skylab, the dispersions were observed for a period of 10 hours, during which time only a very small amount of coalescence occurred. Low gravity thus provided an opportunity to form a dispersion of immiscible liquids which could be solidified in that form. The demonstration showed that composite materials with unique properties could be manufactured by such a process.

Liquid Films

Because of surface tension, a liquid can be stretched into a very thin film. After it is formed, the liquid continues to drain from it, because of surface tension and gravity, until the film becomes so thin that it ruptures. Certain additives to water, such as soap, strengthen the surface of a film, and fairly large films can be formed.

Experiments were performed aboard Skylab to determine how the behavior of films would change

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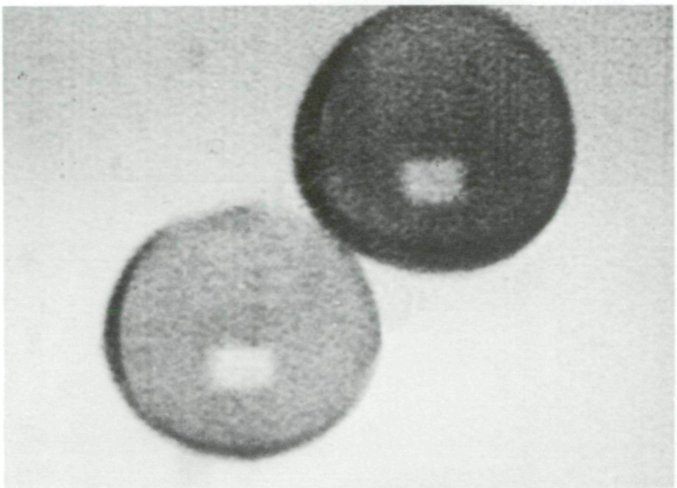

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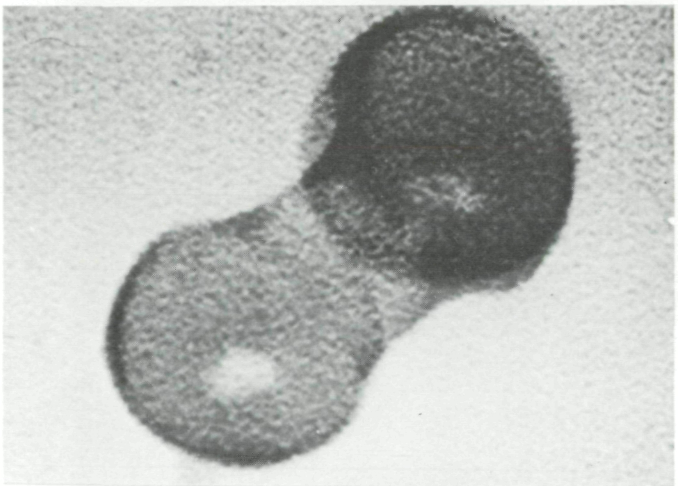

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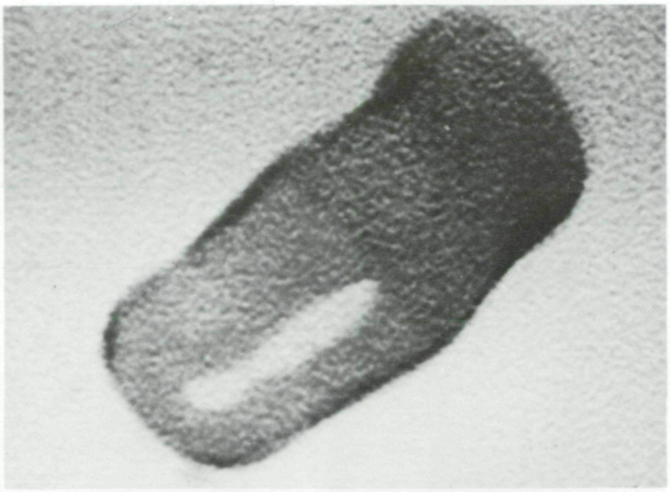

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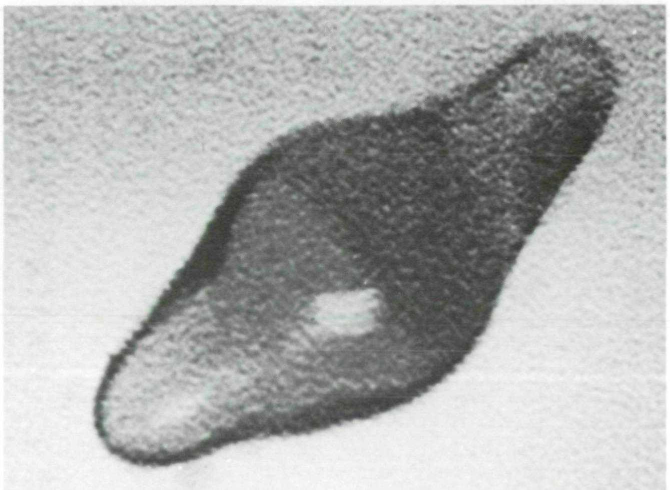
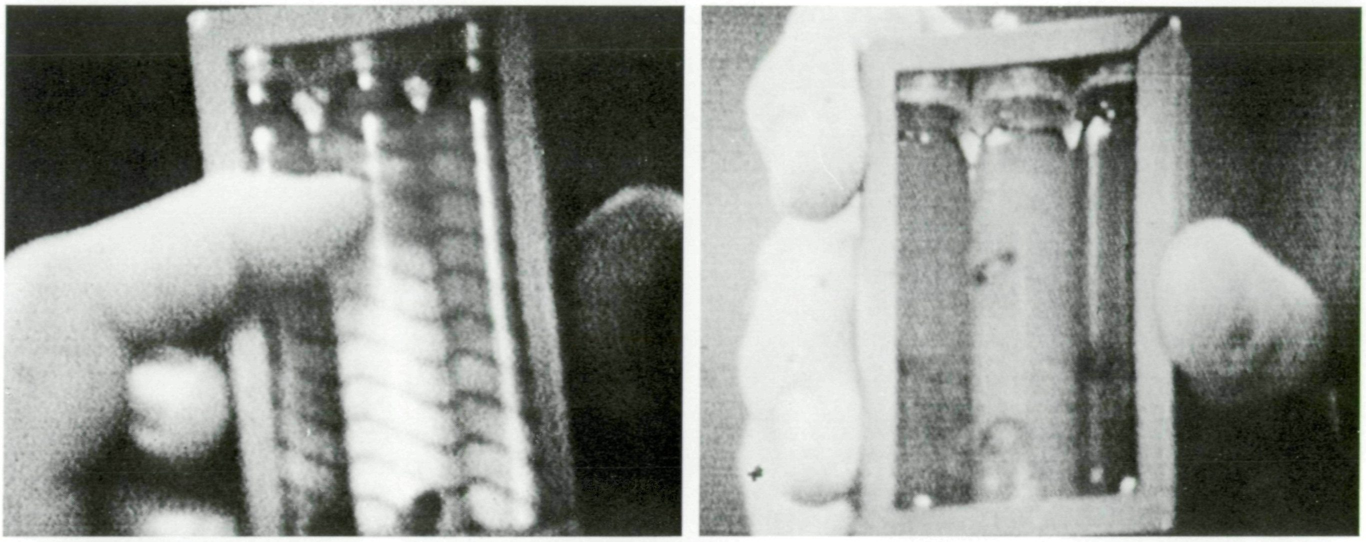


Demonstrations were also made of different sizes of water drops impacting each other to coalesce or form a larger drop. Films of such experiments proved to be of interest to physicists studying the formation of raindrops in clouds.



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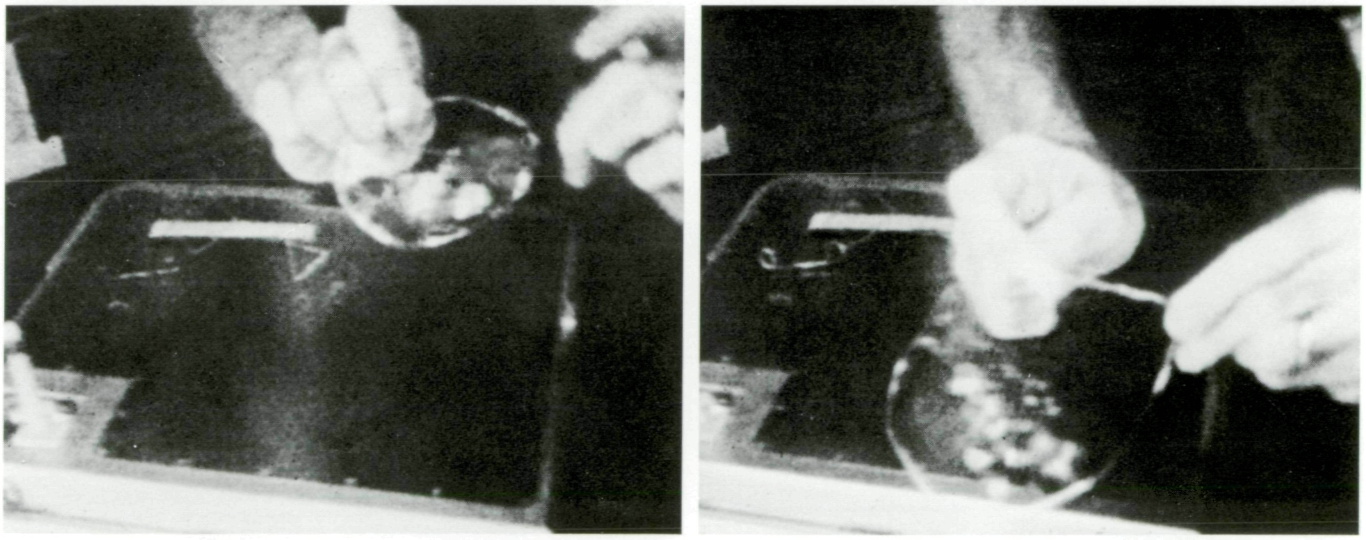
Science demonstrations by the Skylab crews also included those concerning liquids that are not mixable. Three glass vials filled with varying mixtures of oil and water (1) were shaken vigorously (2). On Earth, such an experiment took only 10 seconds for the mixtures to separate. In Skylab, after 10 hours, very little separation had taken place!



Experiments with extremely thin and very large surface films of liquids were also made by the Skylab astronauts to demonstrate the effects of the lack of gravity on such films. Wire loops of different shapes were used to form surface films of water and soapy water solutions.

in zero gravity. Films were formed by expanding wire hoops, a circular one in the form of a lasso and a rectangular one that had one sliding side. The sliding rectangle was shown to be a more controlled method of forming a film. It was demonstrated that large films (3-inch-diameter loop) could be formed from plain water, something that is not possible on Earth. The largest films, formed from a soap solution (6-inch-diameter loop) were about the same size as could be formed on Earth, but films formed on Earth ruptured sooner than those formed in Skylab. With gravity absent, the rate at which liquid drained to the edge of the film was reduced.

Wire was formed to the shape of a tetrahedron and a cube, so that three-dimensional films could be made. When the frame was slowly pulled from the soap and water solution, it was full of liquid. The liquid surface adhered to the wires, allowing the frames to act as containers. When they were shaken, most of the liquid was emptied from them, and the three-dimensional films remained. These films went from the frame to the center of the cube or tetrahedron. As with the loops, the three-dimensional films formed in space lasted longer than those formed on Earth, about 1 minute in Skylab compared to only a few seconds on Earth.

Diffusion in Liquids

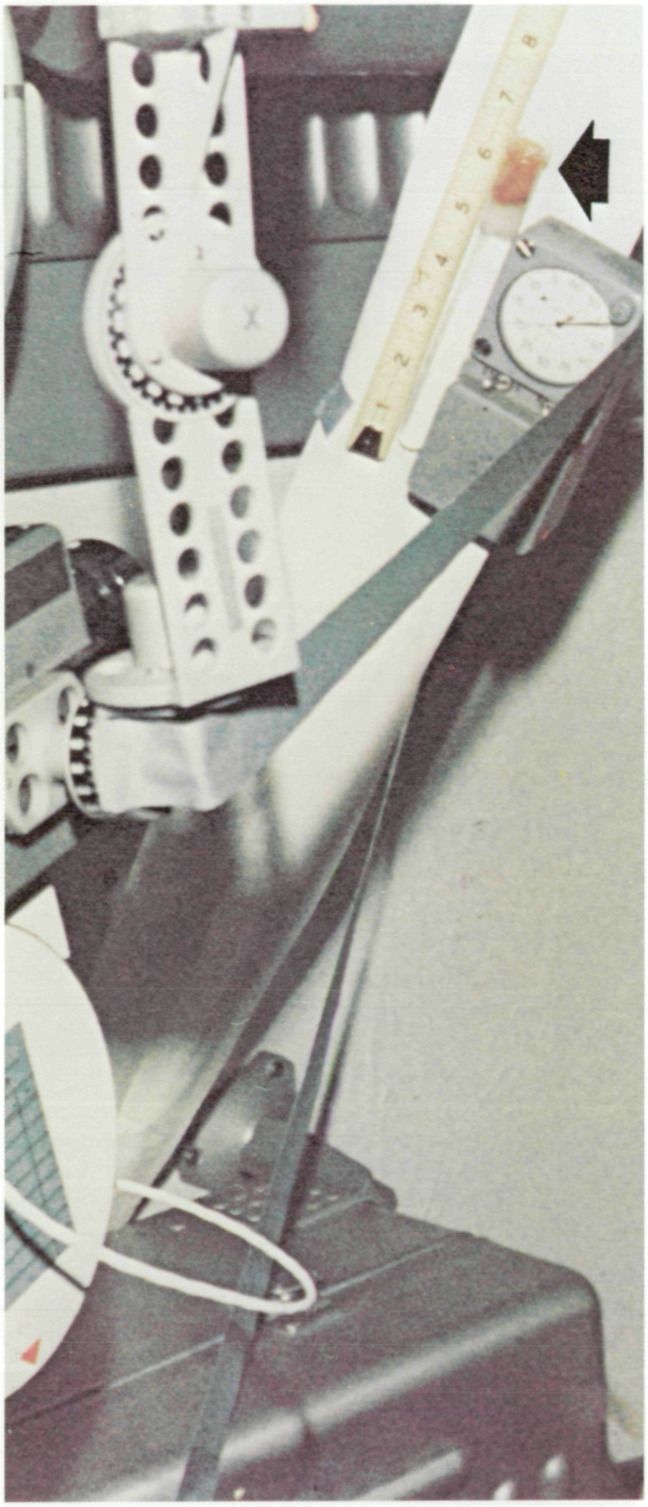
Diffusion is a process by which fluids can become uniformly mixed as a result of the random motions of their molecules. Differences in temperature within a fluid will be equalized by diffusion. When two different fluids in solution are present, diffusion will uniformly mix the two. Diffusion by itself is difficult to observe on Earth because gravity produces convection or circulation within a fluid due to differences in density of its constituents. For this reason, a diffusion experiment was performed in the zero gravity of Skylab.

A tube was partially filled with water, and a concentrated solution of tea and water was carefully placed on top of the water. The diffusion of the tea into the water was observed for a period of 3 days. During this period the tea diffused a distance of approximately 0.8 inch into the water (measured at the center of the tube). Theory predicted the same value for the rate of diffusion.

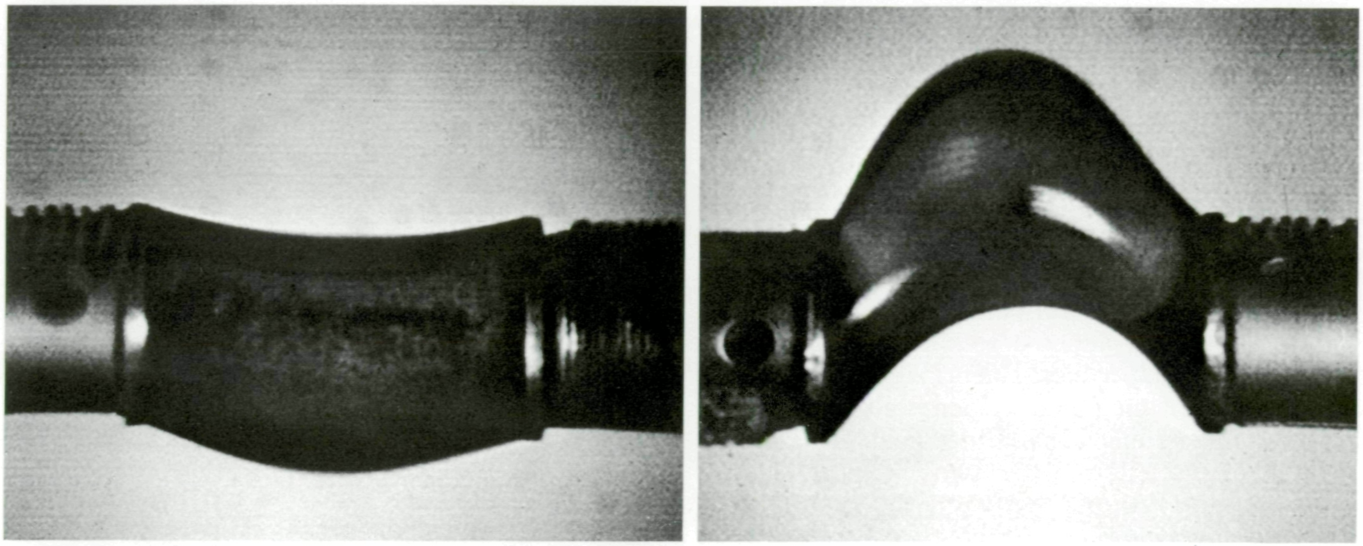
However, an unexpected result occurred when the tea diffused very little along the wall of the tube, apparently due to some effect of its wall. It is possible that electrostatic repulsion between the wall and the tea particles may have produced the bullet-shaped diffusion front.

Liquid-Floating Zone

This experiment was a specific application of zero-gravity fluid mechanics to the processing of



One Skylab science demonstration in fluid behavior concerned the diffusion of one liquid into another. A tube of water was carefully injected on the top with a solution of tea. It was observed closely for the following 3 days.



In a liquid-floating zone demonstration, water suspended between two flat surfaces and rotated produced a fluid "jump rope" effect that was not expected by scientists. Even so, such tests proved that the processing of metals without using containers is feasible in space.

materials in space. John Carruthers of Bell Laboratories, Murray Hill, N.J., suggested a demonstration to investigate a means by which metals can be melted and solidified under controlled conditions without using a container. It is difficult to provide a container for certain molten metals that does not introduce contamination into them and degrade their quality.

A liquid-floating zone is a mass of molten metal suspended between two solid rods of the same metal. In zero gravity, with the proper alinement and spacing of the solid rods, the surface tension force will form the molten metal into a uniform cylindrical shape. The molten metal will then solidify without the undesirable circulation within the metal that would exist in a gravity environment. Thus the liquid-floating zone provides a containerless method of obtaining uniform solidification of a metal in zero gravity. Large single crystals of a metal can be made using this method.

A Skylab science demonstration investigated the behavior of a liquid-floating zone, simulated with water suspended between two parallel circular disks. Zones of various volumes were formed by placing liquid on each disk with a syringe and bringing the disks together to form a single column. The zone was oscillated and rotated to determine its stability. (It is desirable to rotate a zone so that the molten metal will be uniformly heated and mixed.)

When the zone was rotated, it was found that the liquid could swing out from between the disks and rotate like a jump rope. A further increase in rotation rate would cause the zone to break apart. By adding soap to the water, forming a more viscous liquid, the stability of the zone was increased, and the "jump rope" did not form. As the zone was rotated, it remained alined with the disks. At a large enough rotation rate, the zone constricted in the center and finally broke apart. The effect of rotating one disk, both disks in the same direction, and both disks in opposite directions was also evaluated.

The tests demonstrated that the liquid-floating zone method of processing metals in space is feasible. The size, oscillation, and rotation of the zone must be properly controlled to obtain uniform solidification of the molten metal.

Charged Particle Mobility

One of the more promising applications of processing materials in space is the purification of biological compounds by electrophoresis. Electrophoresis is defined as the movement of suspended charged particles through a fluid under the influence of an electrical potential. When dispersed in a water solution, practically all substances acquire an electric charge because they tend to exchange hydrogen ions with their surroundings, and such ions are usually present in water.

Different types of particles or molecules acquire different charges and also demonstrate characteristic degrees of mobility—the ability to migrate—because they experience different drag forces due to their particular sizes and shapes. Assuming a common starting place, continued application of an electric field to a group of different particles suspended in a solution will result in stratification or sorting of the charged ones into separate and distinct zones.

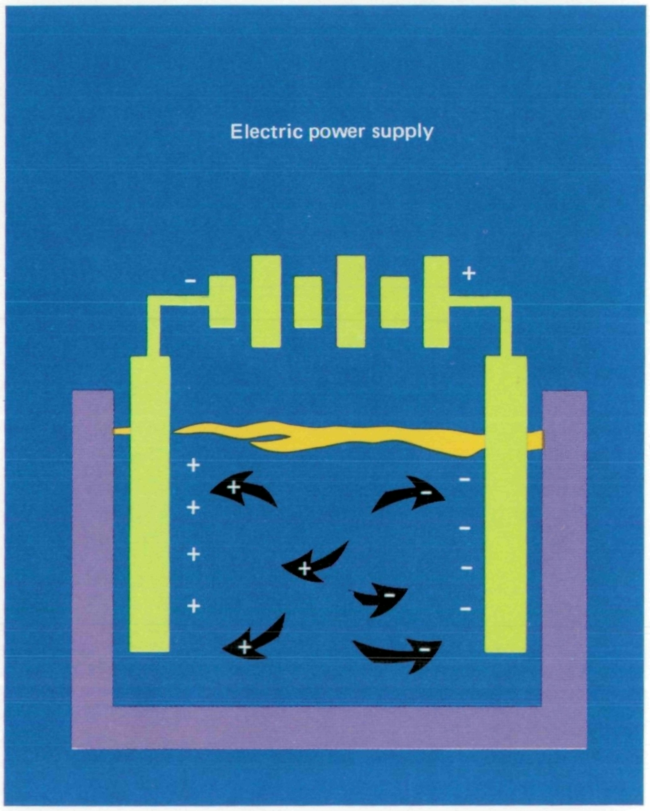
Electrophoresis has contributed significantly to biological sciences and shows potential for large-scale purification of a wide range of medically important substances. It is a useful technique, for example, in the separation of complex biological mixtures of proteins. As a result, there has been an advance in electrophoretic techniques applied to various other substances as well. However, it has not yet been possible to develop electrophoresis to provide commercially significant quantities of materials with the necessary quality control. The scientific, biomedical, and economic implications of such a development could be of major significance. Large quantities of human blood proteins are now separated by standard methods involving alcohol and salt fractionation, or distillation, resulting in low purity. The same situation prevails with enzyme and protein hormones. All of these substances have widespread clinical and research applications.

Even more promising is the possibility of applying electrophoresis to the separation of living cells. It is necessary to isolate each type of cell of the human body to determine its function. Some cells are so much alike, or appear in such small quantities, that isolating them is almost impossible on Earth.

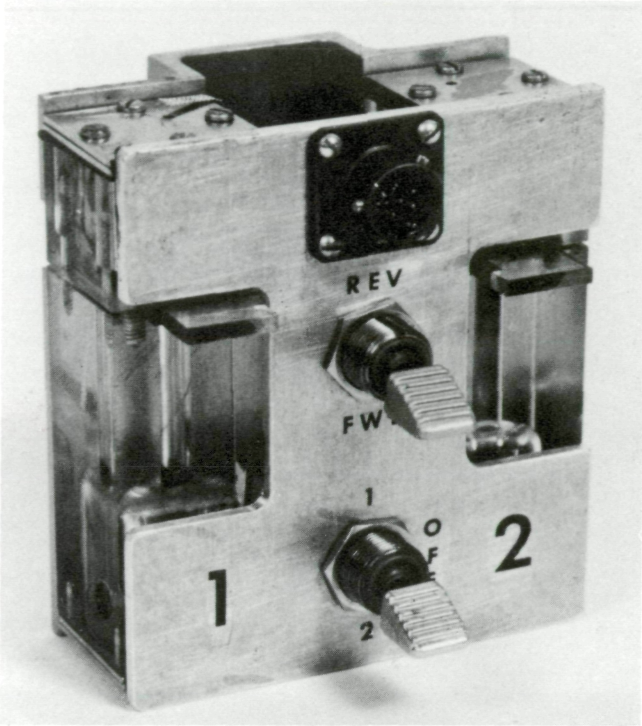
Pure cell populations have widespread potential uses in a variety of applications including preparation of vaccines. Why does the human body reject a transplanted heart but not a tumor? Today the answer is not yet known. Perhaps the answer is in the fact that cells called lymphocytes have not been fully isolated nor is their relation to the body's immune response known with certainty. It may be that their isolation can be accomplished in space. Once the important cells and their behavior have been isolated, it may also be possible to trick the body into rejecting a tumor but not a transplanted heart.

The major problem encountered in this process on Earth is circulation within the transfer medium, primarily caused by convection and sedimentation. These are differential effects of gravitational force on layers of different temperatures and on various particle sizes. The obvious solution of using the space environment to stabilize liquid media for electrophoretic separation was proposed late in 1969. It was postulated that high separation resolution should be obtainable because convective mixing and sedimentation would be greatly reduced or eliminated.

An opportunity presented itself to include a simple electrophoresis experiment, called charged-



Charged particles can be separated by suspending them in a fluid and impressing an electric field upon it. The process is called electrophoresis and has several applications for manufacturing in space.



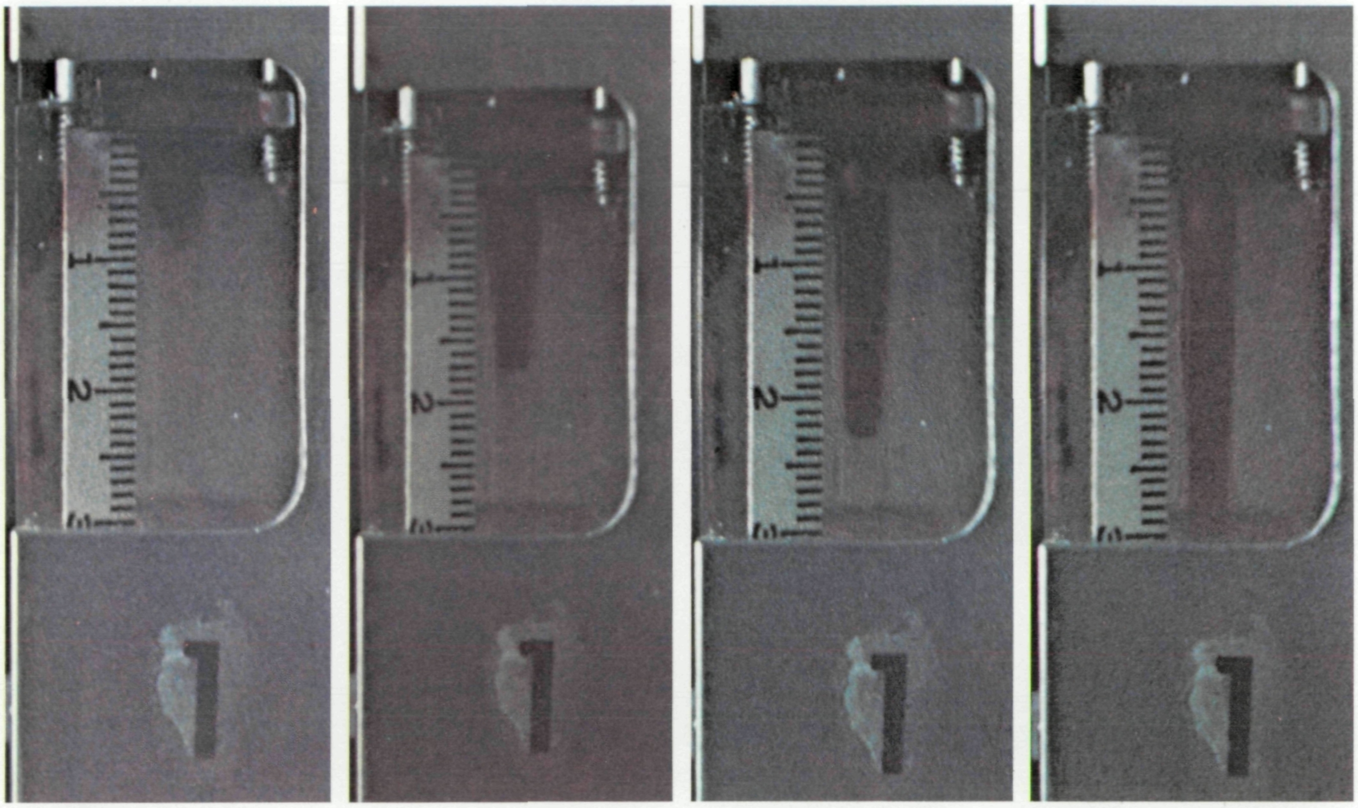
A small electrophoresis experiment was carried aboard Skylab to demonstrate the process in a weightless environment.

particle mobility, as part of the science demonstrations for the third Skylab mission. Electrophoresis experiments performed on Apollo 14 and 16 had indicated the possible advantages of zero-gravity electrophoresis, but they also demonstrated that absence of gravity did not eliminate all problems. Separation boundaries were parabolic, distorted by random fluid motions of undetermined origin. To overcome these difficulties, Milan Bier, a biophysicist at the Veterans Administration Hospital in Tucson, Ariz., proposed the use of isotachophoresis, an electrophoretic technique with self-sharpening boundaries, stabilized by electrical forces. The main limitations imposed in developing the Skylab demonstrations were the short time in which the experiment had to be prepared, the limited power available, and the requirement for the entire package to fit the available volume in an existing launch canister: a cylinder 3.5 inches in diameter and length.

A simple electrophoretic assembly was constructed, consisting of two Plexiglass modules. The observation channel was 0.2 inch in diameter and 1 inch long. One of the two modules contained a mixture of two colored proteins, ferritin and hemoglobin. The second module contained a suspension of human red blood cells. Because of the probability of cell sedimentation due to centrifugal effects during liftoff, the cathode compartment was completely filled with the cell suspension, and a small stirrer was incorporated to permit the astronauts to perform a resuspension of the cells after reaching orbit.

The results of the two experiments were limited. The main reason appeared to be significant leakage of the fluids from both modules, resulting in many air bubbles in the chambers, even though all fluids had been carefully degassed prior to filling with cells. The leakage probably occurred during launch as a result of acceleration and vibration. The protein experiment was a failure, as there was no observable migration of any colored proteins after the astronauts opened the sliding gate with the sample. An examination of the silver anode showed that at no time was there any current through the cell, though there was electrical continuity of all connections. The most likely explanation is that an air bubble completely prevented passage of the electrical current.

The results with the blood-cell suspension were better. Although the view was partially obstructed by air bubbles, the advancing front nevertheless showed little bowing. Upon completion of forward migration, the current polarity was reversed, and the astronauts cleared the air bubbles from the observation channel by mechanical agitation. The crew then repeated the frontal migration a second time. The photographs show an extremely sharp boundary, with a blunt parabolic profile. The sharpness and self-restoring properties of boundaries in isotachophoresis make it an attractive candidate for future space applications.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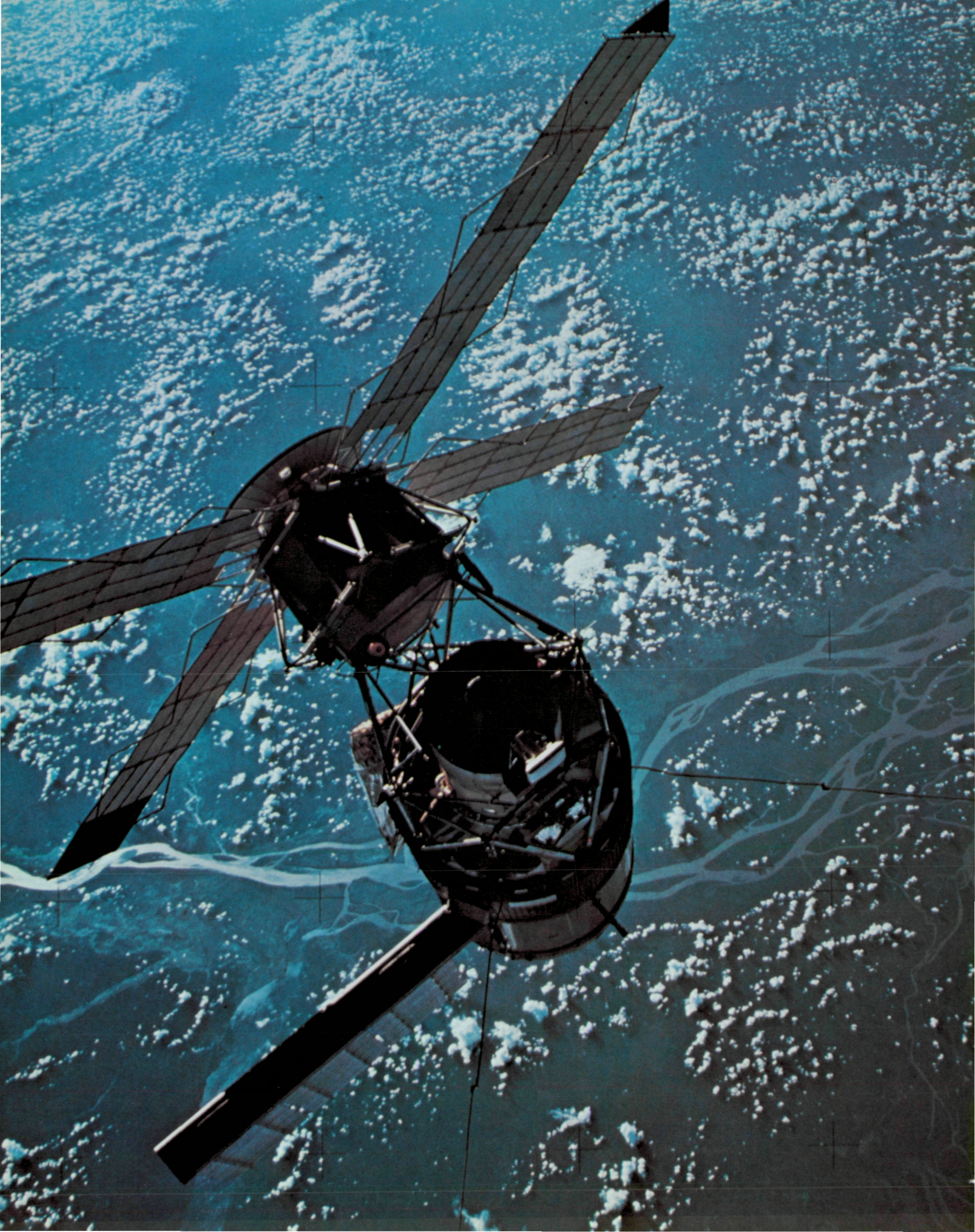
Photographs of the electrophoresis demonstration with human red blood cells produced a very sharp boundary, which indicated that the technique has a definite potential for certain types of manufacturing processes in space, especially the production of highly pure vaccines.



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Mechanics

During the course of the Skylab mission, there were many occasions on which the crew demonstrated important aspects of classical mechanics that are difficult to produce on Earth. Historically, mechanics was the earliest branch of physics developed into an exact science. Archimedes, in the 3d century B.C. said, "Give me a lever long enough, and a place to stand, and I will move the Earth." It remained for Isaac Newton, 17 centuries later, to first give a complete formulation of the laws of mechanics as follows:

(1) Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by forces impressed upon it.

(2) Rate of change of momentum is proportional to the impressed force and is in the direction in which the force acts.

(3) To every action there is always an equal and opposite reaction.

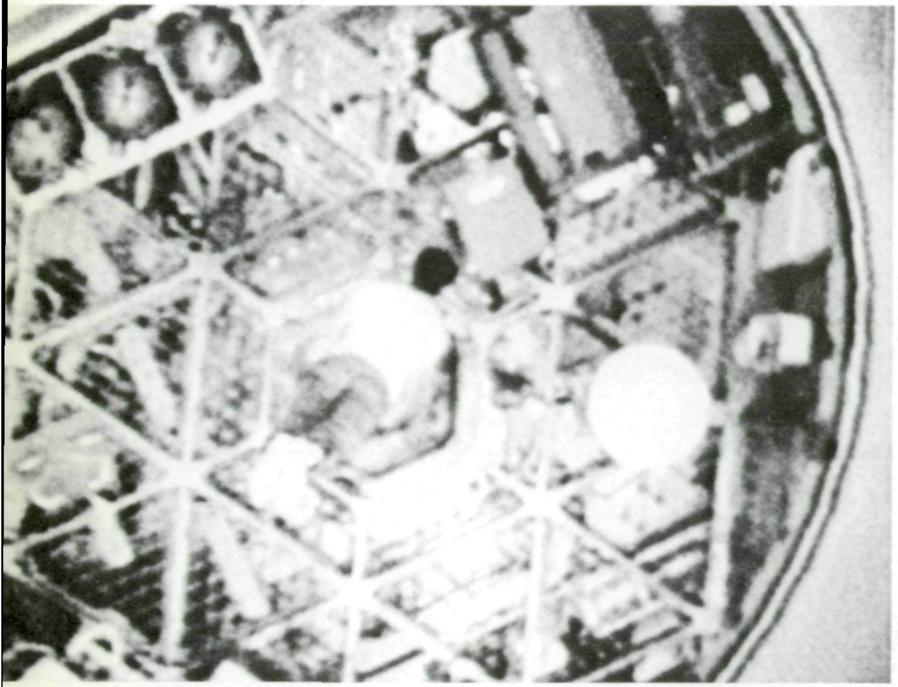
Conservation of Momentum

Figure skaters often demonstrate Newton's second law on ice. With arms outstretched, they start a slow spin and then quickly bring their feet together and fold their arms across the chest. These movements decrease the moment of inertia about the spin axis, causing a rapid increase in angular velocity to maintain constant angular momentum.

In the weightless environment of Skylab, the astronauts performed similar demonstrations. Pushing off from the wall of the 21-foot-diameter upper compartment of the orbital workshop, they flipped and tumbled at varying rates that they controlled by extending or retracting their arms and legs. They also demonstrated perfect military facing maneuvers starting from a motionless, free-floating condition. By spreading the legs fore and aft, then rotating them to the left, the body follows, coming to rest 90 degrees from the original position. Similarly, a free-floating flip was performed by swinging the arms in a circle. When the arms were stopped, the flip stopped.

Spinning a partially filled beverage container showed yet another example of the principle of the conservation of momentum. However, an additional concept was introduced: the conservation of energy. Spinning a plastic bottle about its major axis, the axis of minimum moment of inertia, might be expected to be a stable mode of rotation. In fact, the designers of the Explorer I artificial satellite, launched in 1958, stabilized it by spinning it about its major axis. Before long, Explorer I was tumbling in its orbit. This same effect was demonstrated with the drink container.

Rotation of the partially filled, flexible container resulted in converting some of the rotational energy into heat due to turbulence. The total energy of the system had to remain constant, but the conversion of some rotational energy to heat caused the spin rate or angular velocity to decrease. Since angular momentum, which is the product of angular velocity and moment of inertia, must



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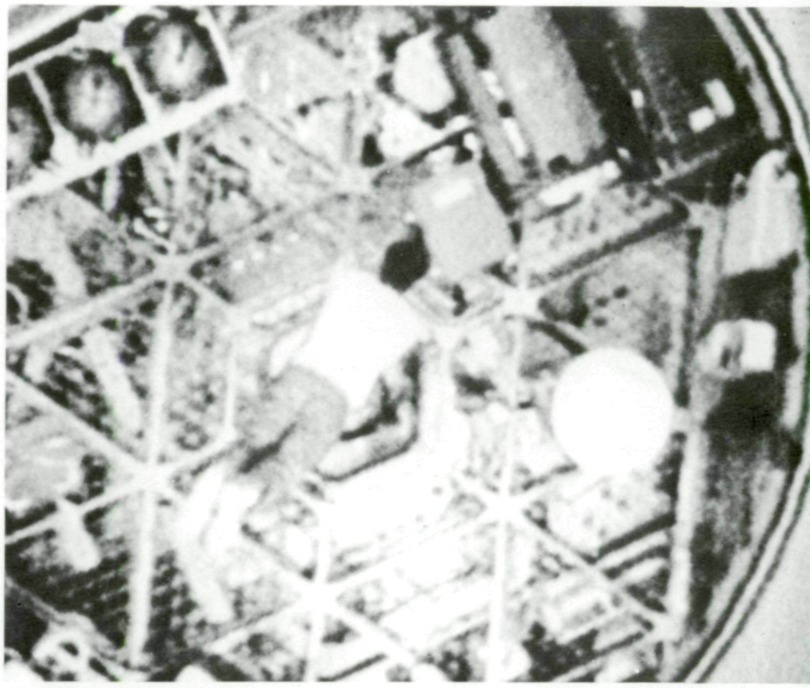

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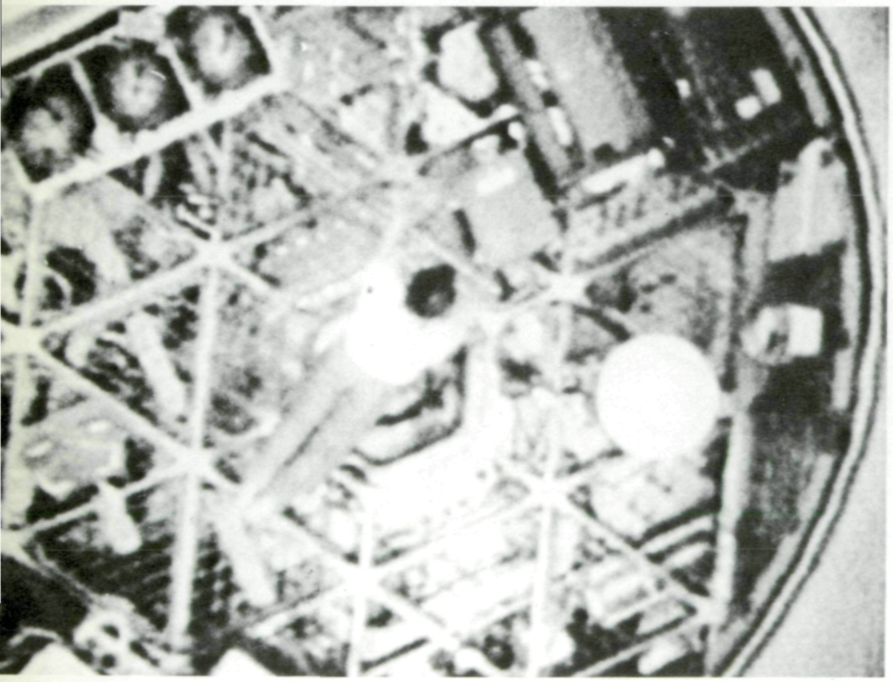

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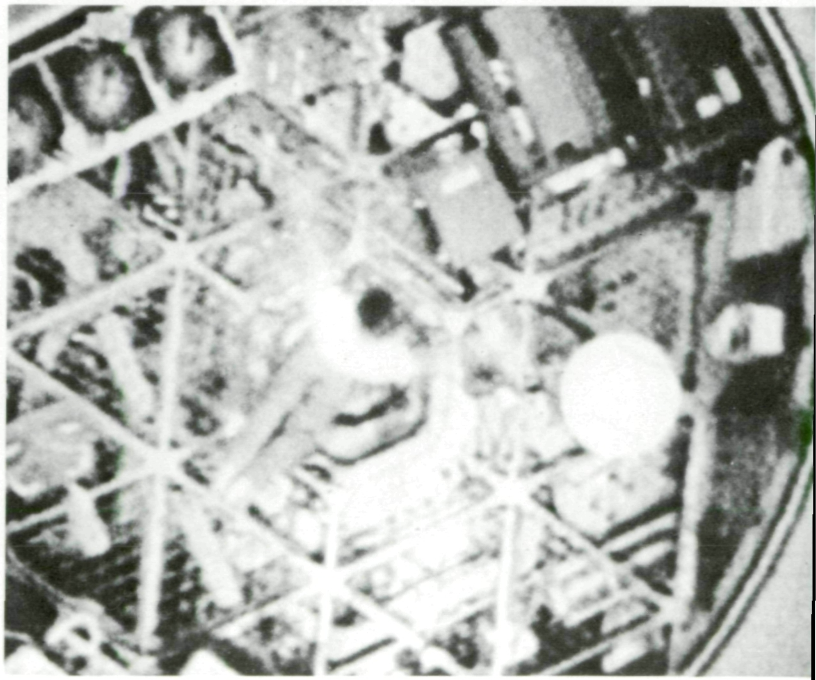

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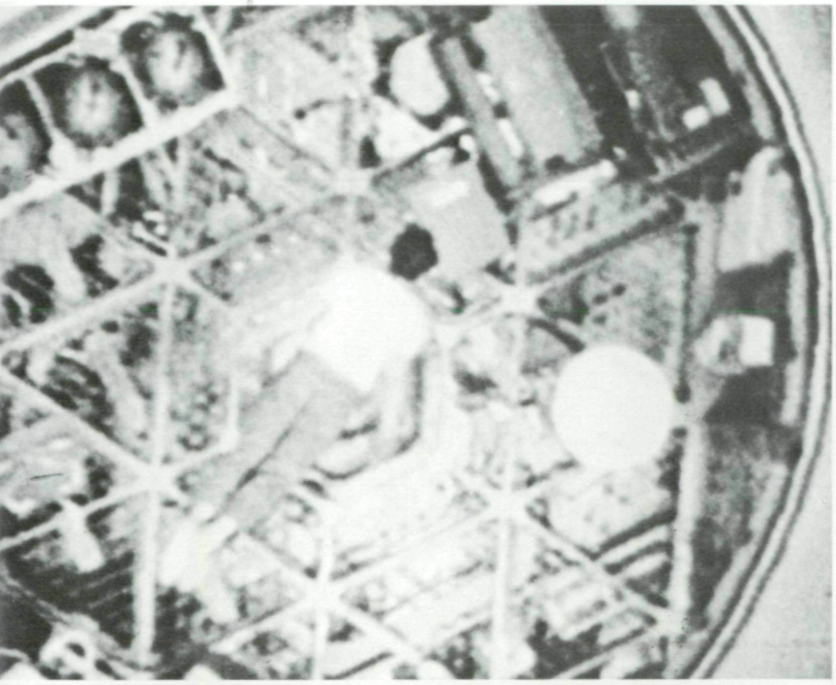
Scientist Pilot Gibson demonstrated the conservation of momentum by rotating his legs quickly. That maneuver transferred momentum to his torso, and his body thus turned. When he ceased rotating his legs, his body stopped turning because no external forces were then being applied to it.



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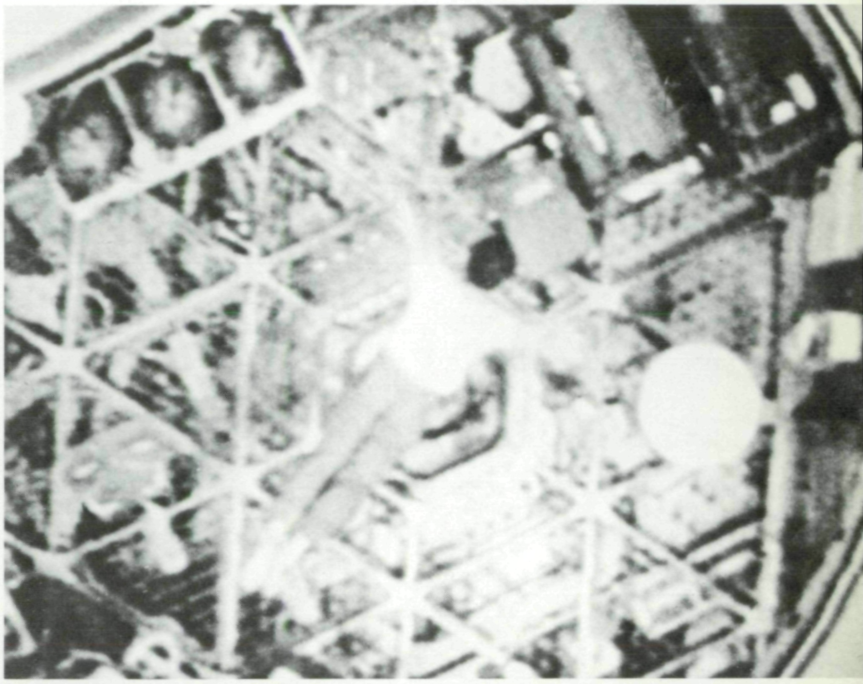

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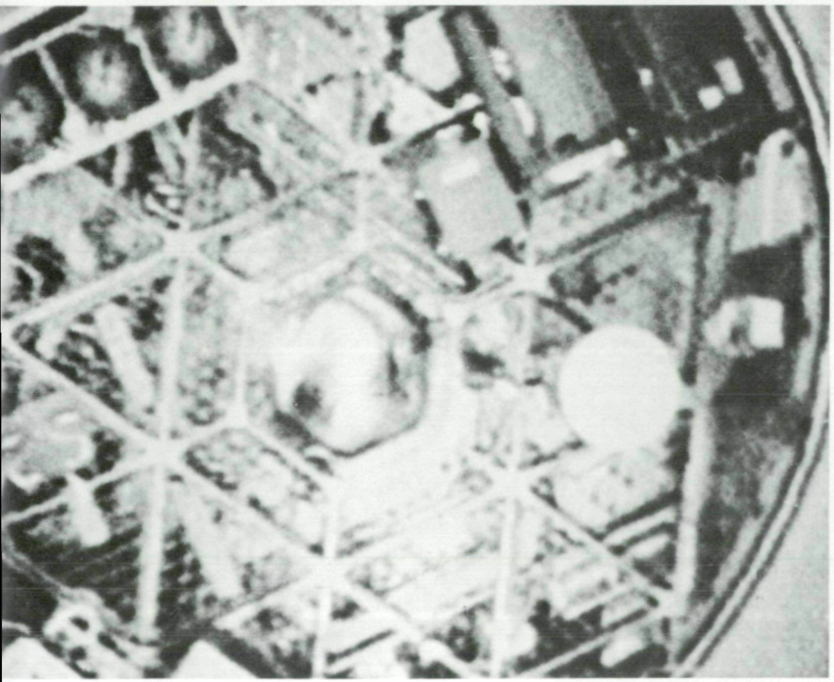

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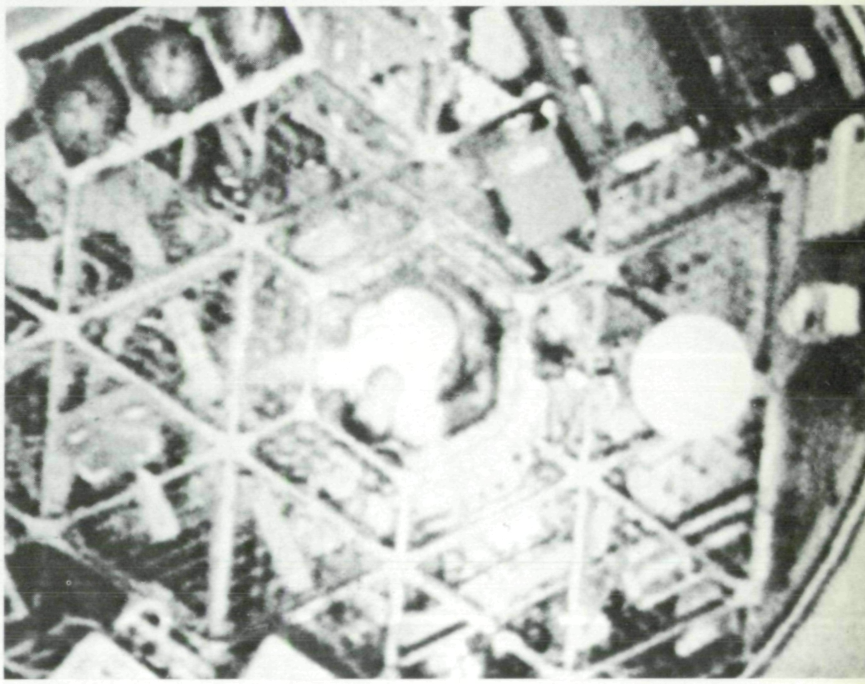

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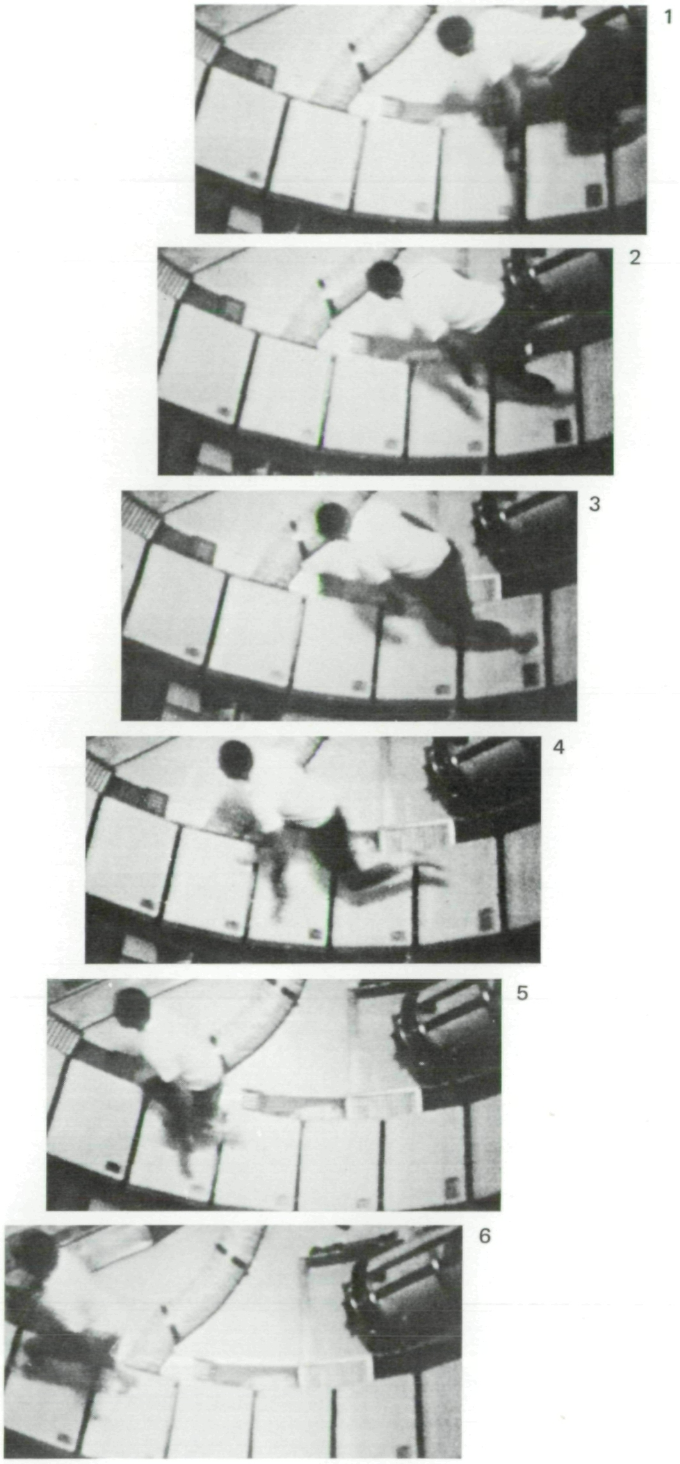
Scientist Pilot Garriott used a Skylab drink container to demonstrate both the laws of the conservation of momentum and the conservation of energy.

remain constant, the moment of inertia had to increase. In order for this to occur, the bottle rotated about a new axis of greater inertia. The bottle, therefore, started to wobble and ultimately to tumble or rotate about a transverse axis at a slower rate. Once tumbling about the axis of maximum moment of inertia was established, the fluid distributed itself uniformly at the ends of the beverage container. No more turbulence was experienced, and the tumbling became the stable mode of rotation. In the case of the Explorer I satellite, four long, flexible antennas absorbed enough energy to induce the tumble.

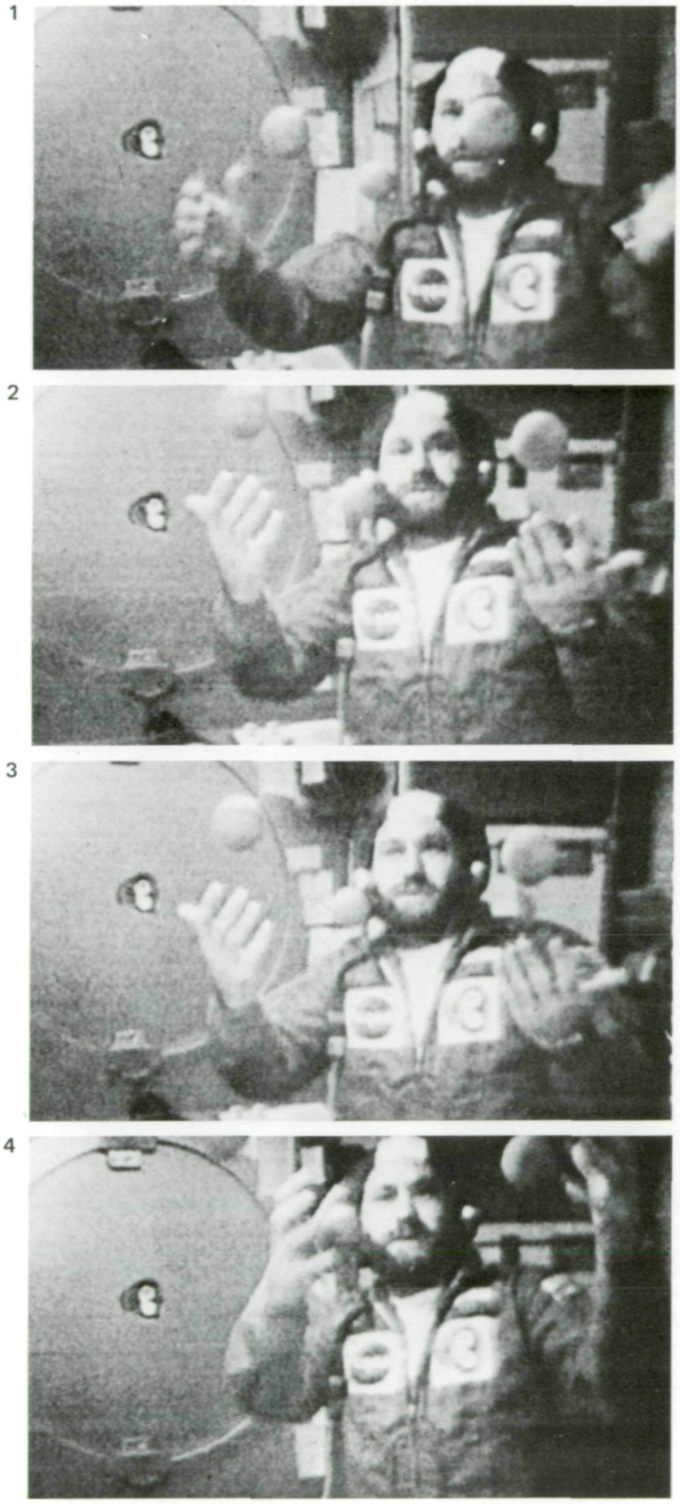
Action and Reaction

During the first mission, the astronauts proved they could have a "track meet" around the lockers in the upper compartment of the workshop. By accelerating slowly, they could develop enough centrifugal force to hold themselves against the locker doors, permitting them gradually to stand up and run. The force, as it turned out, was about the same magnitude as the gravitational force the Apollo crewmen felt as they walked on the Moon. In order to accelerate around the lockers, the men pushed off from the edges of the locker doors. A 150-pound astronaut induced a very slow counter-rotation of the 200 000-pound Skylab. This reaction of the vehicle, although small, was detectable by the precisely pointed solar telescopes. While one crewman was performing solar experiments requiring fine pointing, it was necessary for the other crewman to avoid pushing off the space station walls or floors with much force. They found that they could move around very effectively with light pushes so that their motions seldom affected such experiments.

Another illustration of Newton's law was provided during the third mission. First, Pilot Pogue released three small spheres in the workshop, with virtually zero relative velocity. Commander Carr then fired the reaction control thrusters, accelerating the space station. In the films of the demonstration, the spheres appeared to move up relative to the camera. Actually, it was the camera, fixed to the Skylab, that moved away from the spheres. The expulsion of gas through the control rockets caused the space station to accelerate. The spheres, floating inside, experienced no such force and therefore remained stable in their own orbit while Skylab changed in its orbit.



The conservation of energy and angular momentum was demonstrated by Pilot Lousma who used the lockers in the upper compartment of the Skylab workshop as a racetrack. The centrifugal force he developed was about equal to the gravity experienced by astronauts who walked on the Moon.

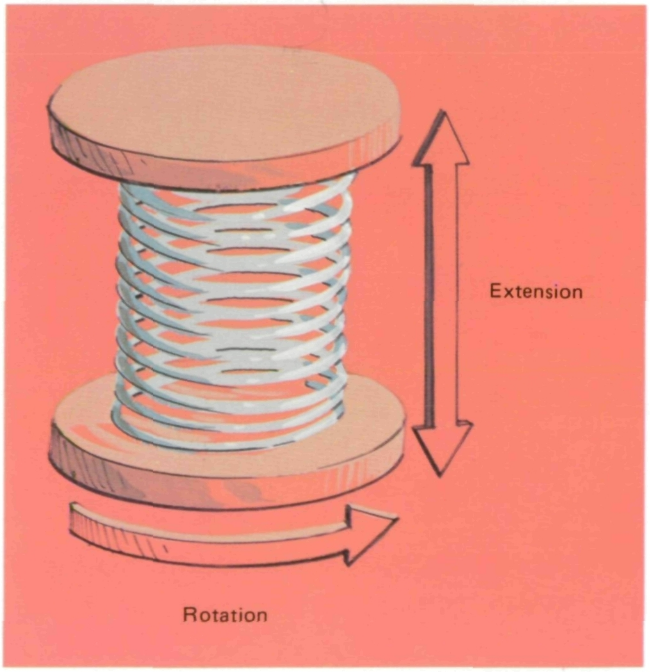


Newton's third law of motion was demonstrated by Pilot Pogue, who released three metallic balls. Skylab was then maneuvered to a slightly lower orbit. The spheres did not receive the acceleration and thus remained stable.

Energy Exchange

Another demonstration in mechanics involved a variation of a classical mechanical oscillator. Known to some as a Wilberforce pendulum, it consisted of two masses connected by a spring. Ideally, the spring would possess only two degrees of freedom, extension and rotation. However, the spring used for the demonstration was the "Slinky" toy, a large-diameter helical coil of ribbon steel, rather than the usual helical coil of round wire. It did not possess the axial rigidity needed to demonstrate the oscillator in an ideal way. The objective was to excite oscillations in the spring-mass system along the centerline of the two masses and then to observe the energy transfer and the resultant motion change from one of translation of the masses along their centerline and alternate expansion and compression of a spring, to one of rotation of the masses about the same axis (twist of the spring).

On Earth, in a gravity environment, the energy transfer is easily demonstrated through the use of a single mass with a crossarm and masses at the ends of the crossarm to "tune" the inertia to the spring. In demonstrating the phenomenon on Skylab,



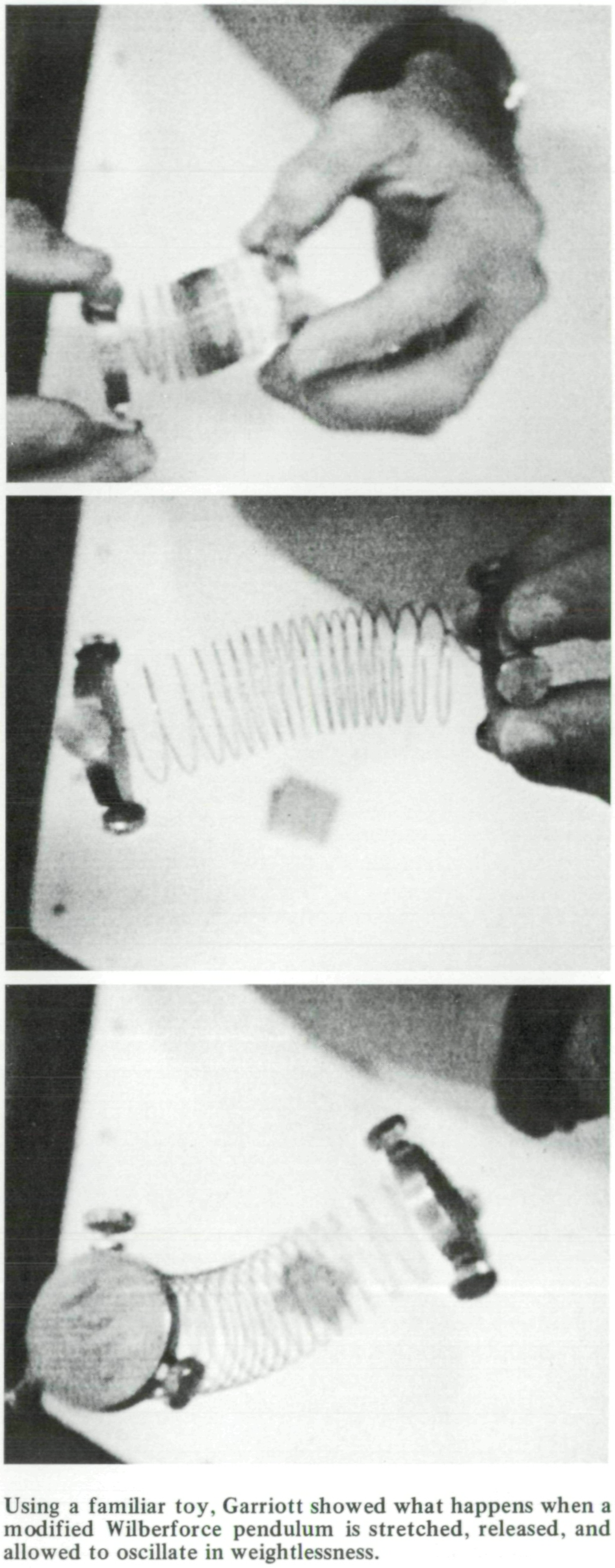
The Wilberforce pendulum, developed in 1894, has long been used in the classroom on Earth to demonstrate mechanical oscillation for students in elementary physics.

however, it was virtually impossible to obtain the desired effect. The lack of adequate axial rigidity of the spring, the difficulty in stretching the spring while maintaining its major axis along the line joining the centers of mass of the two weights, and the inability to release the two weights without inducing extraneous forces, resulted in the spring-mass system going "wild." The spring expanded and contracted, the masses rotated, and the whole system tumbled. However, the demonstration did provide a highly entertaining sequence of unusual motions. Conservation of momentum was undoubtedly maintained, despite the difficulty in describing the resulting motion, either verbally or mathematically.

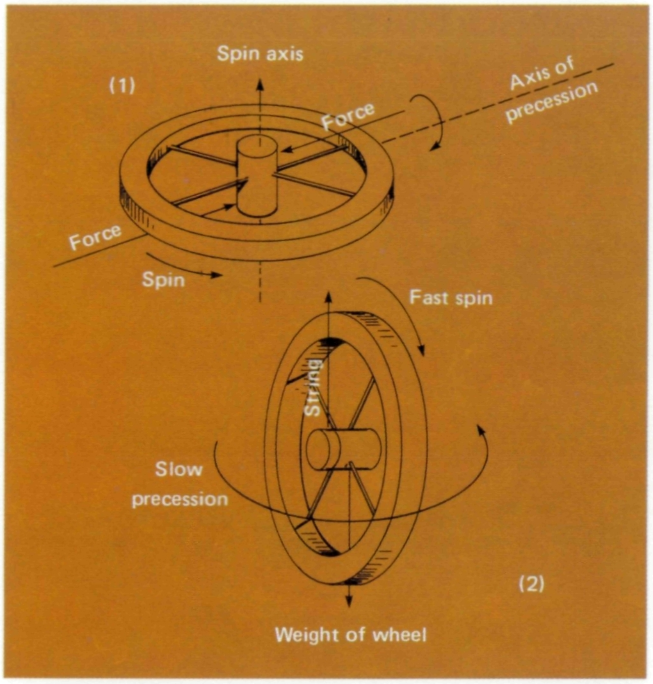
The Gyroscope

The principle of gyroscopic motion is an application of Newton's law which states that a massive, rapidly spinning body strongly resists being disturbed and tends to react to a disturbing torque by precessing (rotating in a direction at right angles to the direction of the torque). The principle of precession has been used to develop the familiar dime-store gyroscope that will stand upright on the rim of a glass or walk a taut string. The gyroscope, however, is not merely a toy; it is a highly useful instrument. Elmer A. Sperry exploited its principles when he developed the gyroscope as a navigational device for ships and airplanes. The gyroscope is unaffected by magnetism, but it can point to true North, regardless of its surroundings. It is widely used in various aircraft instruments as a turn indicator, artificial horizon, attitude or position indicator, and in automatic pilots. Large gyroscopes provided the basic stabilization and control of Skylab's position.

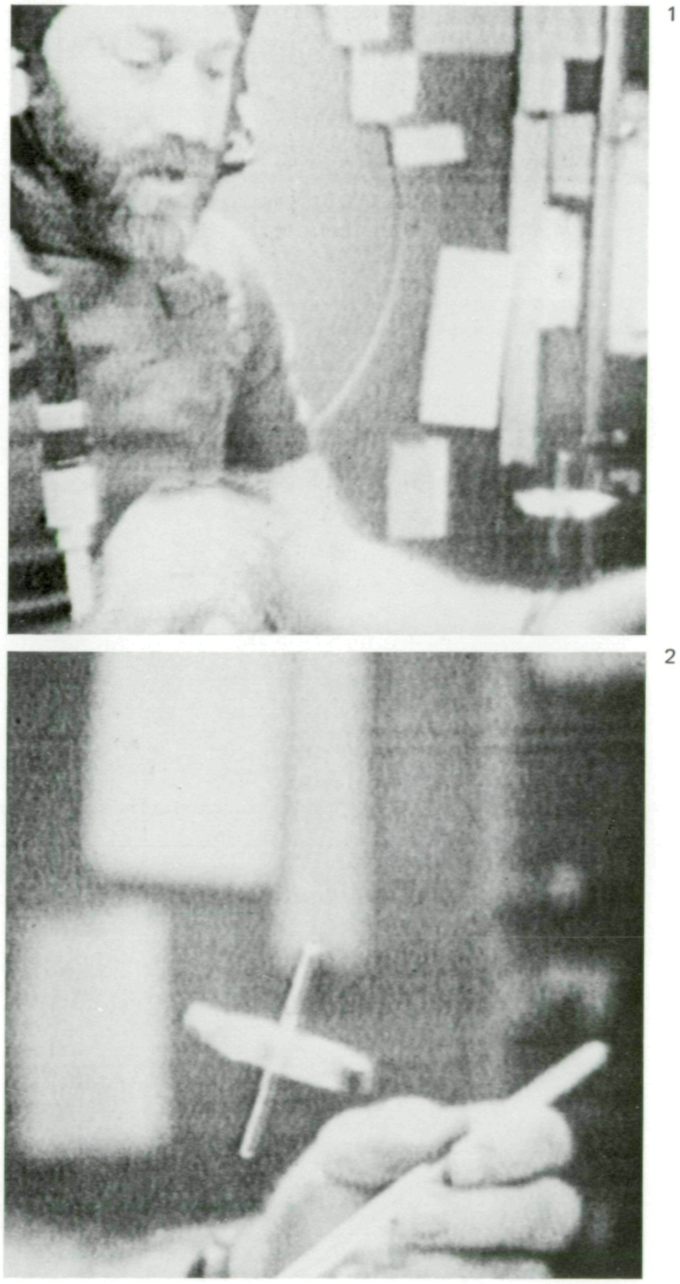
Using a toy gyroscope, Commander Carr carried out an entertaining and graphic demonstration of gyroscopic principles. On January 9, 1974, he demonstrated the unstable motion of the non-spinning gyroscope as it tumbled and drifted under the influence of external forces. After spinning up the wheel, he demonstrated the effects of external forces by showing the precession at different wheel speeds and the effect of wheel speed on the stability of the spin axis. He emphasized that the precession or rotation of the spinning wheel took place only during the application of an external force and that once he removed the external force the gyroscope ceased to precess.



Using a familiar toy, Garriott showed what happens when a modified Wilberforce pendulum is stretched, released, and allowed to oscillate in weightlessness.



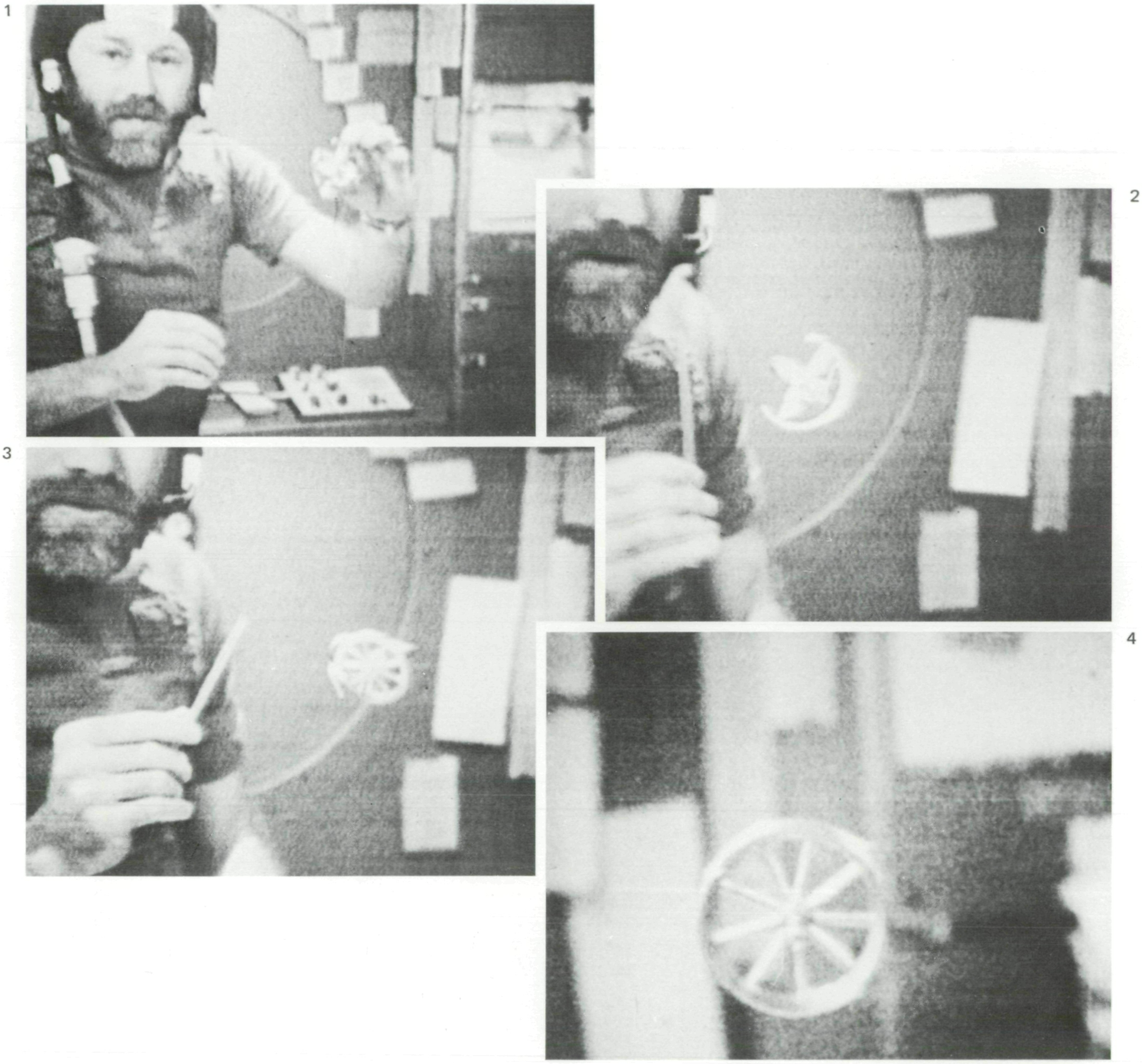
The gyroscope has three mutually perpendicular axes: (1) spin, torque, and precession. The characteristic of precession (2) was utilized by Skylab's control-moment gyroscopes to provide stability to the huge space station.



In the weightlessness of Skylab, Carr spun up a small gyroscope and removed it from its frame (1). By applying a force with a straw (2) to its spin axis, he demonstrated that the law of the conservation of momentum works, since the spin axis turned 90 degrees in response.

Carr also demonstrated that precession can be caused by friction. At high speed, the gyroscope precessed at approximately 90 degrees from the direction of the applied forces, with little wobble. At an intermediate wheel speed, a little more wobble was introduced. At very slow speed (the spokes could almost be seen going around) the resultant precession was about 20 degrees from the theoretical 90 degrees. He explained that this resulted from the friction of a straw applied to the gyroscope axle.

The fact that Carr was able to demonstrate the effects with an unsupported gyroscope greatly enhanced the performance. An excellent 16-mm movie film of this performance was made from the videotape record of the science demonstration and is available from NASA.



Commander Carr (1) demonstrated the effect of applying an external force to a spinning gyroscope (2) and a nonspinning one (3) by tapping each with a straw. Only the nonspinning device tumbled (4).

14

Magnetic Effects

A demonstration of the effects of Earth's magnetic field on objects suspended in zero gravity was performed by Scientist Pilot Garriott. It was televised "live" to Earth and was also recorded on videotape. Action sequences and commentary by him were subsequently used in an educational film for use in secondary schools.

The demonstration began with a discussion by the astronaut of the characteristics of the magnetic field surrounding Earth and other dipole magnets. Classroom experiments involving the use of a magnet and north-seeking compass to plot the magnetic lines of force were mentioned. Garriott asked the audience if Earth's magnetic lines of force extend beyond its atmosphere and whether objects in orbit 270 miles above Earth are affected by these lines of force similarly to objects at its surface.

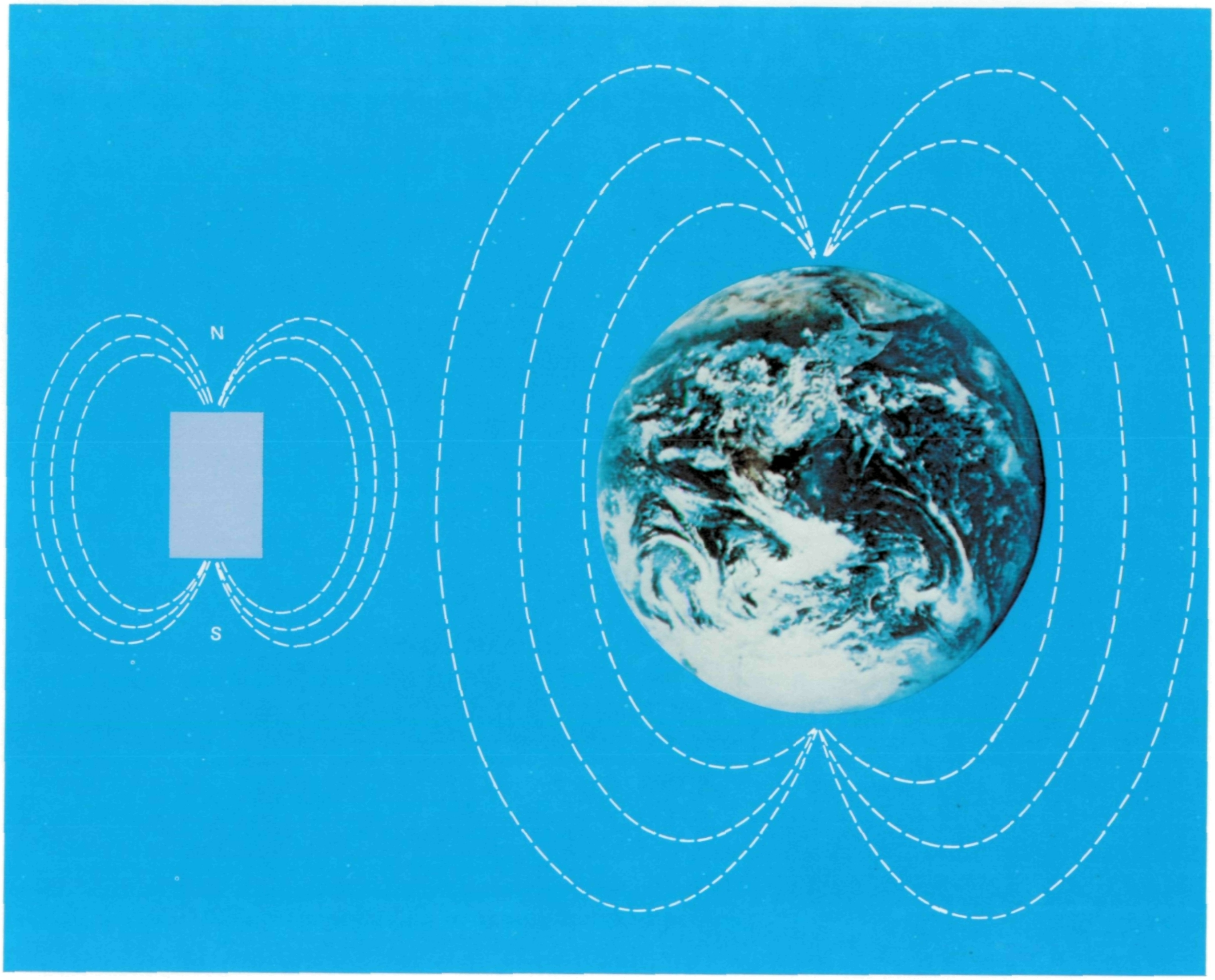
Using small bar magnets, the astronaut showed and explained the tendency of magnets to aline themselves with Earth's magnetic field. A single magnet was released within the zero-gravity environment and began oscillatory movements; however, the magnet ultimately stabilized itself along a line parallel to a magnetic line of force of Earth. Repeated releases of the magnet resulted in identical stabilizations. Also demonstrated during the oscillatory movements was the time required for the magnet to complete one back-and-forth swing as it stabilized. The interval, called the "period of oscillation," appeared constant each time the magnet was released. Garriott explained that this period, together with the magnet's moment of inertia and magnetic dipole moment, is required in the calculation of the strength of Earth's magnetic field.

The tendency for magnets to aline themselves parallel to magnetic lines of force of Earth was further demonstrated by using different combinations of bar magnets. Two magnets, stuck end-to-end, showed the same alinement tendency as the single magnet. However, it was observed that the period of oscillation for the two-magnet combination was approximately twice as long as that for a single magnet. When three magnets were affixed end-to-end and released, they alined themselves in similar fashion, but their period of oscillation was shown to be approximately three times longer.

By affixing magnets side-by-side and releasing them, Garriott compared the stabilization tendency and period of oscillation for one-, two-, and three-magnet combinations. The tendency to become alined along a magnetic line of force was still apparent with three magnets but was more erratic than for the other combinations. Also, because of the erratic behavior, the period of oscillation was more difficult to measure, but it was determined to be approximately twice that observed for the single magnet. The erratic behavior suggests interacting influences of magnetic fields around the three magnets. The observed period of oscillation may be explained as resulting from Skylab's movement to a higher latitude (closer to an Earth pole) during the demonstration, thus being affected by a stronger magnetic force which would cause a shorter period.

As an added demonstration, the astronaut attached a single magnet to a machine nut and released the combination after giving them a spin. The magnet and nut, similar to a gyroscope, exhibited a slow back-and-forth motion and also showed a tendency to stabilize along a magnetic line of force. The back-and-force motion is called the "period of precession" and may be defined as the effect shown by a spinning body when acted upon by an outside, magnetic torque. As the rate of spinning was increased, a lesser period of precession was obvious.

The demonstrations of magnetic effects in space were educationally informative and provided students with an excellent opportunity to observe the effects of Earth's magnetic field on weightless objects. The demonstrations further showed that Earth's magnetic field extends beyond its atmosphere and that the effects of the field on objects in space are comparable to those observed on Earth.



The Earth behaves like a large, dipole magnet, with its field extending outward as far as 10 radii.

Scientist Pilot Garriott demonstrated the behavior of bar magnets in the weightless environment of Skylab. He released a single one (1), two placed side-by-side (2), and two placed end-to-end (3) at right angles to the magnetic lines of force of Earth's field. In each case, the magnets oscillated slowly before becoming stabilized parallel to the lines of force in Earth's field.

15

Particle Physics

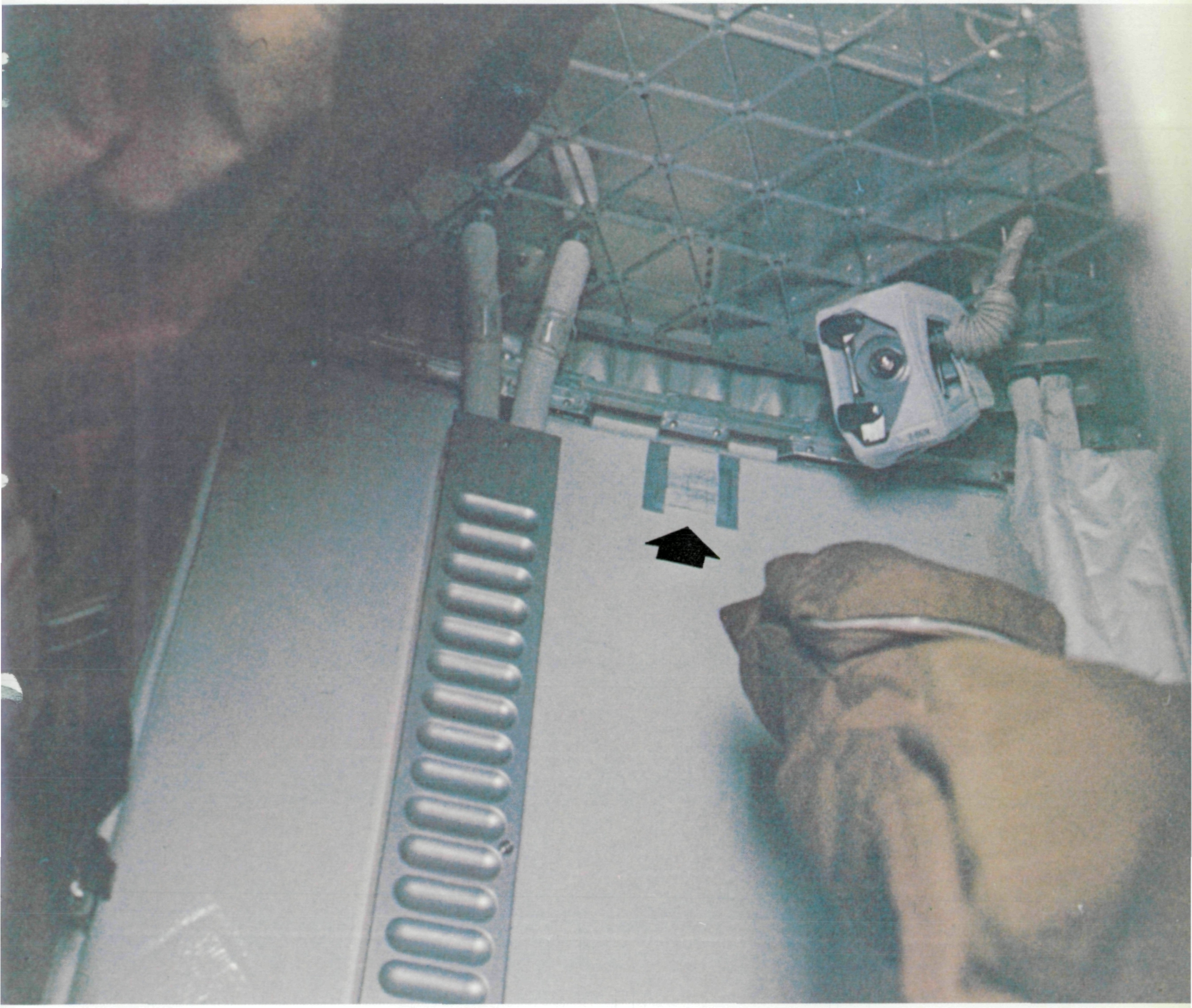
Reacting both to the preliminary results of the neutron analysis student experiment and to the crew's request for additional things to do, Gerald Fishman of Teledyne Brown Engineering, Inc., Huntsville, Ala., proposed a complementary analysis of the neutron flux aboard Skylab. Like Terry Quist's experiment, the measurement technique was passive while in orbit, but it made use of a different detection device. Rather than using the solid-state track detector, it utilized the fact that nuclear particles such as protons and neutrons are capable of transforming stable nuclei into radioactive nuclei, which emit gamma rays with a known energy of decay.

Four "activation packets" containing samples of tantalum, nickel, titanium, hafnium, and cadmium-covered tantalum were launched with the third crew. During the fifth day of its mission, these packets were deployed in the workshop, one in a film-vault drawer, one on the outside of a water-storage tank, one on the dome of the forward compartment in the workshop, and one on the outside wall of the sleep compartment. These packets remained in place for 76 days, after which they were returned to Earth by the crew. In addition to these specially designed activation packets, a large sample of stainless steel from an experiment container and samples of tantalum and indium antimonide from other Skylab experiments were returned for analysis.

A low-level gamma-ray spectrometer system measured the gamma-ray decay rates of all samples over an extended period of time after their return to Earth. All induced radioactivities were found to be very weak. However, the neutron fluxes derived from the demonstration compared well with those derived from analysis of Quist's experiment. In particular, Fishman's results confirmed that the Skylab neutron environment was dominated by high-energy or fast neutrons and that their flux was higher than previously predicted.

The data provided by this demonstration, together with that from Quist's experiment, should provide assistance in the planning and analysis of future particle-physics experiments and astronomy experiments that utilize X-ray, gamma-ray, and other high-energy phenomena to explore the universe.

When the astronauts of Skylab's third crew asked for more work, they were given a special experiment to measure the neutron flux aboard their space station. Each cloth bag contained a special detector for the energetic particles.



Neutron detectors were attached to various surfaces within Skylab. In this picture, a package is on the wall, near the ceiling of an astronaut's sleep compartment.

16

Crystal Growth

The diamond in most engagement rings is an octahedral crystal of carbon, formed naturally by very high temperatures and great pressures deep within Earth. In addition to the valuable diamond, all metals and many other substances, such as relatively cheap salt and sugar, are made of crystals.

Crystals are important to industry because of their unusual properties. For example, certain electrically excited crystals oscillate at extremely stable rates. It is this property that makes the crystal-controlled wristwatch such an accurate time piece. Transistors are fabricated from crystalline material, and crystals are extensively used in precision electronic and optical equipment.

Most artificially produced crystals are formed or "grown" from solutions, melts, or by ion exchange. In order for them to form from a solution, it must be saturated with the substance to be crystallized.

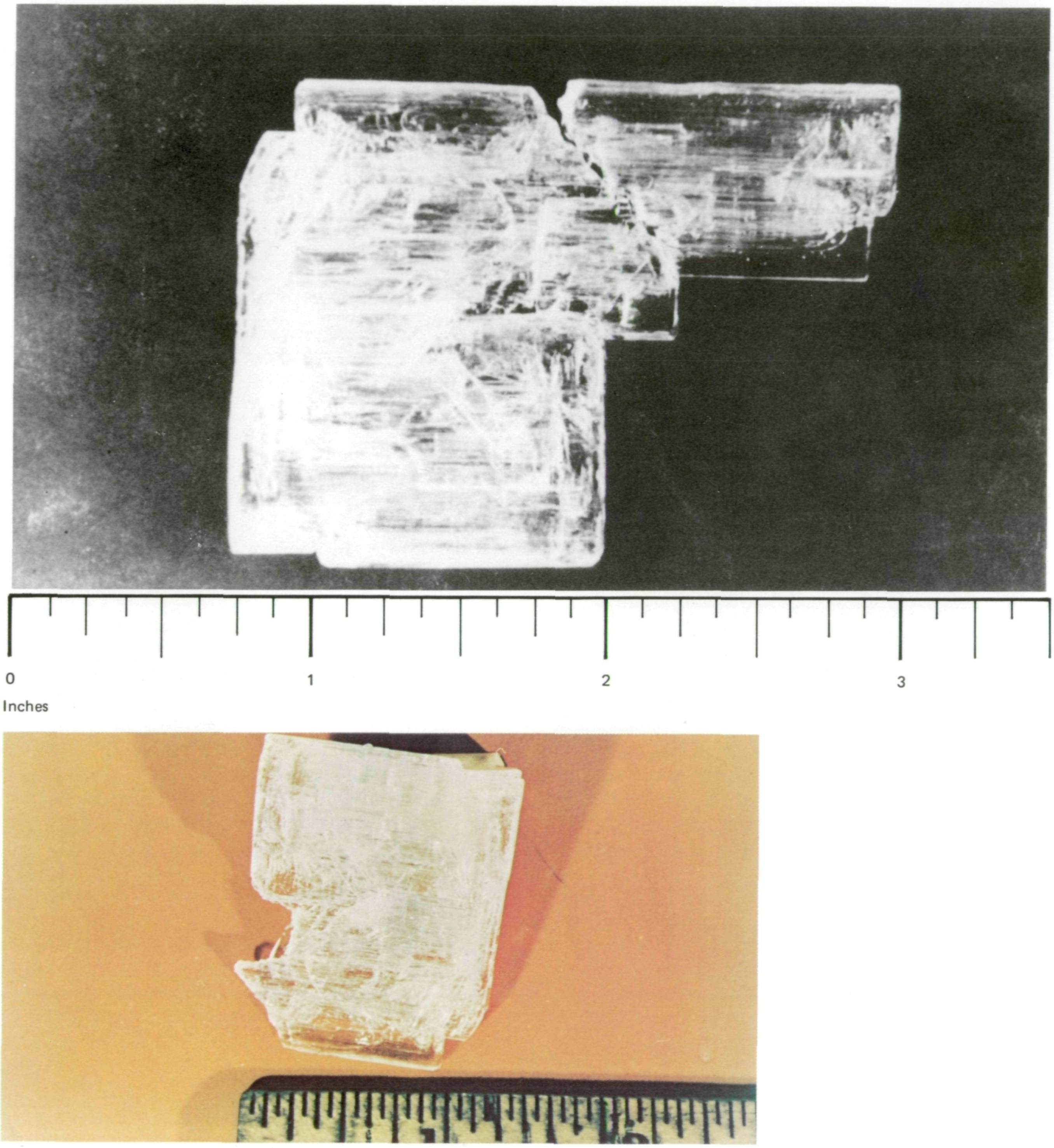
The formation of perfect crystals of large size is not easy on Earth. Circulation or convection in a supersaturated solution poses a problem in the growth of imperfect crystals. Supersaturated solutions are not stable and will deposit their solute material on the walls of a container or on small seed crystals of the solution if the saturation level is high enough.

Rochelle Salt Growth

Growth of most crystals, particularly metallic crystals, requires high temperatures and very carefully controlled cooling rates, accompanied by a precisely regulated withdrawal of the developing crystal. To demonstrate the capability for producing crystals in orbit, I. Miyagawa of the University of Alabama suggested the use of Rochelle salt, a common crystal. The choice was dictated because such crystals can be formed from a solution in near-normal room temperatures, and they can so generate relatively large crystals that have good piezoelectric properties or the ability to generate an electric current when pressure is applied to them, enabling a simple measurement to assess the quality of the crystals.

A small Skylab food can was filled with saturated Rochelle salt solution, Rochelle salt powder, and a Rochelle salt-seeded crystal. The can was placed in a food-heating tray and warmed until three-fourths of the seed crystal dissolved at approximately 158°F. The can was then removed from the tray, wrapped in several towels for insulation, and stored. During storage in zero gravity, the seed crystal slowly regrew as the can cooled down to workshop temperature. The growth occurred because the saturated solution became supersaturated when the temperature dropped, and the solute crystallized out of solution until it became saturated at the lower temperature. This process was carried out slowly in the presence of a "seed" crystal, so that much of the solute deposited on the "seed," resulting in a large single crystal.

Approximately 2 weeks later, the can was opened to observe the results of crystal growth. It



I. Miyagawa, of the University of Alabama, suggested that a meaningful science demonstration in the growth of crystals could be made aboard Skylab. A large crystal of Rochelle salt was grown in the weightless environment, but it broke during reentry into Earth's atmosphere while it was being returned by the astronauts.

contained many small Rochelle salt crystals that had formed in the solution. The astronaut described the solution as "slushy," with crystals appearing "mica-like." The seed crystal, which was returned to Earth, had regrown in a plate about 0.5 inch on each side and about 0.2 inch thick.

The space-grown crystal contained at least five crystals. The corresponding crystal axes of these component crystals are parallel to each other. In Earth-grown crystals consisting of several component crystals, the orientation of any axis of a component crystal relative to any other component crystal is completely random. The unusual arrangement of Skylab's component single crystals suggested the presence of a long-range molecular force of attraction between crystals. It was assumed that this force oriented the crystals so that their axes were parallel when they came close to each other in the solution.

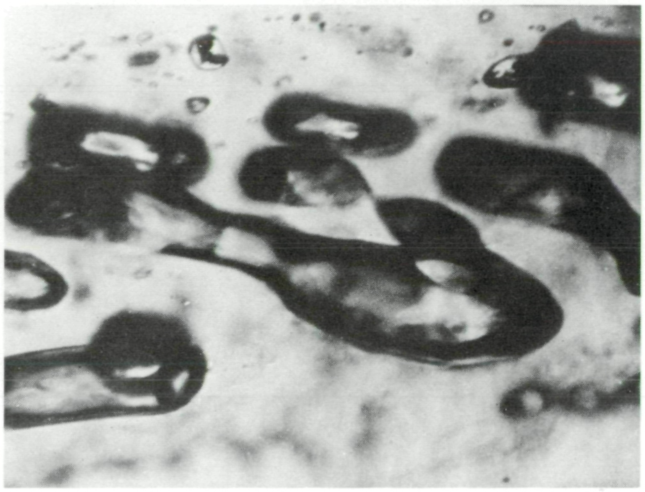
However, the Skylab crystals had several defects. Most appeared to be long, tubular cavities when viewed through a microscope. The average length of the cavities was about 0.16 inch. Almost all of the tubular cavities had their long axis parallel to the crystal axis. Such very regular tubular cavities were not observed in any Rochelle salt crystals prepared in a ground-based laboratory. However, Earth-grown crystals may have several types of irregular microscopic cavities. Although the crystal was not as good as expected (probably because the growth of the Skylab crystals was not precisely regulated), several interesting facts evolved. The demonstration provided the first experimental evidence of molecular forces on growing crystals in zero gravity. For reasons still unknown, the Skylab crystal was much more fragile than similar crystals grown on Earth. Perhaps future space experiments on the growth of crystals of this type will provide control over temperature, growth rate, dissolved air in solution, pressure, vibration, and other factors that may affect the growth of a crystal.

Deposition of Silver Crystals

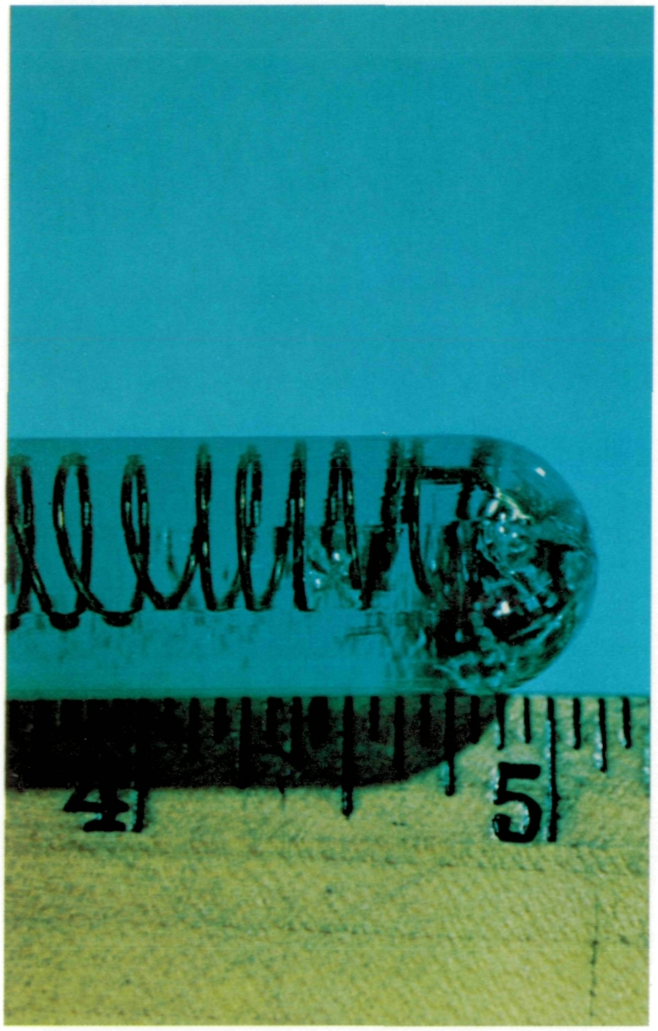
A second crystal-growth demonstration, using an ion-exchange procedure, demonstrated the effect of zero gravity on such a crystal-growth technique. When a copper wire is placed in a silver nitrate solution, silver crystals will deposit on the wire. Many such crystals have been grown by this process on Earth. Results have shown that as the gravity force increases, the crystals become much more compact and cohesive.

Upon examination on Earth, Rochelle salt crystals grown on Skylab were found to have parallel, tubular cavities (1). Similar crystals produced on Earth had irregular cavities (2).


1


2

P. Grodzka of Lockheed Missiles & Space Co. and B. Facemire of the Marshall Space Flight Center provided a silver-crystal-growth demonstration to extend such studies to Skylab's zero gravity. It was expected that weightlessness would have no effect on the microscopic process of diffusion and chemical reaction but that it would affect the motion of silver ions due to the absence of convection. Extrapolating the results of Earth-based studies, the Skylab crystals—grown without convection because of zero gravity—would be less compact and less cohesive than those produced on



Crystals of metallic silver also were grown in Skylab.

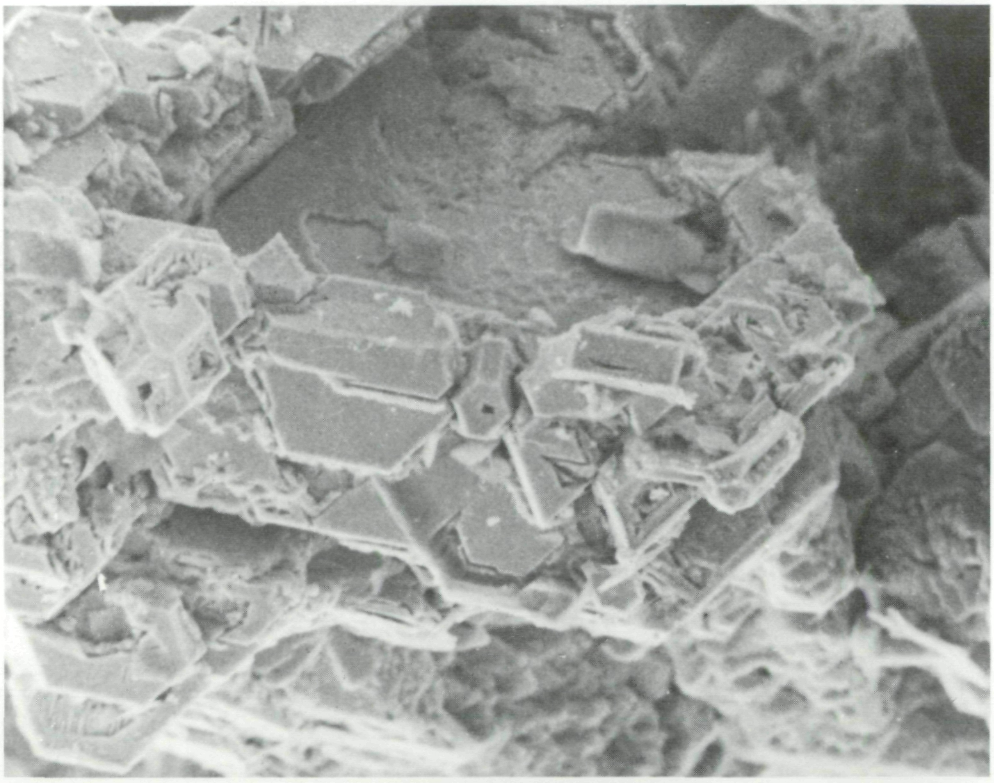
As expected, silver crystals grown in Skylab center were much finer and more powdered than those grown on Earth.

Earth, where similar crystals should be powder-like.

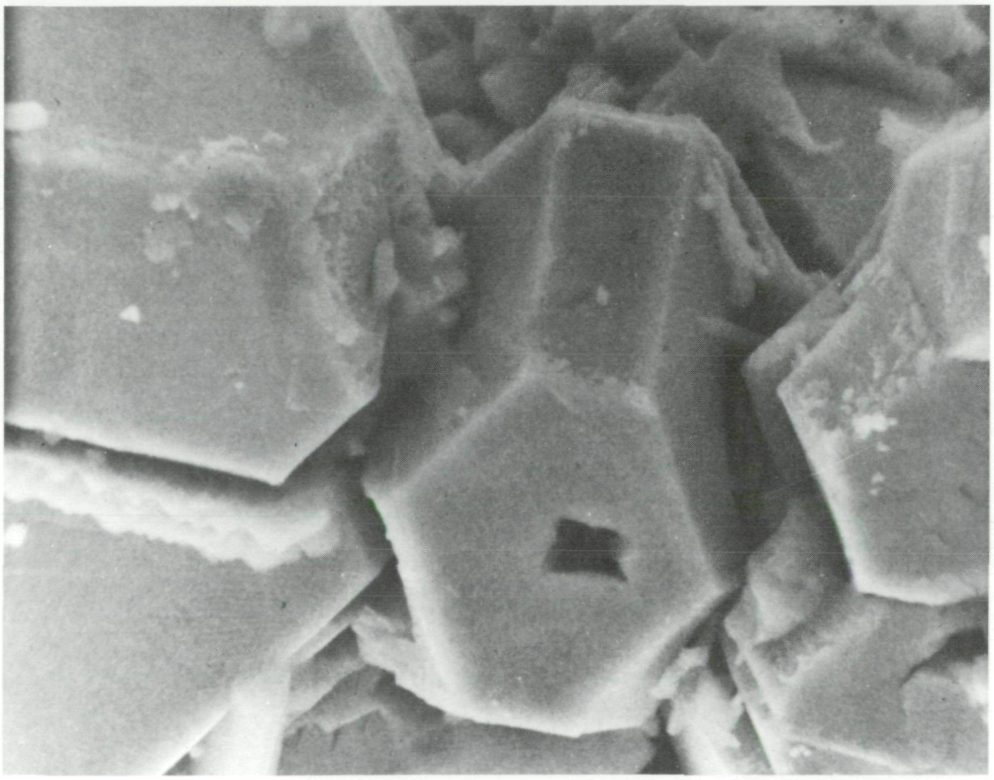
The Skylab experiment, performed by Commander Carr, consisted of inserting a scored, insulated copper wire into a 5-percent aqueous solution of silver nitrate. Silver crystals began to grow immediately at the exposed metal sites. Carr reported that the silver crystals were growing beautifully with a "classical lattice structure." Later, in a debriefing session, he described the crystals as long branches like trees. He also said that most growth occurred during the first 24 to 48 hours, being almost complete by 72 hours.

The vial containing the silver crystals was returned to Earth. Unfortunately, the crystals were knocked loose from their growth sites in return process and handling. But, significantly, they were powdered, as anticipated.

The fact that the Skylab-grown crystals were more powdered than Earth-grown crystals indicated a promising area for space processing: the electrolytic growth of powders for catalyst applications. Silver, for example, is the only known catalyst for converting ethylene to ethylene oxide, a necessary compound for the manufacturing of many petrochemical products.

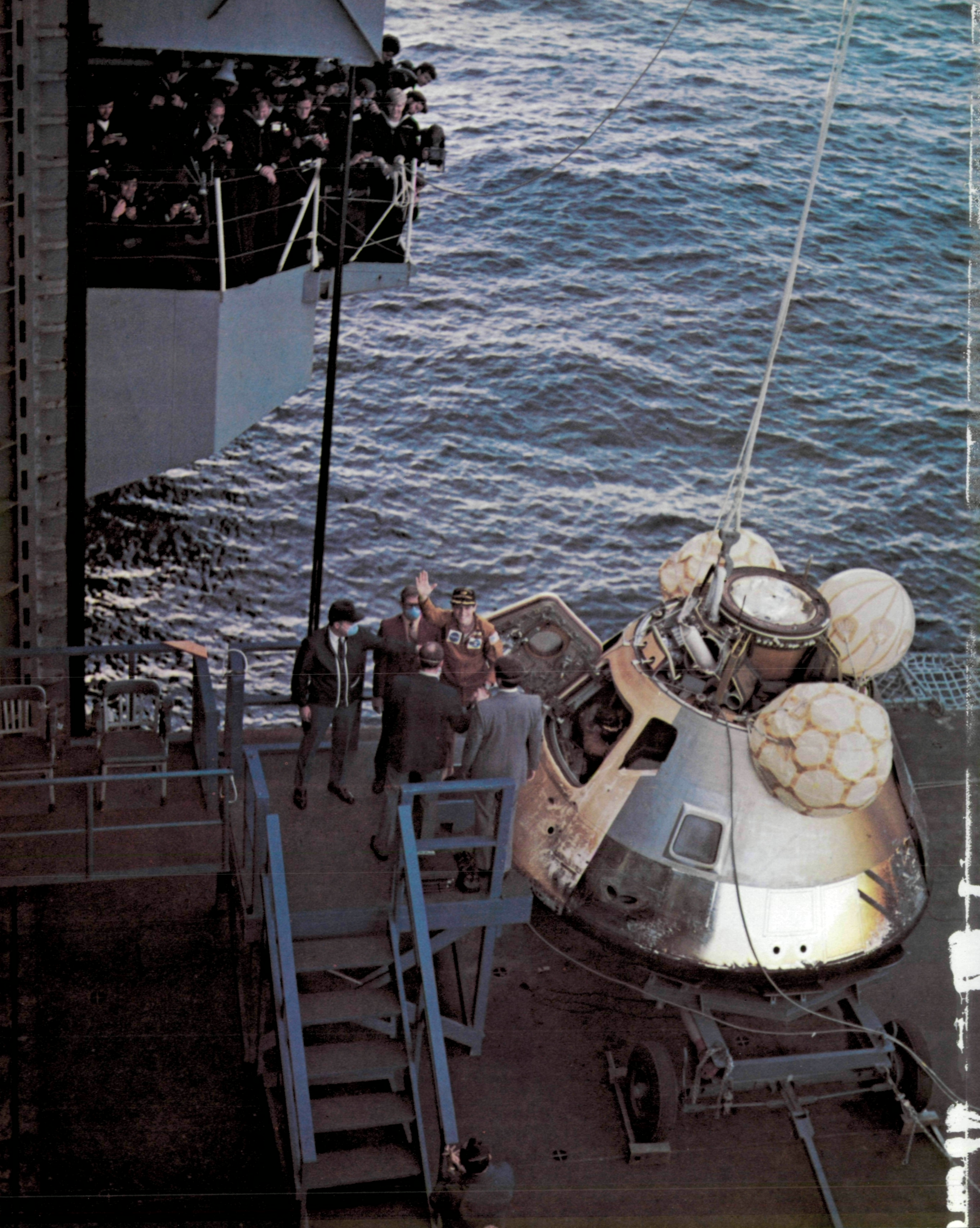


700X



6000X

Photomicrographs at 700X and 6000X show a silver crystal grown in Skylab.



17

Life Sciences

Between 1970 and 1972, approximately 6 million acres of trees were damaged by gypsy moths (*Porhetria dispar lepidotera*) in the eastern United States, and the destruction became more widespread in the years following. Oak trees are particularly susceptible to damage. White oaks, especially, showed a mortality rate of 80 percent after exposure to the moths for only 2 years.

For many years the gypsy moths were controlled by DDT. Since the use of DDT was prohibited in 1969 because of its detrimental ecological effects, the gypsy moth population grew unrestrained. No entirely satisfactory physical or chemical deterrent other than DDT has since been discovered to control the destructive pests.

Gypsy Moth Life Cycle

The typical life cycle of a gypsy moth starts with the laying of eggs in late summer. The eggs then undergo a 9-month dormant or hibernation period called *diapause* and hatch in the spring as larvae, simultaneous with budding of trees. It is the larvae that are most destructive, as they devour the shoots and leaves of the young trees. They live for about 6 weeks before entering another dormant phase of 2 weeks as pupae. July generally marks the emergence of the young gypsy moths. Each female moth will then normally produce some 700 eggs. The lifetime of the moth is less than a year, but its population growth is enormous because of the total number of eggs laid and hatched.

One of the few promising methods of suppressing the moth is by the sterile male technique, which involves rearing large numbers of insects in the laboratory and exposing the males to small doses of radiation to render them sterile. The sterile males are released and allowed to disperse throughout the general moth population. The eggs produced by females that mate with sterile males never hatch. Over a period of years, this technique could be expected to reduce the insects.

The major drawback of this technique is the length of time required to obtain new generations of sterile males. The wild population is expanding too rapidly, while the laboratory population does not develop quickly enough. A significant advantage would be to reduce the diapause for the laboratory groups, but no techniques have yet been found to accomplish such biological change.

It was hoped that the weightlessness of Skylab might induce some intracellular redistribution of material within the embryo or alter the permeability of cell membranes to cause an early end to diapause. Research performed in biological experiments on the Biosat 2 satellite in 1967 had demonstrated the feasibility of such approaches. Thus, the purpose of the experiment was to prematurely terminate the diapause of gypsy moth eggs by exposure to zero gravity. It required a cooperative effort among the Department of Agriculture's Agricultural Research Service and its Animal and Plant Health Inspection Service (APHIS) and NASA.

1

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Gypsy moths are among the worst destroyers of trees, especially the white oak. The life cycle of the pest is shown here with two females laying eggs (1), as many as 700 at a time. The eggs hatch into caterpillars (2) that begin devouring young shoots and leaves (3). A forest can be almost totally destroyed by the caterpillars (4). The caterpillars then mass together for a dormant period of 2 weeks (5) before emerging as adult moths (6) ready to repeat the life cycle. (Courtesy Charles Herron, U.S. Department of Agriculture.)

Gypsy moth eggs were carried to Skylab as a part of an experiment to determine whether weightlessness would affect the life cycle of the insect. The demonstration was part of a plan for controlling or eliminating the moth.

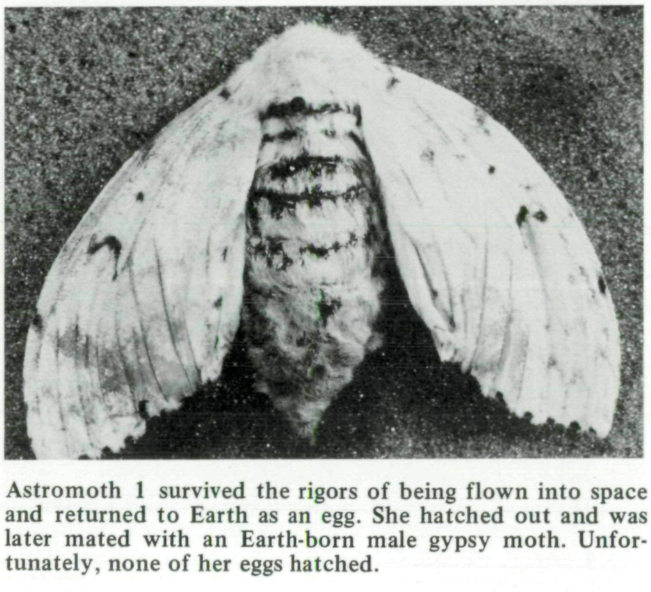
Five hundred gypsy moth eggs were collected from forests near State College, Pa., in October 1973. They were removed from their hairy mass, cleaned, and placed in a vial labeled "wild." Another 500 eggs, from the APHIS Laboratories in Massachusetts, were packaged and labeled "tame." The wild eggs were thought to have been laid about 6 weeks prior to the laboratory eggs. Two vials, containing 200 eggs each from the same populations as the flight eggs, were maintained under similar environmental conditions for the ground-control groups.

The wild and tame vials were launched in the Apollo spacecraft with the third crew, which then checked the vials daily to determine if any of the eggs had hatched. Throughout the 84 days of the mission, only seven of the wild eggs hatched, but their diapause had been reduced significantly—from 9 months to 5 months. None of the tame eggs hatched during the period.

The crew brought the vials back, and the eggs and larvae were returned to their laboratories. Nine more of the wild eggs hatched after return to Earth, with diapause between 9 and 12 months. Only one tame egg hatched, with an 8-month diapause. The moth, a female, was named Astromoth 1 and was reared to adulthood and mated with a male gypsy moth hatched on Earth. Her brood of 300 to 400 eggs was to be examined for morphological changes upon hatching. However, none of them hatched; neither did any of the ground-control eggs.

The results of the experiment were inconclusive. The wadding near the cap of each vial may have prevented adequate oxygen from reaching the eggs. Or, perhaps the regulated humidity of both Skylab and the ground controls was too low, causing the egg shells to harden so that the larvae could not crack through. The fact that none of the ground-control eggs hatched indicated that spaceflight was responsible for the limited success.

Diapause did terminate after 5 months, about half the normal time, for 7 of the 17 flight eggs that hatched. This does indicate some promise for successful results, and the Department of Agriculture is interested in further experiments on Space Shuttle flights. However, in the past few years, other population-control techniques such as new insecticides, parasites, and insect viruses have demonstrated greater effectiveness than the sterile-



Astromoth 1 survived the rigors of being flown into space and returned to Earth as an egg. She hatched out and was later mated with an Earth-born male gypsy moth. Unfortunately, none of her eggs hatched.

male technique for restraining the gypsy moth population. The significant result of this experiment was the demonstration that zero gravity can induce alterations in some biological processes of life forms accustomed to Earth's gravitational field.

Fish Otolith Organ

To obtain a better understanding of the vestibular or otolith organ, which enables an animal to maintain its balance or normal orientation to the gravity force of its natural environment, two small fish were launched with the second Skylab crew. Since, under spaceflight conditions, it is not possible to obtain all of the necessary physiological data about vestibular function from men alone, additional data from animals were desired.

The experimental animals selected had to meet several fundamental requirements. They had to be small and require little or no care by the crew. Also, they had to respond quickly and consistently with regard to their vestibular function. Their vestibular system had to be similar to that of higher forms of life, and they must have been the subject of correlative studies on Earth. The obvious candidate was a small fish. The fish selected for Skylab was the common mummichog (*Fundulus heteorclitus*), which is found along the Atlantic coast of the United States.

Two fingerlings and 50 fertile eggs were carried to Skylab by its second crew. After 3 days in orbit, their plastic acquarium was opened, and the fingerlings were observed to be swimming in an odd, circular pattern. The fish looped sideways, keeping their backs to the light. Loops of small radius alternated frequently with loops of larger radius. The fish swam in left loops about as much as they swam in right loops. This looping swimming decreased slowly in orbit until a normal pattern of swimming prevailed. Within 21 days, the two fingerlings appeared to have adapted to weightlessness, but they would still loop when their plastic acquarium was shaken.

The eggs started hatching after 19 days, with the majority of them doing so during the fifth and sixth weeks of the mission, approximately 2 weeks after the control eggs on Earth hatched. Visual orientation was immediate upon hatching; the young fish kept their backs toward the light as their Earth-hatched cousins also did. However,

Fertile eggs of the mummichog fish were flown to Skylab as part of an experiment to determine the role of the otolith organs in maintaining balance.

they also exhibited the abnormal swimming in tight circles only when the bag aquarium was shaken.

It appears that the Skylab fish utilized visual orientation, turning their backs to the light, as a substitute for gravity. Earth studies on a centrifuge have indicated that the orientation of fish is influenced both by the direction from which the light comes and the direction of the pull of gravity. In Skylab's zero gravity, the fish kept their backs to the light with no measurable deviation. The phototropic (orientation toward light) orientation and the relatively flat aquarium probably explain why they swam in loops. The fish were probably responding to signals from extremely fine hairs in their otolith which straighten out in the absence of gravity. They reacted by swimming in a forward loop which was distorted into a sideways loop by the tendency to keep their backs to the light. Additional experimentation will be needed to explain fully the strange looping and the apparent phototropic response of the fish. The fish hatched in orbit apparently adapted to the zero gravity while still in the egg.

The Skylab aquarium simulated a natural environment for the fish, except for gravity, by providing a dark background (bottom of pond) and a lighted surface (sky).

Two mummichog minnows were also sent into space to observe their reactions to weightlessness. They are barely visible, while eggs can be seen near the top of the photograph.

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AFTERWORD

The students associated with Skylab had the rare experience of participating in a unique laboratory for scientific research. If some of their experiments did not meet their expectations, then they learned the lesson that results of scientific research are no more predictable in space than they are on Earth.

A prime objective of the Skylab student project was to stimulate careers in science for those high school students who exhibited incipient interest. The degree to which this goal was achieved is illustrated by the final report of Gregory Merkel:

> My acceptance as a winner and finalist in the Skylab student project came as quite a surprise to me, and was to become very influential in the decisions I was in the process of making regarding my plans for college. I had already been accepted at the University of Massachusetts at Amherst, and tentatively planned on majoring in art.
>
> Art and science have both been consuming interests throughout my life, and the need to choose one over the other as a major in college was a decision which had many times been an anguishing one. The acceptance of my student project proposal now gave a new dimension to the situation.
>
> Early that spring was the first gathering of all the students at the Marshall Space Flight Center in Huntsville, Ala. It was here that the decision was made that my experiment could not be performed on Skylab. The reason was simple enough, and there seemed no way around it . . . there was really no way in which the experiment could be properly executed.
>
> In an effort to keep me involved in the Skylab program I was told that I would have an opportunity to work with one of the principal investigators on his experiment. Since I expressed that astronomy was one of my growing interests, it was decided that I would become affiliated with one of the astronomical experiments aboard Skylab, the specific experiment not chosen at that time.
>
> Consequently over the summer I did extensive reading on various subjects in astronomy, and as my interest in the subject grew I decided to major in physics and astronomy at the university.
>
> In summary, the experiences I've had as a result of the Skylab student project have all been beneficial. I would say that the most important result of this association was the 2 years I spent as a physics and astronomy major, a course of action which I might not have taken otherwise. In being compelled to delve more deeply into astronomy I've learned things which have had an extremely profound impact on my entire philosophy. I cannot overemphasize how important this understanding of the universe has been in establishing for me an integrated philosophy and in affecting my way of thinking.

When the student project was originally conceived, it was expected that 5 or 6 experiments could be accommodated. As the concept developed 25 students enjoyed the experience of participating in a major space research program, with 19 experiments involved in the flight of Skylab.

The enthusiastic response of students from across the country who submitted proposals as an extracurricular activity demonstrated a strong interest in space. The quality, scientific depth, and understanding of space technology embodied in many of these student proposals greatly impressed the scientists of the Skylab program.

The neutron experiment of Terry Quist provoked enough interest in the scientific community to influence planning for a similar but more sensitive experiment on the Apollo-Soyuz Test Project in 1975. The interest in and failure of Roger Johnston's capillary studies also prompted planning for a similar experiment on the same joint Soviet-American spaceflight.

Every student involved was afforded a unique learning opportunity and contact with the world of scientific research that would have been otherwise impossible. In addition, the general public enjoyed a more personal identification with space exploration through exposure to the enthusiasm of these students. It is to be hoped that more students will be able to learn through participation in future space programs.

Both the student project and the science demonstration program proved that significant investigations can be accomplished in space with simple "carry-on" or "suitcase" experiments. Extension of this concept will enable the development of simple but scientifically significant experiments that can be performed in space at nominal cost in the coming years.

EDITOR'S NOTE

The beginning-to-end association with the Skylab student project has been one of my most rewarding professional experiences. It is difficult to describe, and even more difficult to explain, the enthusiasm which this program generated for the entire Skylab mission. It was certainly greater than anyone envisioned. NASA is to be commended for the interest shown in high school students and the opportunity afforded them to contribute to this significant step in conquering space.

It is impossible to recognize all of the many thousands of people who contributed to the success of the Skylab program—those people whose efforts individually and collectively made this volume possible.

Credit certainly is due to those students who participated in the Skylab student project—not just those whose activities are described herein, but all students who submitted proposals, together with their teacher sponsors. The tremendous efforts of the National Science Teachers Association and the professional scientists and engineers around the country who helped in the most difficult task of selecting proposals contributed to the success of the program.

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Finally, we offer sincere appreciation to Henry Floyd, of the Marshall Space Flight Center. Henry's patience, understanding, and tireless effort lent direction to the program from beginning to end.

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Skylab Demonstration Films and Television Series

1. Six films, each 14 minutes in length depicting Skylab science demonstrations conducted in space, are distributed through the NASA free loan libraries. Astronaut Owen Garriott serves as teacher/narrator. Titles include: Zero G (HQa-260A), Conservation Laws in Zero G (HQa-B60B), Gyroscopes in Space (HQa-260C), Fluids in Weightlessness (HQa-260D), Magnetism in Space (HQa-260E), Magnetic Effects in Space (HQa-260F). To order, teachers should contact the NASA Educational Programs Office, Code FE, National Aeronautics and Space Administration, Washington, DC 20546.
2. The American Association of Physics Teachers (AAPT) in cooperation with NASA developed a series of 12 single-concept films on demonstrations conducted aboard Skylab. Each film is accompanied by a teaching guide. For additional information contact AAPT Publications Department, Graduate Physics Building, SUNY at Stony Brook, Stony Brook, NY 11794.
3. The Alabama Educational Television Network, in cooperation with the NASA MSFC Education Programs Office, produced a 16-program series "Science From Skylab." Educational television stations wishing to schedule should contact the Educational Programs Office, NASA Marshall Space Flight Center, Marshall Space Flight Center, AL 35812.

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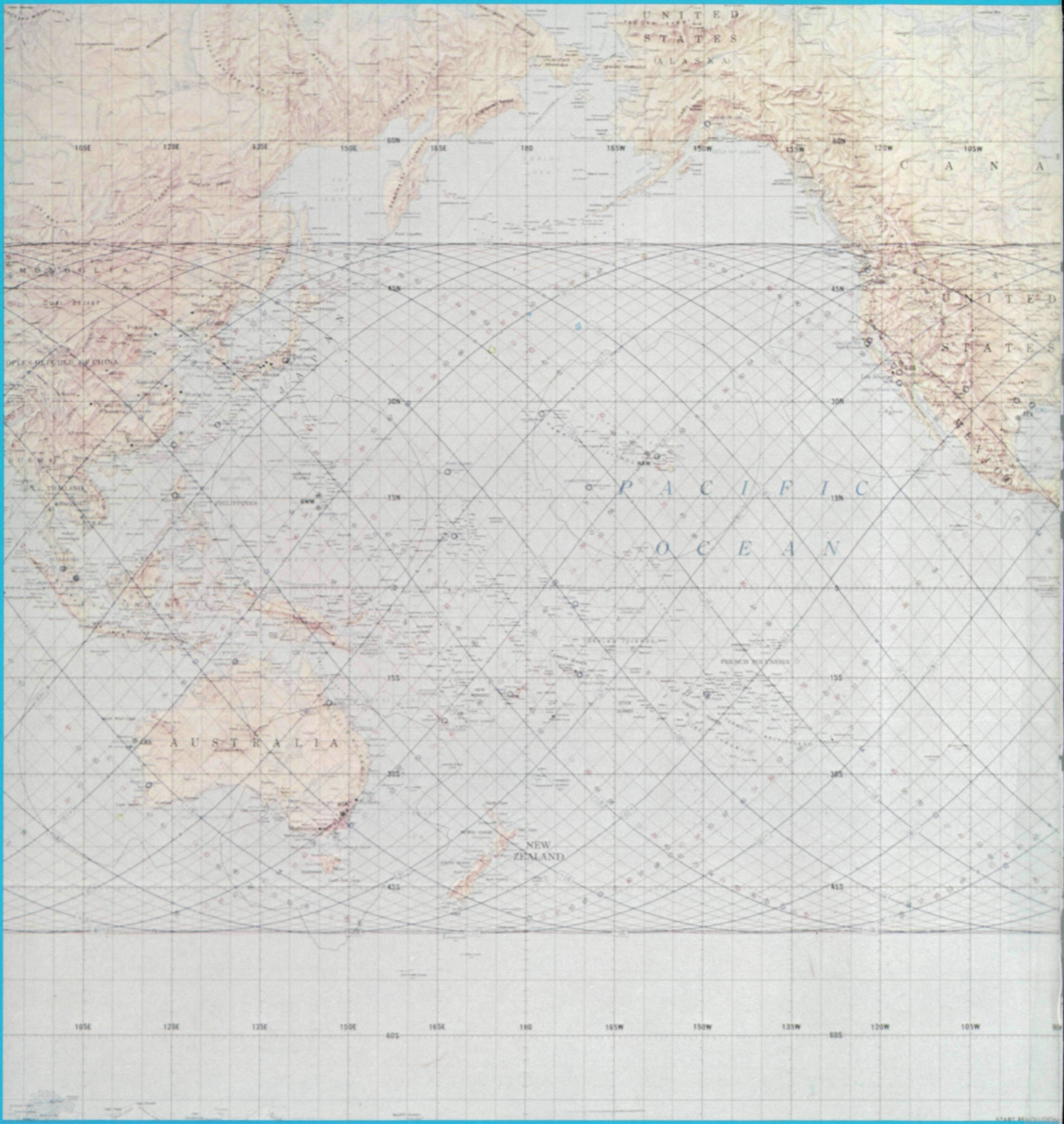
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