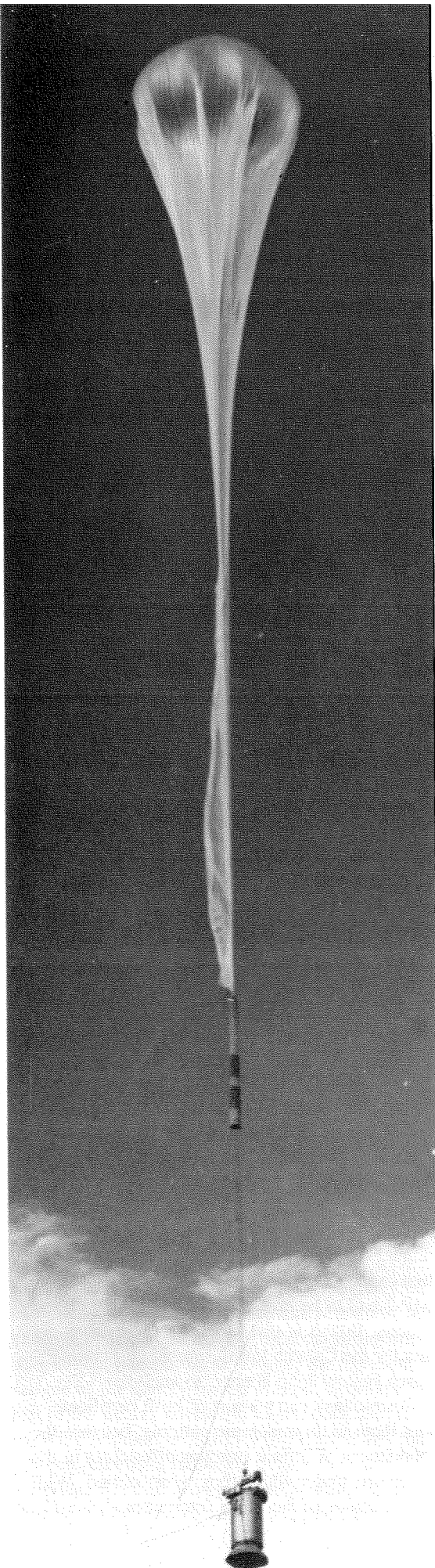


Star Stuff

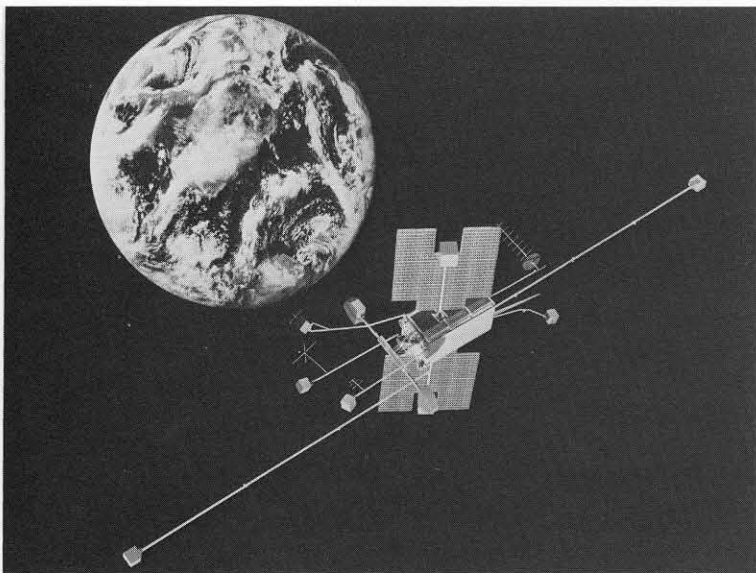
by Dennis Meredith



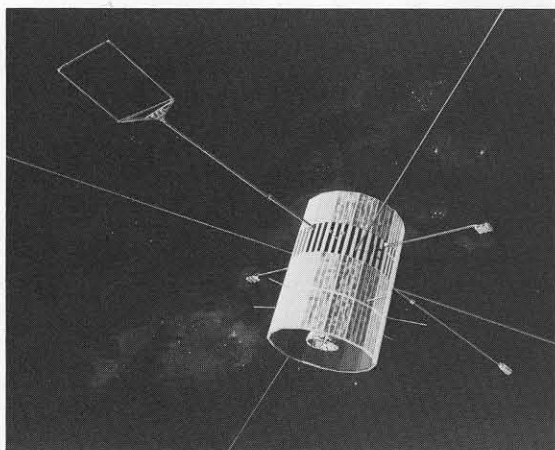
WHILE we humans may never reach the stars — at least not in this millennium — in a very real sense the stars have already reached us. Careening about our Milky Way like chaotic flights of cosmic bullets are swarms of high-energy charged particles. They have been blown out of exploding stars or launched into flight by the shock waves from such explosions. For millions of years they have ricocheted about the galaxy, their paths altered by collisions with other particles and the deflection by galactic magnetic fields. These particles are known as cosmic rays, and they bombard the solar system from all directions. They are mainly the nuclei of atoms stripped of their electrons and accelerated to a wide range of velocities, from a few percent to more than 99 percent of the speed of light. Like bullets, they come in a wide variety of calibers, from the BBs of hydrogen nuclei to the howitzer shells of uranium. And each atomic nucleus also comes in a number of different isotopes.

The sun answers back with its own flux of solar energetic particles. These particles flow outward in billowing gusts along the warped magnetic field lines of the rotating sun. During the immense explosions called solar flares, the intensity of such particles can jump to one million times normal in an hour. The sun also emits waves of very low energy particles, called the solar wind, which act as a barrier against galactic cosmic rays, so that only the higher energy galactic rays make it all the way upstream into the interior of the solar system. Another source of energetic charged particles in space is the magnetospheres of the planets, which both accelerate and trap particles, sometimes squirting them out into interplanetary space.

Cosmic rays carry memories of their birth and travels in their charge, mass, energies, and streaming patterns. By using balloons, rockets, satellites, and space probes, physicists have managed to loft particle detectors above the atmo-



Top, OGO-6 (Orbiting Geophysical Observatory), launched in 1969, carried Vogt's and Stone's first Caltech-built cosmic ray detector into space. Right, IMP-8 (Interplanetary Monitoring Platform) launched in 1973 provided one of the first long looks at high-energy particles from the sun, the galaxy, and the earth's magnetic field.



sphere (necessary because the atmosphere stops almost all extraterrestrial cosmic rays) to capture glimpses of the particle stream. It has been a highly successful effort, and over just the last few years, sophisticated new detectors have allowed the knowledge of cosmic rays and their solar, planetary, and galactic sources to grow enormously.

Scientists at Caltech's Space Radiation Laboratory, led by Professors of Physics Edward Stone and Rochus Vogt have been among the leaders in these studies. Their research group, a team of physicists, students, engineers and other essential staff members, as well as collaborators at other institutions, have built and flown detectors aboard satellites with an alphabet soup of names — OGO, IMP, ISEE, and HEAO — as well as aboard balloon flights and the two Voyager spacecraft, now speeding into the outer reaches of the solar system.

The scientists are continuing a long tradition of pioneering cosmic ray research at Caltech. The many cosmic ray studies at the Institute included

those of Robert A. Millikan, whose research did much to characterize these particles, and who in fact dubbed them "cosmic rays." One of Millikan's students, Carl Anderson, who is now Board of Trustees Professor of Physics Emeritus, was awarded the Nobel Prize in 1936 for his discovery of the positron using cosmic rays as a source, and his cosmic ray studies yielded evidence of some of nature's fundamental particles. Another Millikan student, H. Victor Neher, who is also now an emeritus professor of physics, continued and enlarged Millikan's studies for several decades. And still another who worked as a student with Millikan on cosmic ray research is William Pickering, professor of electrical engineering emeritus.

The current era of cosmic ray research at Caltech was marked by the launching of NASA's Orbiting Geophysical Observatory (OGO-6) in 1969. It carried Vogt's and Stone's first Caltech-built cosmic ray instrument into space. OGO was soon followed by two "IMPs" — Interplanetary Monitoring Platforms 7 and 8 — launched by NASA in 1972 and 1973. They carried a new generation of silicon charged-particle detectors designed by Stone and Vogt, with electronics built under the supervision of William Althouse. These satellites, orbiting midway between the earth and the moon, gave scientists one of the first continuous, long-term looks at the swarms of high-energy particles from the sun, the galaxy, and the earth's magnetic field. Among many other discoveries, the IMP spacecraft yielded evidence showing that the planet Jupiter acted as a powerful particle accelerator, flinging dense waves of high-energy electrons at least 200 million miles into space. These Jovian electrons — with energies of several million electron volts (MeV) — often totally dominate the flux of cosmic ray electrons surrounding earth.

The IMPs also revealed how the charged particles trapped in the earth's magnetic field behave. For example, they found that surrounding the "tail" of the earth's magnetosphere, which is swept back by the blowing solar wind, is a layer of high-speed electrons. This 15,000-mile-thick layer is apparently accelerated by the earth's magnetic field. The IMP satellites proved more than capable; they were extraordinary. While IMP-7 had to be turned off in 1978 for budgetary reasons, IMP-8 is still sending back streams of data for the Caltech group, including Senior Research Fellow John Bieber, to analyze.

Cosmic rays carry a sort of birth certificate with them in their isotopic patterns, because the abundances of certain isotopes offer clues to the conditions under which they were formed. With the launching of the Third International Sun-Earth

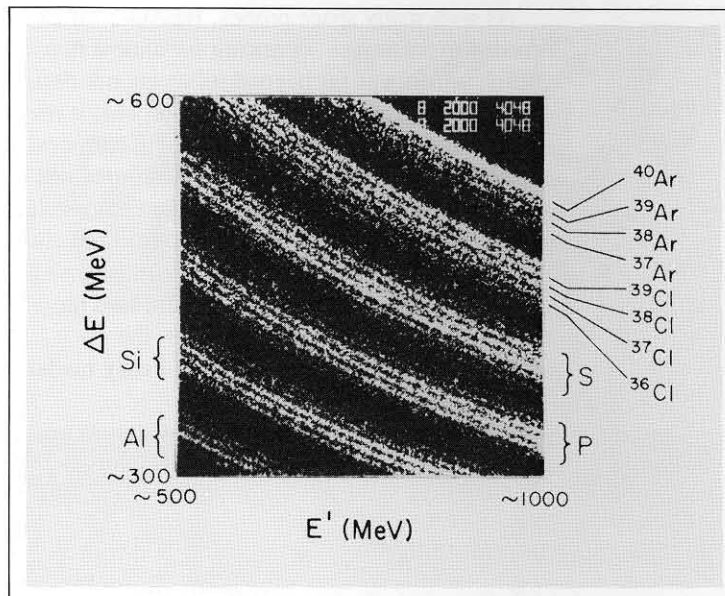
Explorer (ISEE-3) in 1978, Stone, Vogt, and their colleagues provided the first instrument that could read this birth certificate with high resolution. Senior Scientist Alan Cummings oversaw the production of the unique silicon detectors that made this possible. The spacecraft was also unique because it orbited the sun at the “libration point” over one million kilometers from earth — the point at which the gravitational pull of the sun and earth neatly balance one another.

The Caltech-built instrument on board ISEE was called a cosmic ray isotope spectrometer, and it yielded several surprises. For one thing, it made the first high-resolution measurements of heavy nuclei accelerated during a solar flare — a magnetic explosion on the sun that can release the energy of a million hydrogen bombs. The Caltech scientists used the ISEE instrument to measure the isotopic patterns of carbon, oxygen, neon, and magnesium as they spewed out of flares.

Surprisingly, the ISEE experiment represented one of the first times scientists had ever directly measured the isotopic composition of the sun. Despite the fact that the sun is by far the dominant object in the solar system, there is very little direct information about its composition. Most of our information about solar system compositions comes from studies of terrestrial and meteoritic material.

ISEE also provided the first hints that our solar system may be made of distinctly different stuff from that in nearby regions of the galaxy. The ISEE instruments revealed that galactic cosmic rays possess a distinctly different isotopic composition from solar cosmic rays. The Caltech scientists confirmed earlier measurements showing that, compared with the common isotope of neon ^{20}Ne , there is more than three times more of the heavier ^{22}Ne in galactic cosmic rays than in solar cosmic rays. They subsequently found that the heavy isotopes of manganese ^{25}Mn and ^{26}Mn are also more abundant in galactic cosmic rays.

Many astrophysicists have concluded that these differences are not isolated; in five cases in which the cosmic ray isotopic composition has been precisely determined, the galactic material is different from the solar material. Thus, we may have been cooked up using a different recipe from the rest of the galaxy. Perhaps, say the scientists, because our solar system condensed out of cosmic dust almost five billion years ago, we represent a sample of the galaxy frozen in time, while the rest of the galaxy continued to percolate along, evolving without us. ISEE is still active, and the Caltech scientists, including Senior Research Associate Richard Mewaldt and graduate student John Spalding, expect further insights from the



long series of scientific questions they will ask of ISEE’s rich trove of data.

While ISEE was able to capture and measure elements as heavy as iron, beyond iron in the periodic table of the elements lies additional important information about how cosmic ray nuclei are formed in stars. The elements heavier than iron, ranging up to uranium, require special conditions to create because, unlike lighter elements, they absorb energy during their formation rather than releasing it. Certain of their isotopes are believed to be formed by “rapid” neutron capture, possibly when a violent supernova or its remnant pulsar slams neutrons into the nucleus in a process taking only a few seconds. Other heavy isotopes are formed by “slow” neutron capture, in which neutrons are added one at a time in the thermonuclear fires of stars that evolve more slowly.

As valuable as these ultra-heavy cosmic ray nuclei are to science, collecting them is no easy matter, because they are up to 100 million times scarcer than their lighter cousins. Large-area detectors and long exposure times are needed to detect significant numbers of them. But, working with researchers from the University of Minnesota and Washington University (the team leader is Martin H. Israel, professor of physics at Washington University, Caltech PhD ’69), the Caltech scientists were able to build the largest area cosmic ray detector yet used in space. It included two ionization chambers, each measuring two square meters in area. In 1979, it was carried into space on NASA’s High-Energy Astronomical Observatory (HEAO-3). Among the nuclei detected so far are zinc, selenium, krypton, molybdenum, xenon, and barium.

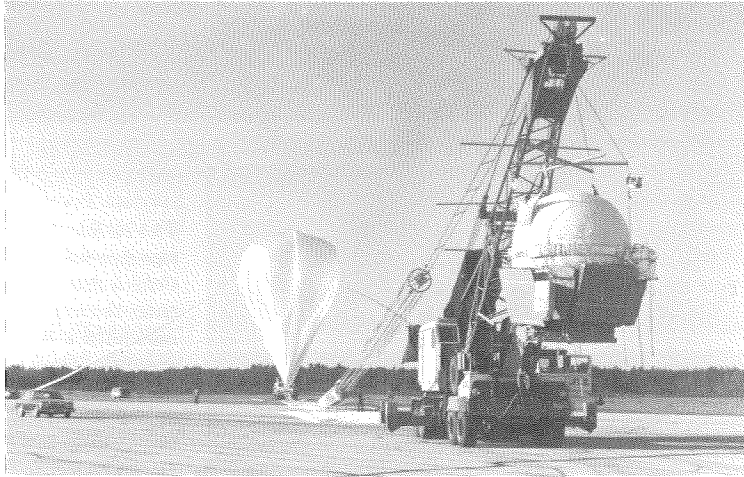
This on-line display of raw isotope data was acquired with the Caltech Heavy Isotope Spectrometer Telescope (HIST) during a calibration at the Bevalac. The experiment involved a ^{40}Ar beam incident on a polyethylene target, where many of the ^{40}Ar ions break up into lighter nuclei. The instrument measured the particles, each plotted here as an individual point, emerging from the target. The broad bands are due to the elements aluminum to argon, and each broad band consists of narrower parallel “tracks” corresponding to individual isotopes. These data provided the first experimental proof that cosmic ray instruments composed of silicon detectors could identify individual isotopes of heavy elements with high resolution. HIST was carried into orbit on ISEE-3 in 1978.

As with many space probes, HEAO-3 far exceeded expectations, operating for almost two years, which was far beyond its six-month design lifetime. And as with many space probes, it revealed to the researchers a fascinating complexity in cosmic ray nuclei formation. Some previous experiments had suggested that ultra-heavy galactic cosmic ray nuclei were formed almost exclusively by rapid neutron capture in supernova explosions, and the HEAO-3 group did find these nuclei, such as selenium. However, the experimenters also found many ultra-heavy nuclei,

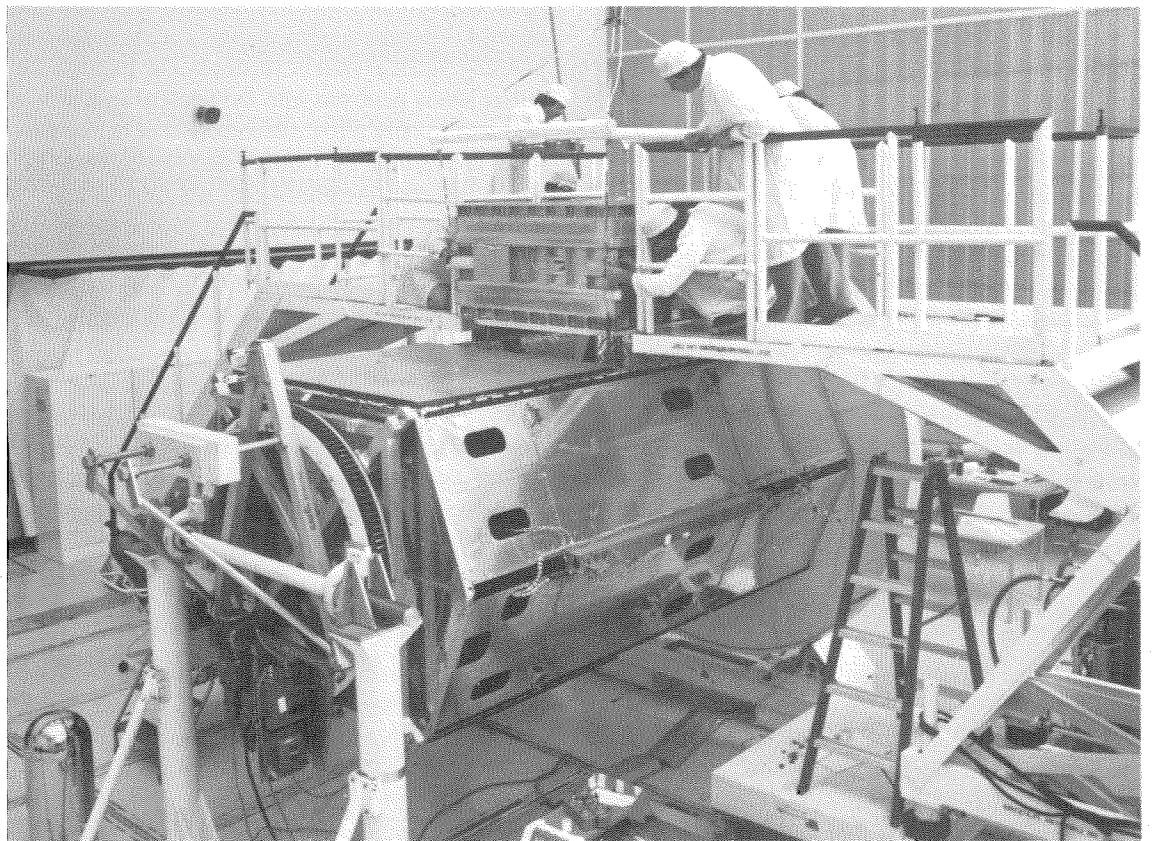
such as strontium, that were formed by the gentler slow neutron capture process.

The confounding question then became how these slow-cooked nuclei could have been launched to near light speeds if they were not formed in a violent explosion. According to a recent model proposed by Caltech Professor of Theoretical Astrophysics Roger Blandford in collaboration with Jeremiah P. Ostriker of Princeton, the shock wave from a supernova sweeping through space might accelerate such non-supernova material. The HEAO-3 team, including Senior Scientist Tom Garrard, is continuing its analysis of the satellite's data, sorting out more and more of the ultra-heavy elements. Eventually, they hope to have sorted out the elements all the way to uranium.

Continuing the Caltech group's effort to measure cosmic ray isotopes, Senior Research Associate Andrew Buffington and Senior Scientist Stephen Schindler are currently leading a collaborative effort with the Danish Space Research Institute to complete a new instrument capable of high resolution in detecting rare cosmic ray isotopes with energies above a billion electron volts. The detector, weighing several thousand pounds, will be launched by balloon next fall and should provide the Caltech scientists still another valuable chance to capture material from the stars.



Top, an instrument designed to search for cosmic ray antiprotons and antihelium nuclei is readied for balloon launch at The Pas, Saskatchewan, in 1980. Right, half of the cosmic ray instrument (the other half goes into the opposite side) is lowered into the HEAO-3 satellite at the TRW Inc. plant. HEAO-3 was launched in 1978.



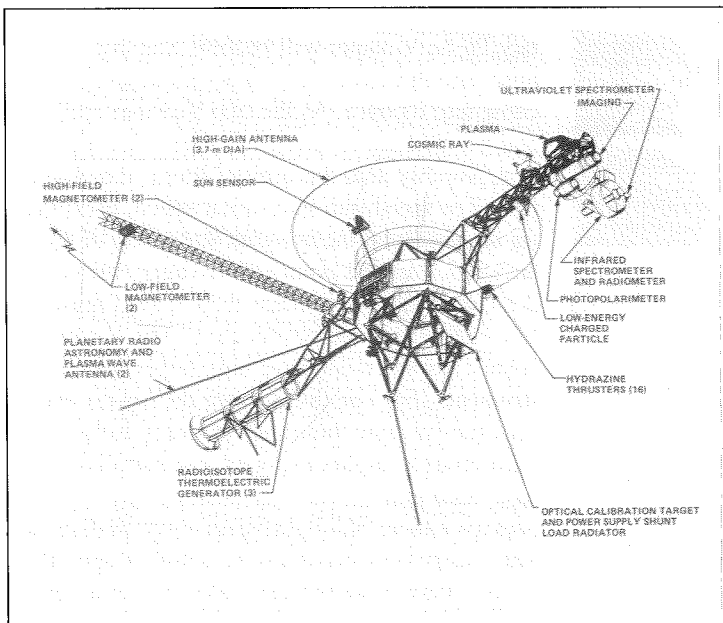
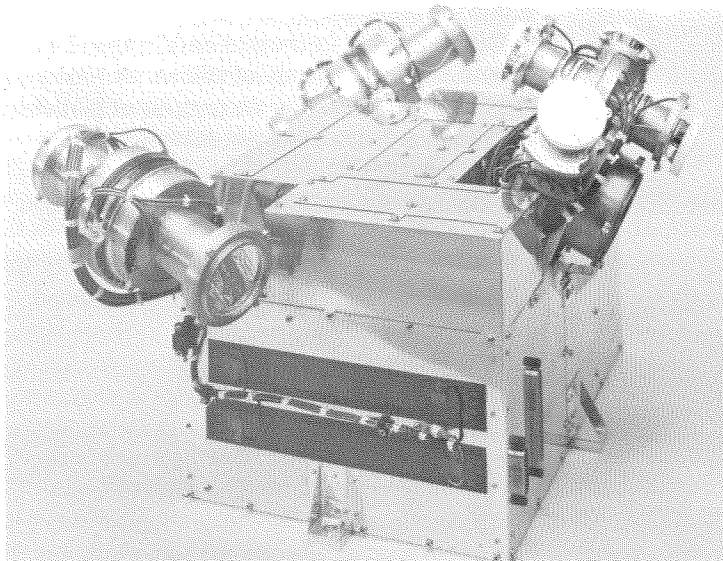
The scientists hope the new detector will yield insights into the age of cosmic rays and the material they have encountered in their travels. The abundances of certain isotopes of cobalt, nickel, and iron, for instance, can give scientists a measure of the time between birth and acceleration, because these isotopes decay only as atoms with orbital electrons, and not as stripped nuclei traveling at high speeds. Still other radioactive isotopes of aluminum, chlorine, calcium, manganese, or iron can function as cosmic ray "clocks" to measure how long cosmic rays have been rattling about the galaxy.

In 1980 Buffington and Schindler also flew a balloon-borne experiment to search for cosmic ray antiprotons and antihelium nuclei. While earlier high-energy studies had shown a few antiprotons among cosmic ray protons, most scientists believe these didn't come from any large antimatter source in the galaxy, but were merely the result of ordinary cosmic ray protons striking atoms in interstellar gas. Physicists have succeeded in producing similar small numbers of antiprotons on earth by colliding particles in high-energy accelerators.

Since such antiprotons were far less likely to be produced at low energies, Buffington and Schindler studied cosmic rays with energies one-tenth as high as in the earlier studies, expecting to see less than one-tenth as many antiprotons in their experiment. But surprisingly, they found just as many as the high-energy experiments had revealed. The "Mystery of the Too Many Antiprotons" remains to be solved. Is it the first hint of an exotic region of antimatter somewhere in the universe? Or is it a strange quirk of ordinary cosmic rays that scientists still do not understand?

While Stone, Vogt, and their colleagues were developing better and better detectors for their balloon and satellite experiments, they were also helping send detectors far beyond the local environment of the earth. Working with scientists from Goddard Space Flight Center, University of Arizona, and University of New Hampshire, the Caltech researchers are participating in the cosmic ray experiment aboard the two Voyager spacecraft. Vogt is principal investigator for the cosmic ray investigation, and Stone is a co-investigator as well as the Project Scientist for the overall Voyager mission.

The small 16-pound Voyager cosmic ray package is located about halfway out on the instrument booms of the two probes. The task of the silicon detectors is to measure the energy spectrum of electrons and cosmic ray nuclei — ranging from one to 500 MeV, as well as the abundances of atomic nuclei from hydrogen through



iron. The scientists' targets have also included the radiation belts of Jupiter and Saturn and the particles erupting from solar flares. Just as the cameras of the two Voyager spacecraft have returned stunning pictures of Jupiter and Saturn, so the cosmic ray packages have also performed brilliantly.

Among many other discoveries the scientists found that, compared to common solar system material, Jupiter's trapped radiation belts are heavily enriched with high-energy oxygen, sodium, and sulfur nuclei, zipping through space at up to 10 percent of the speed of light. The sulfur probably originated from the famous volcanic eruptions on Io and the sodium from surface deposits on that moon. Graduate student Neil Gehrels studied the flow and fate of this material

The cosmic ray instruments aboard Voyager 1 and 2 each consist of seven telescopes — two double-ended ones (left) for high-energy cosmic rays and a quartet of telescopes (right) for low-energy particles. Beneath the latter is a telescope designed to measure cosmic ray electrons. The instrument is located half way out on one of Voyager's booms, as shown in the diagram.

within the immense Jovian magnetosphere.

The cosmic ray instrument on Voyager 2 even yielded evidence recently of still another moon around Saturn. Studying the patterns of particle absorption around the planet, Research Fellow David Chenette detected a "shadow" indicating that the particles were blocked by a small moon sharing the orbit of Mimas.

In analyzing Voyager cosmic ray data from solar flares, graduate student Walter Cook found that abundances of some elements in flares indicated that they sampled material from the sun's corona — the hot, low-density region above the sun that produces the solar wind — rather than from the underlying photosphere, which is the sun's glowing "surface." The mechanism by which the sun apparently filters photospheric material to produce the coronal composition is not yet understood.

Sometime during the next two decades Planetary Probe Voyager will become Starship Voyager, and the cosmic ray experiment will really come into its own. As the two Voyager craft reach a distance of several billion miles from the sun, possibly near the orbit of Pluto, they are expected to speed into interstellar space, escaping for the first time the constant streaming of the solar wind. Past this point the Voyager cosmic ray detectors will give humans their first glimpse of low-energy galactic cosmic rays. The Voyager cosmic ray scientists have high hopes for their instruments. For one thing, since the lowest energy rays survive only thousands of years, rather than millions as at higher energies, the particles must have been emitted recently from nearby objects, perhaps a mere 500 light-years away. In fact, the low-energy rays may even be non-isotropic; that is, they may come preferentially from one direction. Since there have been few violent cosmic-ray-producing events in our galactic neighborhood recently, the researchers hope to use the Voyager instruments to associate cosmic rays for the first time with a specific astronomical object.

While Stone, Vogt, and their fellow scientists look forward with excitement to the future Voyager explorations, they have also faced disappointment in their other major exploratory project; the American half of the Solar-Polar mission was canceled in the recent round of federal budget cuts. The joint European-American program was to have consisted of twin probes vaulted out of the plane of the ecliptic to orbit over the sun's poles. Aboard the American craft was to have been a large high-resolution cosmic ray instrument built by the Caltech group and its collaborators. Had the probe flown above the sun's poles, the physicists would have explored a region of the

How to Catch

CAPTURING a cosmic ray is not as difficult as it might seem, because the energetic particles leave considerable evidence of their passing. They ionize gases, damage solids, and create electrical disturbances in crystals, and all of these phenomena have been used as bases for cosmic ray detectors. However, sorting out the cosmic ray nuclei from one another is another business entirely.

In fact, the first primitive device used to study cosmic rays — the ionization chamber — told little more about the rays than that they existed. The ionization chamber is basically a gas-filled insulated chamber into which a pair of electrodes is inserted. When a charged particle passes through the chamber, it ionizes the gas in the chamber, creating a current. Physicists using these devices quickly discovered that some mysterious source of ionizing radiation tended to produce signals in the chambers, even when radioactive materials were not present. It was eventually discovered by launching ionization chambers on balloons that this radiation came from outer space.

Still later an improved, high-voltage version of the ionization chamber, called the Geiger-Mueller counter, came into wide use. This counter produced an electrical signal each time a charged particle passed through the gas in the high-voltage chamber.

An advanced version of the ionization chamber served as the basis for the cosmic ray detector aboard the satellite HEAO-3. In this detector, cosmic ray particles traversed a complex stack of ionization chambers in which the size of the signal caused by each particle was precisely measured. The result was that scientists could characterize the particle by how much energy it lost traversing the series of detectors. In addition, HEAO contained more than 1,000 smaller ionization chambers in an X-Y grid pattern that were individually

solar system possibly as strange as any alien planet. For one thing, the craft might have sailed through a sort of polar doldrum in the solar wind, where low-energy galactic cosmic rays may come streaming into the solar system, carrying with them information about the rest of the galaxy. The detector system for the canceled mission, however, is already largely completed, and the Caltech scientists hope eventually at least to fly it aboard an earth-orbiting satellite.

While cosmic ray research has taken great strides in the last few years, volumes of tantalizing questions about the universe still remain — many of which this group of Caltech researchers feel they could answer by sifting through data on star stuff, the fascinating storm of particles that swirl about us as cosmic rays. □

a Cosmic Ray

instrumented to determine the position and angle of incident particles.

To yield still more information about the cosmic rays, the HEAO-3 detector also featured a Cerenkov detector. This device is based on the fact that a form of light called Cerenkov radiation is produced when charged particles pass through certain materials at very high velocities. The particles produce a sort of electrical shock wave in the material, resulting in a flash of light along the particle's "wake." In Cerenkov detectors, photomultiplier tubes are used to detect the flashes from cosmic rays.

When cosmic rays pass through certain plastic or inorganic materials and excite the molecules in them, the recombination of ions in the particles' wake also produces a flash of light. This phenomenon has become the basis for scintillation counters used as cosmic ray detectors.

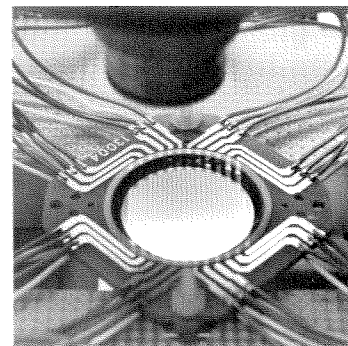
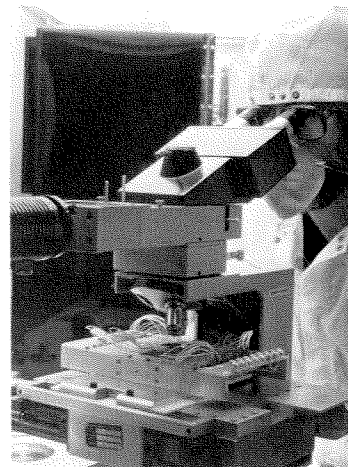
The detector being developed for the balloon-borne isotope spectrometer is a form of scintillation counter. It consists of stacked discs of highly polished sodium iodide crystals about half a meter in diameter. These plates are surrounded by a series of photomultipliers that can track the particle through the detector. By comparing the signals from several discs, each viewed by six photomultipliers, scientists can determine, not only the particles' charge and mass, but also the precise angle and position at which the particles traversed the detectors, and thus can correct for the variations in thickness of material seen by particles entering at different angles. Signals from Cerenkov detectors above and below the detector array can be compared to find the velocities of the particles.

Of all cosmic ray instruments in use today, solid-state silicon detectors yield the most accurate measurement of energy deposition by energetic particles. Sili-

con detectors are basically thin wafers of silicon crystal with gold and aluminum electrodes attached. A cosmic ray striking the detector produces a tiny electrical signal that is linearly proportional to the energy lost by the particle. By measuring electrical signals in a stack of such wafers, scientists determine a particle's energy and charge. The ISEE instrument could resolve cosmic ray isotopes (mass), where earlier instruments could identify only elements (charge), because of the development of two-dimensional, position-sensitive solid-state detectors that can track the particle through the detector stack, allowing precise corrections for the detectors' position and angular response. The electrodes on these position-sensitive detectors are a criss-crossed grid, so that each cosmic ray impact is precisely located.

Silicon detectors have been the basis of instruments on board OGO, IMP, ISEE, and Voyager, and were to be launched on the canceled Solar-Polar mission. The Solar-Polar instrument was to have included far superior silicon detectors 30 square centimeters in area, versus 9 square centimeters for the ISEE and Voyager detectors, and 3 square centimeters for the IMP detectors. In addition, the Solar-Polar position-sensitive detectors were to be four times larger than on ISEE. Such increased detector area is important because it increases the number of cosmic ray events detected per unit of time.

Regardless of whether they are silicon detectors, scintillation counters, Cerenkov detectors, or ionization chambers, modern space-borne cosmic ray detectors are remarkable scientific instruments — among the most sensitive and stable devices launched by man to study the universe. They are manufactured with painstaking care and carefully calibrated by bombarding them with precise beams of particles from high-energy accelerators, such as the tandem Van de Graaff in Caltech's Kellogg Laboratory and UC Berkeley's Bevalac accelerator. All this ingenuity pays off: modern detectors operate for many years with variations of less than hundredths of a percent to measure with extreme precision the infinitesimal impacts of cosmic ray nuclei.



Through a microscope Richard Mewaldt examines a position-sensitive, solid-state detector. The silicon detector, seen below in a laboratory test set-up, has deposited on its surface an array of parallel gold stripes (each .8 millimeters wide) that are used to determine the position of incident particles.



Members of the Space Radiation Laboratory Voyager team, led by Rochus Vogt (dark shirt) get the first look at real-time data from their cosmic ray instrument during Voyager 1 launch operations at JPL.