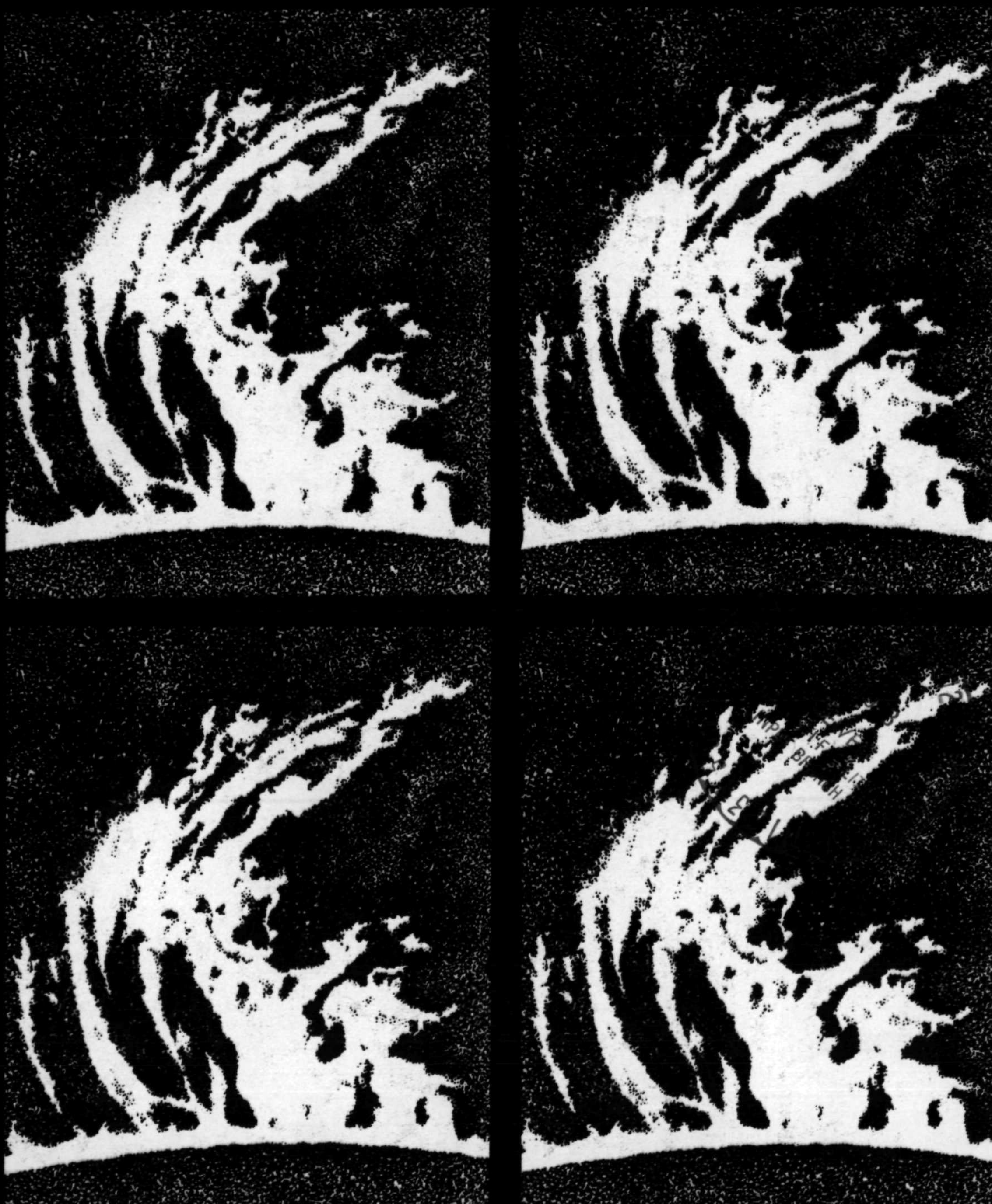
America in Space | The First Decade

SPACE PHYSICS AND ASTRONOMY



National Aeronautics and Space Administration

America In Space: The First Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

October 1, 1968

Titles in this series include:

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SPACE PHYSICS AND ASTRONOMY

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C., 20546

Introduction

In 1958 the National Aeronautics and Space Administration became responsible for developing space science. In that year it took up the work from where balloon and sounding rocket flights had carried it. Four American artificial Earth-satellites had already been put into orbit, and had discovered the Van Allen trapped radiation belt. NASA began immediately with its creation of intensive programs of scientific study. These programs were divided into several disciplines: energetic particles and magnetic fields to study cosmic rays and other energetic particles in space, and to extend magnetic field measurements above the surface of the Earth; ionospheres and radio physics; planetary atmospheres, including that of the Earth; solar physics; astronomy; and cometary physics and interplanetary dust. "Space Physics and Astronomy" describes the progress that has been made in these studies during the first ten years of NASA's existence. It represents one of the avenues selected by the Agency to disseminate the knowledge that it has gained in its programs in keeping with its responsibilities.

John E. Naugle
Associate Administrator for
Space Science and Applications

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Space Physics And Astronomy

Inside The Cocoon

On clear Moonless wintry nights the stars look so close that it is hard to imagine that we live on a cozy planet well insulated from outer space. Three unseen barriers deaden the sights and sounds of the vast, stormy space beyond the Earth. These barriers are the atmosphere, the ionosphere, and a new one discovered by satellites, the magnetosphere. Visible light penetrates these barriers easily; but most meteors, ultraviolet light, long radio waves, and subatomic particles never make it to the Earth's surface. In effect, the Earth is wrapped in a three-ply cocoon.

We need the insulation. Without the atmosphere and magnetosphere to absorb and ward off space radiation, life on Earth might not survive. So potent is space radiation that some scientists now wonder if the mass extinctions of earthly life so obvious in fossil-bearing rocks might be due to temporary losses of our planet's protective magnetic field.

Scientific curiosity about the universe and our place in it is our major stimulus for reaching out beyond the Earth's surface. A few meteorites, cosmic rays, the mysterious auroras, and a thin but steady stream of tantalizing hints about outer space continuously slip through the Earth's insulating layers. To find out more about these phenomena, scientists realized they had to take their instruments to higher altitudes to reduce the absorbing effects of the atmosphere.

In 1643, Torricelli simply climbed a mountain to see what happened to his barometer. Large kites carried instruments even farther. By 1900, balloons had lifted instruments beyond 50,000 feet. Scientific rocketry began in 1929 when Robert H. Goddard installed scientific instruments on one of his rockets. With the rocket, science could, in principle, reach any spot in the solar system. Rockets probed outer space a decade before the first satellites were launched in 1957. Earth satellites turned out to be superb instrument carriers; staying in orbit for years and circling the globe in a matter of hours. They radio back information about our atmosphere and what transpires beyond it.

Scientists found many unexpected things when the first rockets and satellites broke through the atmospheric barrier. Outer space is not an empty vacuum. It seethes with flotsam and jetsam from the solar system. The Sun violently stirs a thin extraterrestrial soup of particles and magnetic fields. Movement and interaction are everywhere.

m = meter
μ = micron = 10^{-6} meters
Å = Angstrom unit = 10^{-10} meters
x = x unit = 10^{-13} meters

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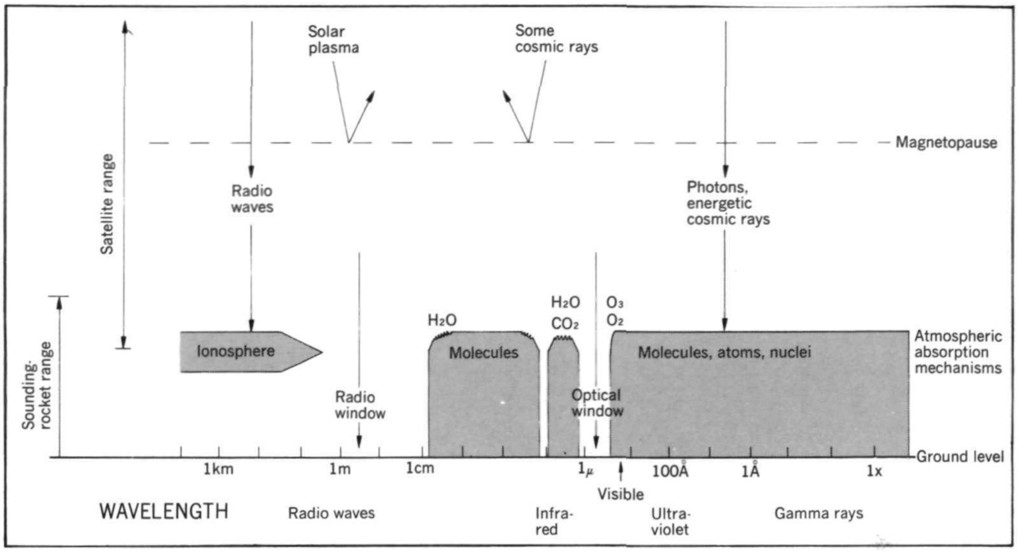


1 *The Earth's magnetopause, ionosphere, and atmosphere absorb or turn back most of the incoming radiation. Only a small portion of the electromagnetic spectrum reaches the Earth's surface through the windows. Satellites carry instruments in and above these insulating layers.*

The past decade has been exciting and rewarding for space science, but the new knowledge and insights have not come easily. And there are many things we still do not understand.

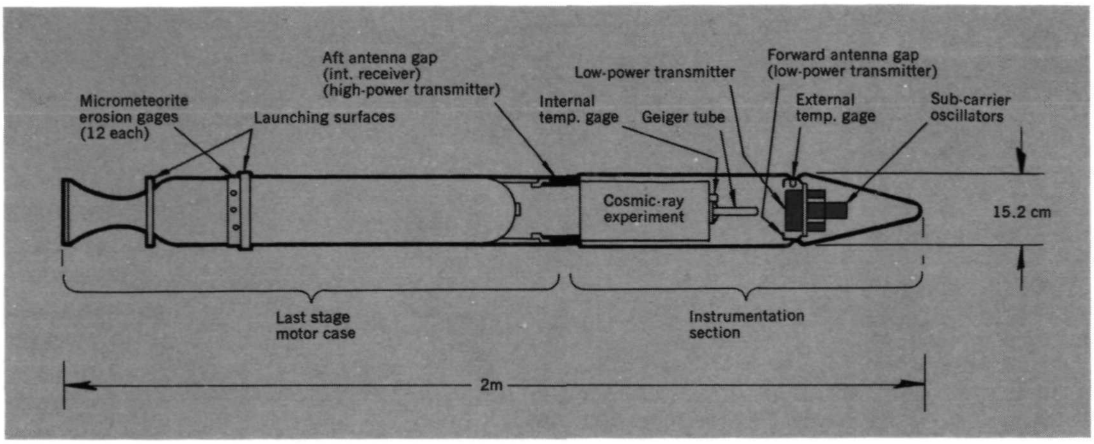
The Great Radiation Belts

Scientists began probing the upper reaches of the atmosphere in 1946 when captured German V–2 rockets arrived at the Army's missile test range at White Sands, New Mexico. Many of these early rockets carried Geiger counters and other radiation detectors to high altitudes. James A. Van Allen, Fred Singer, and other researchers wanted to see how the intensity and nature of cosmic rays varied with altitude and latitude. Like everyone else they were perplexed by the polar auroras (northern lights); perhaps high altitude rockets might find subatomic particles that stimulated the upper atmosphere to emit the eerie greenish light typical of auroras.

One hint came during the summers of 1952 through 1955, when Van Allen's group from the University of Iowa launched rockoons (balloon-launched rockets) from the deck of a Coast Guard cutter in Baffin Bay near the north magnetic pole. Van Allen's Geiger counters detected considerable soft (low energy) radiation at the peaks of the rocket trajectories—some 50 to 60 miles up—where the Earth's magnetic lines of force bend down toward the pole. The results were intriguing. What a boon an artificial satellite would be. It could criss-cross the polar regions north and south several times a day. Van Allen thus became a leading proponent of the embryonic U.S. satellite program and an advocate of placing radiation detectors on the first spacecraft.

Van Allen was successful in his campaign; Explorer I (January 31, 1958) carried a Geiger counter. After the fourth stage of the Jupiter C rocket successfully injected Explorer I into its orbit, the satellite began to climb towards its apogee of nearly 1600 miles. Once in each revolution, every 107 minutes, Explorer I's Geiger counter counted subatomic particles between altitudes of 225 and 1600 miles. As telemetry data were relayed via worldwide tracking stations, Van Allen

2 *Explorer III was almost identical to Explorer I. The whole last stage of the Juno launch vehicle went into orbit.*



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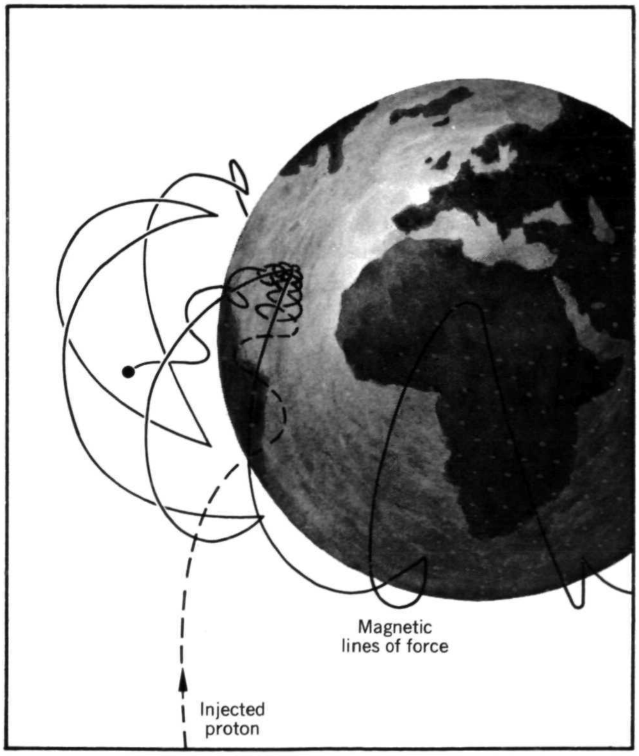
and his associates saw that their Geiger tube did not seem to be working properly. The counting rate first rose as the satellite swung up toward apogee, confirming the existence of the intense soft radiation discovered at lower altitudes in the early 1950s. But as Explorer I passed the 600-mile level, the counting rate abruptly dropped to zero. And it remained zero until the satellite descended below 600 miles. So it went on each orbit. Either the counter was faulty or—just possibly—the counter was saturated; that is, there was so much radiation above 600 miles altitude that the counter couldn't cope with it. This latter surmise was disturbing and completely unexpected by most scientists.

To resolve the question, Explorer II was launched on March 5; but the rocket's fourth stage did not ignite, and the satellite ended up in the Atlantic. Explorer III was successful on March 26, 1958. Telemetry showed the same pattern in the Geiger counting rate. No one questioned now that the counter was saturated by unexpected intense radiation.

Why was there a belt of intense radiation above 600 miles? Even before Explorer I, a few brave souls, such as Fred Singer and Nicholas Christofilos, had suggested that electrons and protons might be trapped by the Earth's magnetic field and forced to spiral from pole to pole along the magnetic lines of force. In fact, the Norwegian astrophysicist Carl Störmer had shown the possibility of magnetic trapping as far back as 1904. Nevertheless, most scientists were profoundly surprised by this first great discovery of space science.

Magnetic trapping is easy to visualize. When a charged particle, such as an electron or proton, moves in a magnetic field, it experiences a force perpendicular to both its direction of motion and the magnetic lines of force. Thus, charged particles spiral around the lines of force and follow them corkscrew fashion as they converge on the Earth's magnetic poles. Approaching the polar atmosphere, some particles collide with atoms

3 *Magnetic trapping of a charged particle. A proton, perhaps originating in the decay of an albedo neutron, spirals from pole to pole along magnetic lines of force.*



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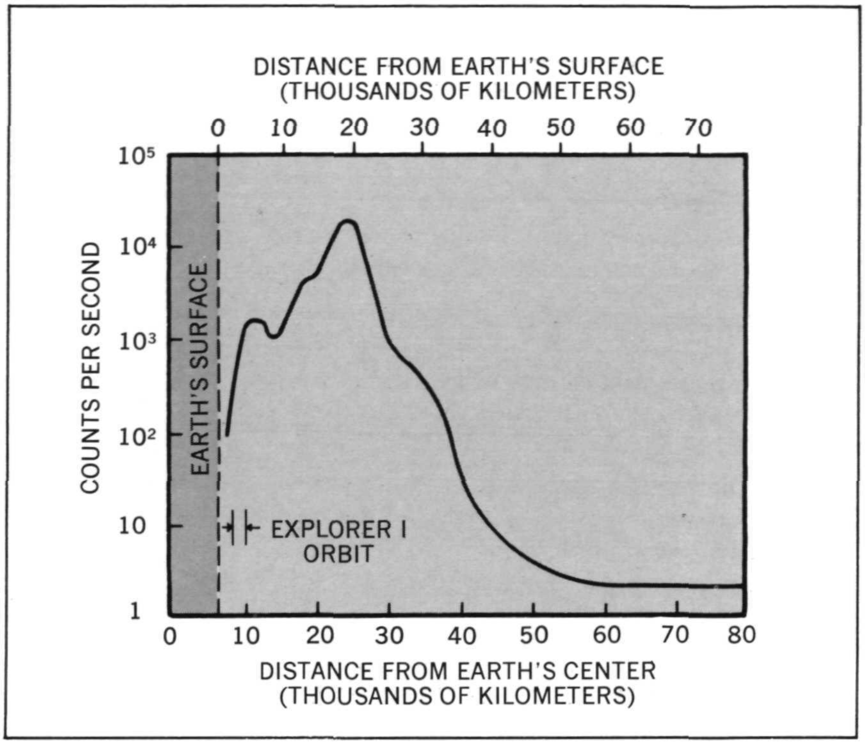

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and molecules in the upper atmosphere and get knocked out of the belt; others (in fact, most) are reflected back along the lines of force. The magnetic poles act like magnetic mirrors. The converging magnetic lines of force slow down and reverse the direction of travel of charged particles. The reflected particles spiral from pole to pole, taking only a few seconds for a round trip. The word "trapped" is apt; the particles are released only when they collide with the upper atmosphere.

The belt of radiation surrounding the Earth was quickly named the Van Allen belt. Naming something does not mean we understand it. In 1958, no one knew what kinds of particles occupy the belt or where they come from. More satellite experiments were needed.

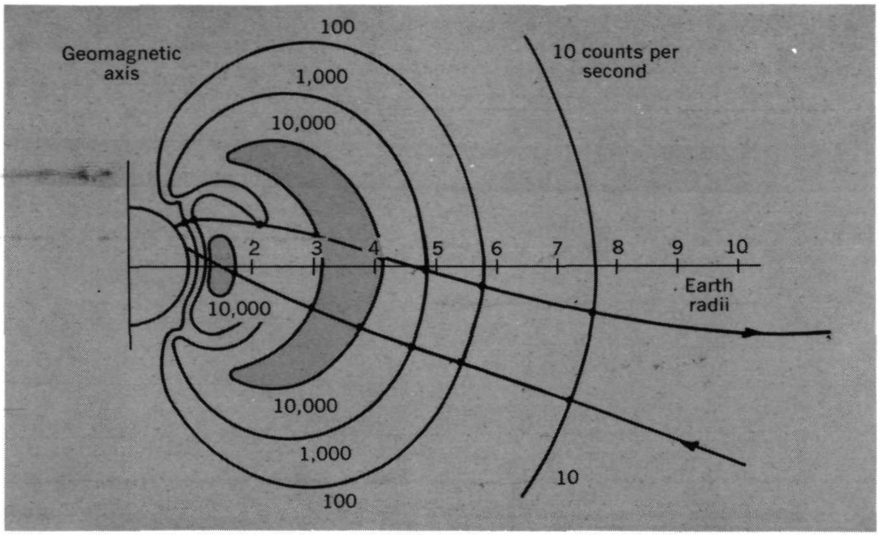
Van Allen quickly readied a payload consisting of two Geiger counters—each surrounded by different amounts of particle shielding—and two scintillation counters, which would respond to particles in a different way from the Geiger tubes. Explorer IV went into orbit on July 26, 1958. It mapped the radiation belt out to about 1400 miles and yielded some information on the energies of the trapped particles. By combining Explorer IV data with that from the deep space probe Pioneer III (launched December 6, 1958), Van Allen was able to draw his famous map showing two concentric belts of charged particles. The map was appealing because some order was made out of the chaos of telemetry data. Nevertheless, the identities of the particles were still unknown, and comparison of data from the various satellites and probes showed that the configuration of the belts probably changed appreciably with time.

Satellite radiation instruments were not yet sophisticated enough in 1958 to identify and sort out all the nuances of the Van Allen belts. It was a high altitude rocket flight with a recoverable payload that first gave science a detailed picture of the denizens of the inner Van Allen belt. Launched in April 1959, an Atlas rocket carried a stack of photographic emulsions into the inner belt. Upon recovering the stack, Stanley Freden and Robert White, at the University of California's Radiation Laboratory, studied the tracks made by the inner belt particles and soon determined that most were very energetic protons.

Where did these high energy protons come from? Theorists had already proposed one explanation for the origin of most of the inner zone protons. When powerful cosmic rays (described later) smash oxygen and nitrogen nuclei in the Earth's atmosphere, neutrons are emitted in the ensuing nuclear reactions. Some of these neutrons head toward outer space and pass through the Van Allen belts in the process. Being electrically neutral, the neutrons would

4 The radiation counter on Pioneer III recorded two radiation peaks as it penetrated the Van Allen belts on its flight toward the Moon on December 6, 1958. Explorer I had repeatedly grazed the lower edge of the belts.

5 The famous kidney-shaped picture of the radiation belts drawn by Van Allen after the flight of Pioneer III. In modern maps, the two belts are not so well defined.



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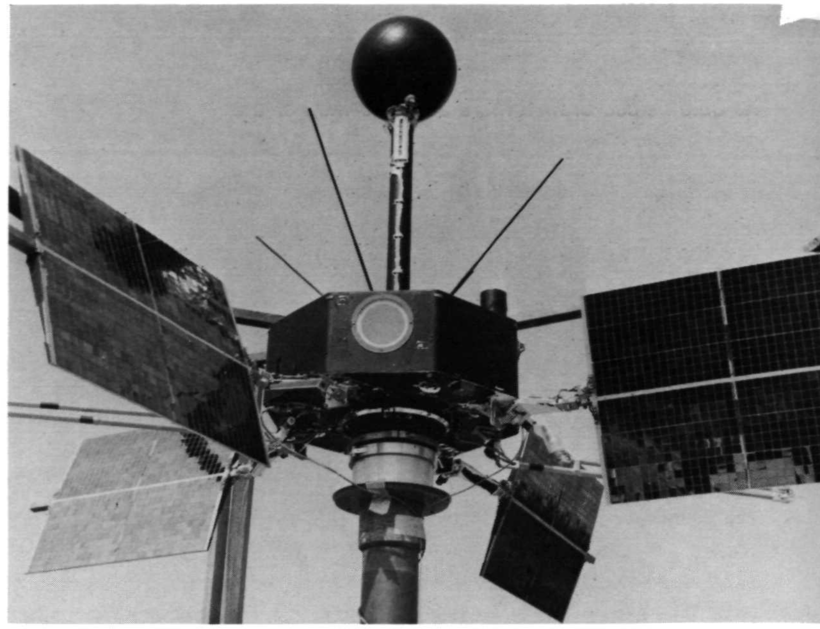
not be trapped and would ordinarily escape the Earth completely. A neutron, however, is not a fundamental particle; that is, it splits spontaneously into simpler particles—a proton, electron, and neutrino. If a neutron splits (decays) while in the region of the Van Allen belts, the resulting proton and electron may be captured by the belts. This is called the neutron albedo hypothesis.

The outer belt is more mysterious. First of all, though, the distinction between the two belts is somewhat blurred. Electrons and protons are trapped in both regions; there is also a slot between them where radiation levels are lower. Some scientists prefer to speak in terms of a single radition zone rather than two well-defined belts.

Consider protons alone. Van Allen's early map indeed showed a zone of high radiation levels beyond the inner proton belt; but was it composed of protons? The National Aeronautics and Space Administration (NASA) began a comprehensive program aimed at answering such questions when it was founded in 1958. Using scintillator counters aboard Explorer XII in 1962, Leo R. Davis and James M. Williamson, at Goddard Space Flight Center, showed that there are more protons in the outer belt than the inner belt. However, proton energies in the outer belt are too low to contribute to the particle counts observed by Van Allen. Again, a rocket provided the necessary clues. In 1959, a rocket carried an electron spectrometer (an instrument that sorts out electrons according to their energies) into the outer belt region. J. B. Cladis and his associates at Lockheed concluded that the spectrometer data proved that the penetrating component of outer belt radiation was composed of high energy electrons.

Another facet of the problem was discovered in the early 1960s by Brian O'Brien, then at the University of Iowa. Using data from the Injun I and Injun III satellites, O'Brien demonstrated that auroral activity was linked to sudden increases in the population of outer belt electrons. No one is certain where these electrons come from, but some of them may splash over from the outer belt into the auroral zones, causing our northern lights.

Recent satellites have continued the exploration of the Earth's great radiation belt and mapped it in greater detail. The more the belts are studied the more complex they seem. First, they are strongly affected by the Earth's magnetic field, which has long been known for its vicissitudes; second,



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both the belts and the Earth's magnetic field depend upon the whim of the Sun, which can reach across 93,000,000 miles to jostle and distort both. The rest of the radiation belt tale, therefore, must be told in terms of our planet's magnetic field and the long reach of the Sun.

The Magnetic Shell Around The Earth

The Earth's first line of defense against solar and cosmic projectiles (that is, charged subatomic particles) is its magnetic field. Magnetic lines of force can deflect charged particles as well as trap them. Our magnetic field thus constitutes one of the three barriers that insulate us from the turmoil of outer space. The magnetic field's protection is so effective that Earth-bound science remained quite innocent of—even naive about—the true character of the Earth's field until satellites began to explore it.

A pre-satellite picture of the Earth's magnetic field was drawn as early as 1600 by William Gilbert in his famous work *De Magnete*. Detailed maps produced for navigators provided mathematicians such as Laplace, Poisson, and Gauss with enough data to create a mathematical model. In essence, the model assumed a (fictitious) bar magnet inside the Earth.* To account for the fact that the magnetic poles are not geographically opposite one another, mathematicians had to bury their magnet some 450 miles from the center of the Earth. The mathematical model predicted that the Earth's lines of force would gently curve around from pole to pole, creating the kidney-like pattern so familiar from magnetic experiments with iron filings in school.

As always, however, a few perceptive individuals swam against the current of scientific thought and stated that the Earth's field out in space might not resemble that of a bar magnet at all. Von Humboldt, the great German naturalist, was the first to suggest that all was not serene in space. In 1806, he found that the peculiar quiverings of his compass needles, a phenomenon known for centuries, could be linked to auroral displays. Soon, scientists discovered that *both* the auroras and von Humboldt's magnetic storms were stimulated by solar activity. With this long range Sun-Earth intimacy in mind, Sidney Chapman and V. C. A. Ferraro postulated in 1931 that the Sun might emit bursts of plasma† during solar storms, and that these plasma clouds might completely envelop the Earth and bottle up its magnetic lines of force.

** Many geophysicists believe that the Earth's field is created by the dynamo action of an electrically conducting fluid circulating inside the Earth.*

† A plasma is a mixture of positive ions, negative ions and neutral atoms that is electrically neutral. A plasma can conduct electricity.

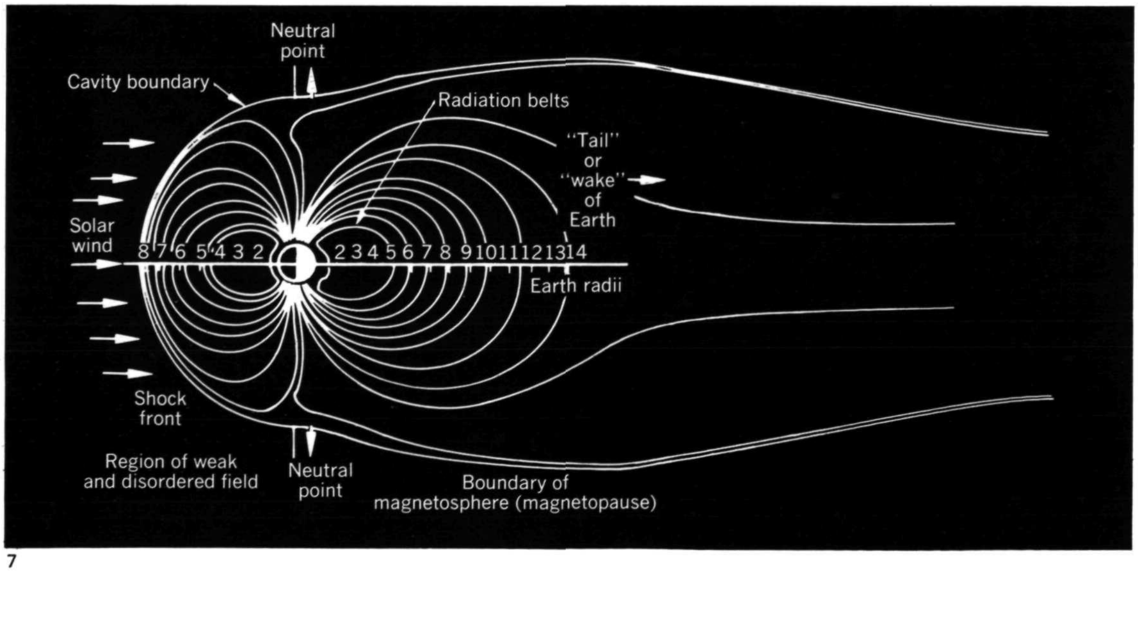
6 *Explorer XVIII, the first IMP (Interplanetary Monitoring Platform), was launched into a highly eccentric orbit on Nov. 26, 1963, repeatedly piercing the magnetopause. Its data helped draw a more accurate map of the magnetosphere.*

NASA's Vanguard III was the first U. S. satellite to carry a magnetometer into space, but its orbit did not take it beyond the Van Allen belts. In 1958 and 1959, the Pioneer III space probe and the Explorer VI satellite penetrated deep into space. Both found that the Earth's field was in a state of extreme disorder five to eight Earth radii out. At this time, discovery of the Van Allen belts had already revolutionized thinking about what was happening a few hundred miles overhead. It now appeared that there might be a steady wind of solar plasma buffeting the Earth. As this electrically conducting wind blew against the Earth's magnetic lines of force it drove them backwards, away from the Sun. On the night side it drove them far downstream from the Earth. In terms of 1959 thinking, the Earth was enclosed in a streamlined, tear-shaped bottle, with magnetic walls that kept most of the solar wind outside. Over the surface of this protecting bottle, and as a result of the full force of the solar wind, shock fronts formed similar to those in front of a supersonic plane. When Explorer VI and Pioneer III passed through these shock fronts they recorded the turbulent situation on their magnetometers.

Many of the Explorer satellites launched in the early 1960s included magnetometers and solar plasma detectors in their payloads.This permitted scientists to draw a better picture of the magnetic bottle that the Earth carried with it around the Sun. In particular, Norman Ness, at Goddard Space Flight Center, helped refine the picture with his magnetometers on the IMP (Interplanetary Monitoring Platform) satellites. Ness confirmed the existence of a shock front about ten Earth radii out in the direction of the Sun. Within this shock front was the bottled magnetic field of the Earth; outside was the weaker interplanetary magnetic field created by the Sun. As the IMP satellites probed the leeward side of the Earth, away from the Sun, magnetometer readings showed the trailing tip of the teardrop to be hundreds of thousands of miles long. It was more like a long "tail." Even the Moon passed through it on occasion.

Today's pictures of the Earth's field bear little resemblance to those idealized dipole fields drawn in the 1950s. The Earth is now pictured as existing in a very elongated magnetic bottle oriented with

7 *A recent view of the magnetosphere shows the Earth with a long tail extending hundreds of thousands of miles leeward of the Sun.*



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its long direction pointing away from the Sun. The shell of this bottle is called the magnetopause, and the space inside is the magnetosphere, although it is far from spherical in shape.

The details of the Sun-molded magnetosphere are still being investigated. The dimensions and character of the Earth's tail have not been fully determined. Perhaps charged particles find that this tail, wherein magnetic fields are very low, is a chink in the Earth's magnetic armor. The Van Allen belts may be populated by invaders entering through this route. Further, the propagation of magnetic storms, with their magnetohydrodynamic waves, is not well understood. We have come a long way from von Humboldt's nervous compass needles, but more discoveries are imminent.

Wind From The Sun

In the turbulent drama high above our atmosphere, the Sun is the obvious villain, continuously stirring the particle populations of the Van Allen belts and pummeling the magnetosphere with bursts of plasma. This transient and intransigent behavior is superimposed upon the steady-state solar wind.

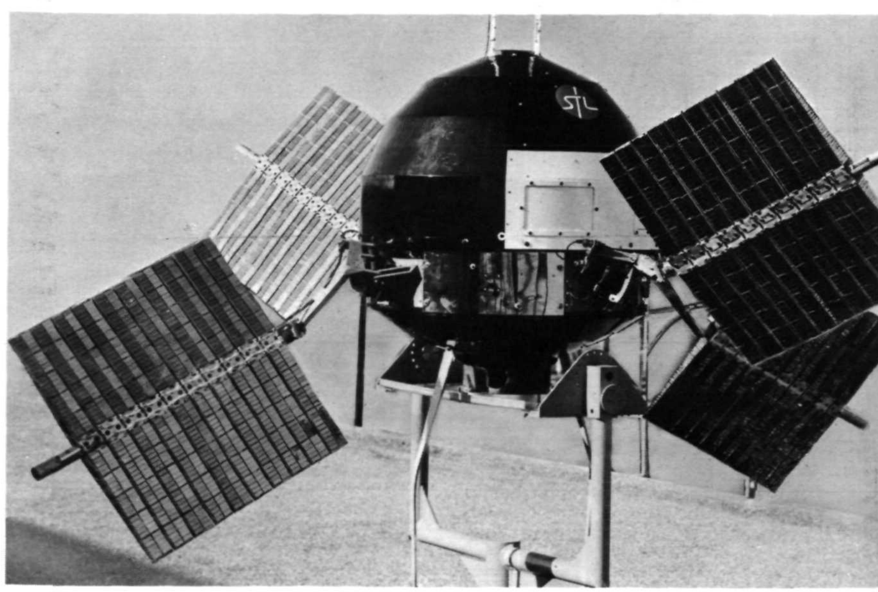
The idea that the Sun could spew forth ionized but electrically neutral gas seems to have originated with Felix Lindemann, an English physicist, in 1919. Chapman and Ferraro had employed this concept in 1931 as a possible explanation of magnetic storms. This was all untested theory, though, and the transient magnetic storms required that the Sun emit vast globs of plasma in the direction of the Earth only occasionally.

The German physicist, L. F. Biermann, tried to explain comet tails in the early 1950s by suggesting that there might also be a constant solar wind blowing through the solar system. Biermann proved that comet tails, which always point away from the Sun—regardless of the comet's direction of travel—could not be explained by the pressure of sunlight or any then known mechanical force. He suggested that the Sun boiled off a continuous flux of plasma that blows comets' tails as wind blows a candle's flame.

Just prior to the first satellites, the American astrophysicist, Eugene N. Parker, showed theoretically that the Sun should be boiling off vast amounts of plasma as a consequence of its high temperature. This outrushing plasma would fill the whole solar system, bathing all comets and planets.

Thus, as the U.S. and Russia prepared to launch their first satellites in 1957, there was a substantial

8 *Pioneer V, shown mounted on the top of the Thor-Able rocket just prior to launch. The Pioneers gave us our first good solar wind data outside the magnetopause.*



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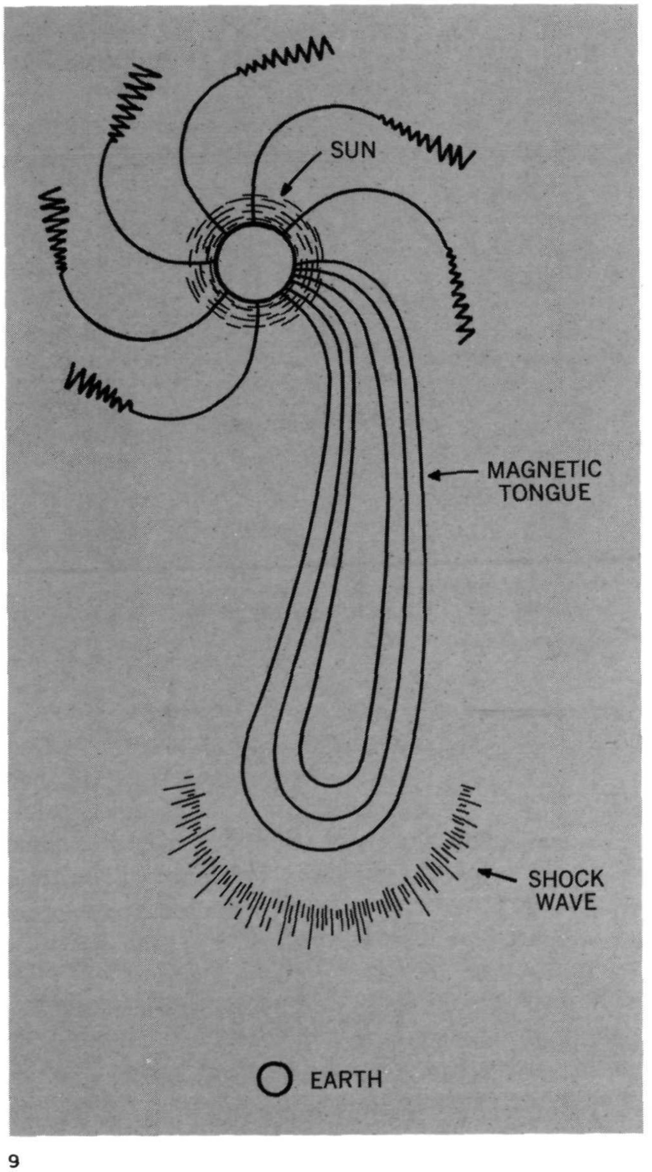
body of theory predicting the existence of a solar wind, as Parker so aptly named it, traveling at several hundred miles per second and consisting of less than 100 particles per cubic centimeter. In retrospect, the bottling up of the Earth's magnetic field by the magnetopause should not really have startled anyone, but it did.

Strangely, in view of the good chances of finding a solar wind, the early satellites did not carry plasma probes—the instruments which collect and measure low velocity ions and electrons. Not until the Russian Moon probe Luna 1 was launched on January 2, 1959 did anyone try to measure the solar wind directly. The first U. S. plasma probe was on Explorer X, launched March 25, 1961.

9 *Idealized view of a plasma tongue erupting from a solar flare. These plasma storms are not as well organized as the sketch shows.*



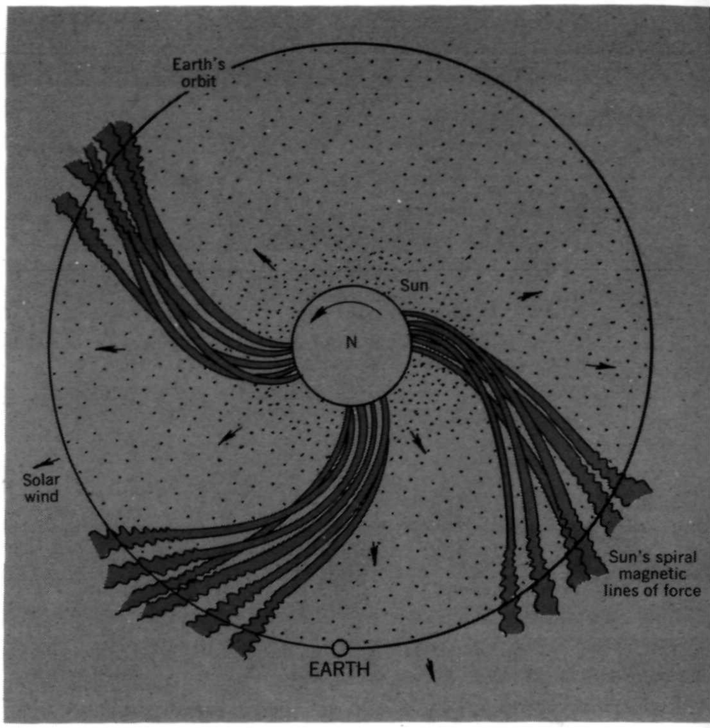
Both spacecraft confirmed the fact that a steady solar wind blows past the Earth at about 200 miles per second (300 km/sec). More detailed study of the solar wind had to wait until NASA launched its first planetary probe, Mariner II, which departed for Venus on August 26, 1962. The plasma probe on Mariner II indicated that the average velocity of the interplanetary solar wind along the spacecraft's trajectory was actually about 300 miles per second (500 km/sec). The particles—mostly protons and electrons with about 5% helium ions—number about 5 per cubic centimeter.

Scientists say steady-state solar wind to differentiate between the wind that blows all the time and the great plasma tongues that erupt sporadically from the Sun's surface during solar flares. The steady-state solar wind is really quite gusty, as plasma probes on the Mariner and Pioneer probes have demonstrated. Terrestrial optical and radio telescopes show the Sun's surface and corona to be in continual turmoil, so it is not surprising to find the solar wind (really a long-range extension of the corona) to be correspondingly fitful.

We see a visible flare lash out from the Sun's surface; a day or so later, the shock wave preceding the plasma increase slams into the Earth's magnetosphere, causing the first phase of a magnetic storm; soon the Earth is engulfed by the plasma increase. During the main phase of the magnetic storm, long distance terrestrial communications are disturbed, and there is a noticeable drop in the intensity of cosmic rays arriving at the Earth's surface.*

** Called a Forbush decrease, the drop is due to the fact that the plasma tongue has added a second magnetic bottle around that created by the magnetosphere. Fewer cosmic rays penetrate both walls.*

10 *The steady solar wind drags the Sun's magnetic lines of force with it in a radial direction. Sun's rotation causes spiral effect.*



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The Sun has a magnetic field that may pervade the entire solar system, from Mercury to beyond Pluto. This field would be like that of a bar magnet if it were not for the heavy handed solar wind. The solar wind blows so hard that magnetic lines of force are blown out radially as if they were paper streamers in a gale. The Sun's magnetic lines of force would stick straight out radially were it not for the Sun's rotation every 27 days. Rotation causes a garden-sprinkler effect, resulting in spiral lines of force. Further, the turbulence in the solar wind tosses the lines of force about, giving the diagram of them a frizzled look.

At the Fringes of Our Atmosphere

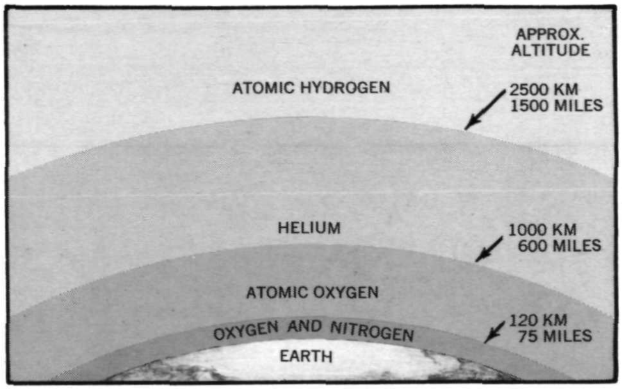
Far beneath the stormy magnetopause and radiation belts, a thin film of air clings to the Earth. In thickness, our atmosphere might be compared to the skin of an orange, for it is only a few hundred miles thick compared with the Earth's diameter of some 8000 miles. In terms of substance, though, the orange analogy fails. The atmosphere weighs only 14.7 pounds per square inch—equivalent to 34 feet of water. Yet, this thin gas we call air gives us oxygen to burn with the food we eat; aircraft wings get lift from it; and, most important, it shields us from the dangerous solar ultraviolet rays and much of the radiation not deflected or trapped by our magnetic field.

The lower atmosphere, with its immense cyclones and anti-cyclones swirling across the globe, can be studied by watching meteorological balloons, by sending up instruments on balloons and rockets and listening to the signals they send back, and, of course, by picture-taking satellites.

Focus on that part of the atmosphere above 50 miles. It is often called the thermosphere or exosphere to distinguish it from the layers below. It is a thin mixture of gas atoms and molecules—gas so thin at 200 miles altitude that a gas molecule travels a mile, on the average, before it hits another. Being so diffuse, this air does not behave like the relatively thick and viscous stuff we know at sea level.

Satellite instrument designers have found that air temperature cannot be measured with an ordinary thermometer; the air is too thin and contains too little heat to be able to affect the thermometer. Instead, they have to measure the speeds of the atoms, molecules, ions, and electrons that make up the air. From speed they compute kinetic temperatures of over 1000°K in the thermosphere. This hot, rarefied world changes from day to night, from season to season, from sunspot peak to minimum. It glows as the Sun excites its atoms. Around the poles it flickers with ghostly auroras. It is such a different world that dozens of satellites have been sent up to participate in exploring it. More specifically, NASA has constructed a series of Atmosphere Explorers, Ionosphere Explorers, and Orbiting Geophysical Observatories to probe this mysterious region.

All satellites that brush the top of the atmosphere with their orbits help scientists infer the density



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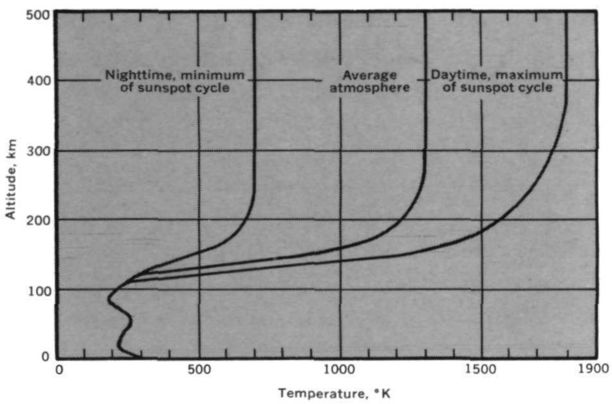


11 The heavy atoms and molecules settle predominantly toward the bottom of the atmosphere.

12 The temperature of the thin atmosphere at satellite altitudes is very high. It is affected strongly by the rotation of the Earth and the sunspot cycle.

of the atmosphere. The early satellites surprised everyone by slowing down and reentering the atmosphere rather rapidly. The upper atmosphere was denser than expected. Precise telescope and camera tracking of satellites, especially the Echo balloon satellites, soon revealed that the upper atmosphere was not only higher and more dense, but more fickle than supposed. Sunlight, especially, had a great effect. The part of the atmosphere facing the Sun bulges out conspicuously. As the Earth rotates, the bulge travels around the Earth once a day like a monstrous tidal wave. At 400 miles altitude, the kinetic temperature of the Sun-heated bulge may be almost 800°K higher than the atmosphere on the dark side of the Earth. Further, densities and temperatures change markedly during the eleven-year cycle of solar activity. So, just by watching satellites in their orbits and using the methods of thermodynamics, scientists with tracking equipment all over the world were able to draw a radically new picture of the upper atmosphere.

By studying the orbital data for Echo I, the Belgian aeronomist Marcel Nicolet was able to deduce in 1961 that a layer of helium exists in the region from 600 to 1500 miles altitude when the Sun is active. This was confirmed in 1963 by a mass spectrometer installed on Explorer XVII, which detected the helium directly. From the standpoint of gross composition, the atmosphere is four-layered. The major constituents are: the familiar oxygen and nitrogen mix at the lowest level; then, atomic oxygen; next, the newly discovered helium-rich layer; and finally, the lightest gas of all, atomic hydrogen. Our atmosphere is stratified with the heaviest atoms and molecules at the bottom and the lightest at the top.

It is startling to discover that the Earth has a corona rather similar to that of the Sun. Satellites find no sharp upper boundary to the atmosphere. A hydrogen geocorona reaches outward thousands of miles, eventually merging imperceptibly with the interplanetary milieu—really the extended solar corona. Hydrogen atoms in the geocorona, heated by the Sun, attain such high velocities that they can escape the gravitational pull of the Earth altogether. Like the Sun, the Earth is continually releasing hydrogen, a little helium, and a few heavier elements.

Sounding rockets and ground observations of chemicals released at high altitudes have detected tidal oscillations in the atmosphere similar to those observed in the oceans. More fascinating, however, are the so-called gravity waves, which move upward from some unknown disturbance in the lower atmosphere and surge through the upper layers of the atmosphere. The horizontal width of the wave motion may be several hundred miles in extent, with periods on the order of 100 minutes.

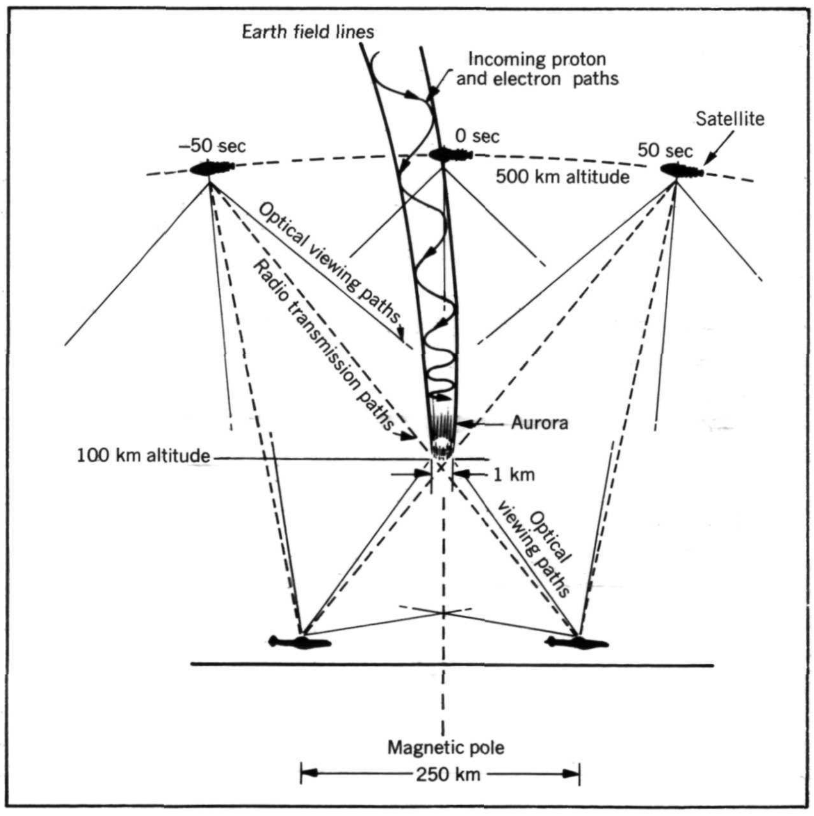
As if the atmosphere were not complex enough with its stirrings and pulsations, it also turns out to be the scene of exotic chemical reactions. The best-known reaction occurs when ultraviolet light from the Sun dissociates diatomic oxygen molecules. Single oxygen atoms then combine, on occasion, with diatomic oxygen molecules to form triatomic ozone.

13 *Satellites like this Direct Measurements Explorer (Explorer XXXI) have been able to provide data taken directly in the ionosphere and upper atmosphere.*

On a clear Moonless night away from city lights, a faint glow in the sky can be seen that increases toward the horizon. This is the airglow, a complex phenomenon that no one has unraveled satisfactorily. Airglow—similar in some ways to the weird greenish light emitted by the polar auroras—is emitted by excited atomic oxygen, the hydroxyl ion (OH^-), nitrogen, and other atoms and free radicals. In some undetermined way, solar energy stimulates unusual chemical reactions in the rarefied upper atmosphere that we have difficulty in reproducing in terrestrial laboratories. Sounding rockets and satellites equipped with spectrometers analyze the airglow and help scientists identify the chemical reactions transpiring a few hundred miles up. Despite numerous satellite and rocket experiments, airglow mechanisms remain elusive.

More spectacular are the colorful polar auroras. The dancing auroral flames and draperies are

14 *Aircraft and satellites can make simultaneous observations of auroras from different vantage points.*



usually green and blue-green, with occasional patches and embroidery of pink and red. Somehow, high in the atmosphere, the Sun, the Earth's magnetic field, and the oxygen and nitrogen atoms in the atmosphere work in concert to put on this eerie display. Many satellites in the NASA Explorer series, the Observatory series, and Air Force programs have transported plasma probes, spectroscopes, and other instruments into the auroral zones to try to divine the origin of the auroras. Satellite experiments have been coordinated with rocket and aircraft flights to obtain top and bottom views of the auroras. Even with all this effort, the auroras remain enigmatic.

For a while scientists believed that the auroras were stimulated by spillover of charged particles from the radiation belts which are magnetically focused on the polar regions. The logic seemed sound: the disturbed Sun dispatches globs of plasma in the direction of the Earth; these are caught and focused by the Earth's magnetic field; the solar particles precipitate into the auroral zones; there they excite atmospheric atoms and create the auroras. But calculations show that the energy emitted by an auroral display is considerably greater than that present in the motion of charged particles in the radiation belts. In fact, it may be that the radiation belts are actually populated when the Earth's magnetic field captures electrons from the auroral regions instead of vice versa. Obviously, more auroral experimentation is needed.

The ionosphere is better understood than the auroras. The ionosphere is created when solar ultraviolet radiation and X-rays ionize atoms in the upper atmosphere. The freed electrons are highly mobile and cause electromagnetic effects as well as the reflection of radio waves. The existence of an ionosphere was suggested by Gauss in 1839 and in 1878 by the Scottish physicist Balfour Stewart. Stewart postulated that minor variations in the Earth's magnetic field were caused by fluctuations of electrical currents at high altitudes. His idea lay dormant until Marconi proved in 1901 that wireless signals could be transmitted across the Atlantic. Beginning in the 1920s with the experiments of Edward V. Appleton and M. A. F. Barnett, in England, and Gregory Breit and Merle A. Tuve, in the United States, science

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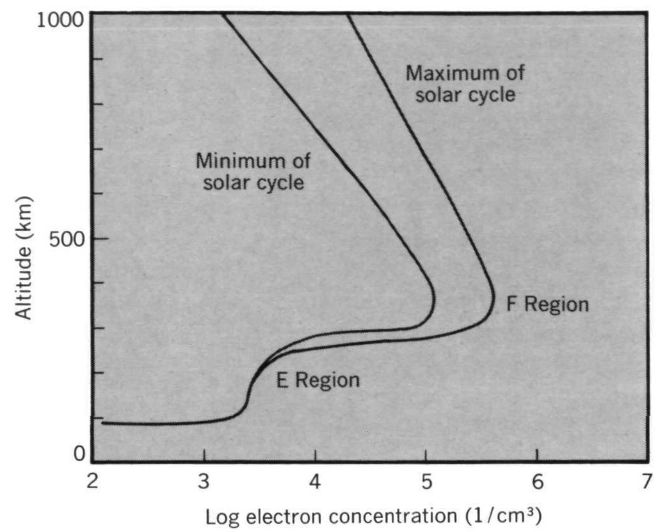

15 *The layers of the ionosphere are created by solar radiation. Like the temperature of the upper atmosphere, electron concentration varies strongly with solar activity.*

began to probe the bottom of the ionosphere with pulsed beams of radio waves. By measuring the times of the echos, the heights of the reflecting layers were determined. The ionosphere, however, turned out to be complex and ever-changing. By increasing the frequency of the radio waves, one can probe farther into the ionosphere. The critical reflection frequency depends upon the density of free electrons. Radio waves above 20 MHz (megahertz)* pass right through the ionosphere into outer space. Work at various frequencies soon disclosed that the ionosphere is layered, and that the layers shift up and down during the day; layers sometimes fade away completely and then reappear. When NASA was created in 1958, it was already obvious that one of its missions would be to explore this ionized region of the atmosphere further.

Sounding rockets had been making brief incursions into the ionosphere for many years, and the National Aeronautics and Space Administration naturally continued with this technique. But how could satellites be used to advantage? Satellites could not orbit in the relatively dense D region of the

** One megahertz = one megacycle per second (old terminology) = one million cycles per second.*

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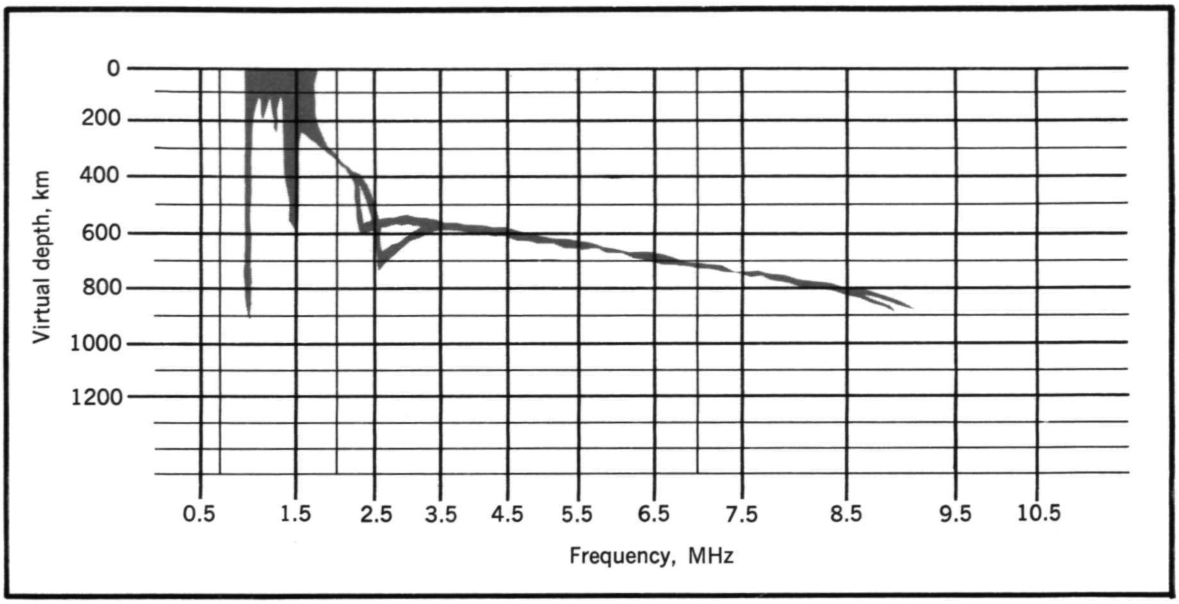

ionosphere, which in the daytime extends roughly from 35 to 55 miles. Satellites would have to look down on most of the ionosphere. In this position, they could direct pulses of radio waves from above rather than below. This approach was first used on Alouette I, a joint U.S.-Canadian satellite, launched on September 28, 1962. Alouettes I and II and Explorer XX are all termed topside sounders, although they also contain other experiments. Collectively, they have been able to map the upper portion of the F region, which could not be sounded from the ground. These maps of electron density have to be drawn for the entire Earth, for various times during the day, season, and sunspot cycle. Like the neutral atmosphere, the solar plasma, and the radiation belts described earlier, the structure of the ionosphere is complex and highly variable in time. The layers are wrinkled, shifting, and wax and wane as the solar input changes and as the whole atmosphere stirs in response to thermal and electromagnetic forces.

Satellites can also make direct *in situ* measurements of the so-called diffusion-dominated region of the ionosphere, roughly above 150 miles altitude. Direct measurement satellites, such as Explorers VIII and XXXI, have measured electron and ion densities with various electrical probes.

Beacon satellites—Explorers XXII and XXVII—have sent out radio signals to receivers on the Earth below to investigate the different ways in which radio waves can be propagated through the ionosphere. Ionosphere ducting is of great interest, because signals sometimes can be transmitted around the world if they are trapped between dense layers of electrons. A simple way to study the ionosphere is simply to listen—with a radio, of course. Receivers on the ground and on satellites can hear whistlers, which are radio signals created by lightning flashes. Whistlers propagate through the ionosphere, creating much of the background noise we hear on ordinary radio sets.

Summarizing briefly, the upper atmosphere consists of several co-existing populations of particles—ions, electrons, free radicals, neutral atoms and molecules—that interact not only with each other, but with the radiation belts above and the dense neutral atmosphere below. The whole brew is heated and stirred by the Sun and changes with every electromagnetic disturbance that happens by.

The Sun: Interplanetary Weather Maker

The solar wind blows through the solar system causing comet tails to flare out, stimulating the Moon to luminesce, to say nothing of roiling the Earth's tenuous upper atmosphere. Solar radiation—both

16 *Ionograms, such as this one taken by Alouette I, permit scientists to chart electron density from the top of the ionosphere. The depth at each frequency is found by timing the echoes.*

17 *Intensity of solar radiation above the Earth's atmosphere. Actually more than half the energy in sunlight never reaches the surface. Radio portion of the spectrum not shown.*

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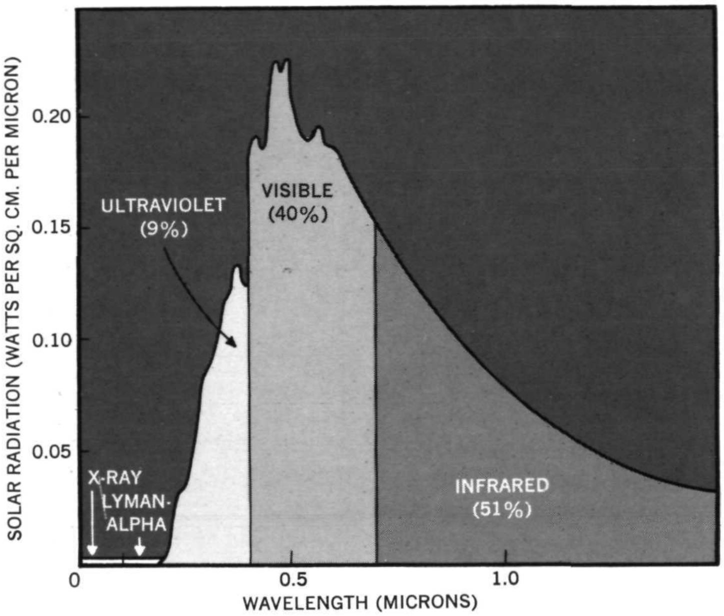


electromagnetic and particulate in nature—also affects the Earth. Radiations from the Sun permit us to diagnose our nearest star and find out what makes it work. If we can understand the Sun, we will also know how many other stars in the universe work; we will also know better how the Sun controls interplanetary weather.

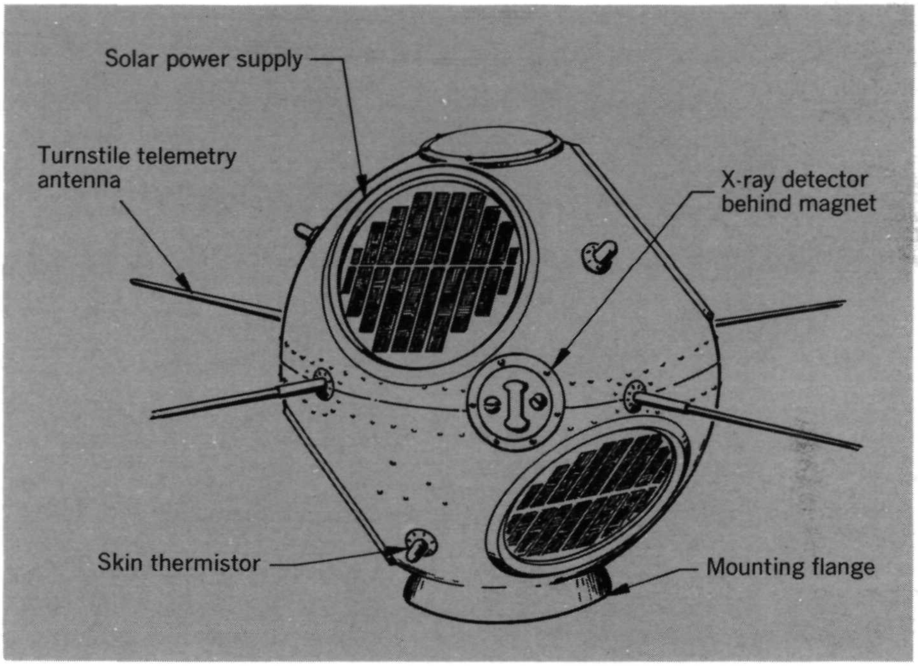
We can see the Sun so well from Earth, why bother with rockets and satellites? The answer, of course, is that we see only those parts of the sunlight and radiation flux that penetrate all the way through the atmosphere and even then atmospheric turbulence hampers observations. To see solar X-rays, high energy protons, and the far ultraviolet, instruments must be carried above the atmosphere and pointed accurately at the Sun.

Long before the advent of satellites, scientists were mounting spectrographs on high altitude balloons and rockets. Captured V–2 rockets, for example, took spectrographs up over 100 miles where they automatically found the Sun, locked onto it, and made spectrograms. The U.S. Naval Research Laboratory (NRL) pioneered many such rocket techniques in the 1950s. Even though the rockets broke through the atmosphere for only a few minutes, NRL scientists were able to measure the Sun's radiation in the far ultraviolet region for the first time.

When long-lived satellite instrument platforms became available in 1958, NRL, the Air Force, and NASA began planning new solar instrumentation. NRL was first into space with such instruments when it launched a small piggyback satellite called Greb 1 (later renamed Solrad 1), on June 22, 1960. Piggyback means that Greb 1 hitch-hiked a ride into orbit on a larger satellite—Transit 2A, in this instance. Greb 1 carried small ionization chambers that monitored solar X-rays and the Lyman-alpha line of hydrogen, which helps diagnose solar processes but is too far in the ultraviolet to see from the Earth's surface. With Greb 1, its several successors, and sounding rockets, NRL was able to correlate visible solar events with solar X-ray and Lyman-alpha activity.

18 *The piggyback satellite, Greb 1 (Solrad 1), was launched on June 22, 1960. The Naval Research Laboratory installed X-ray and Lyman alpha detectors to monitor the Sun's radiation.*

19 *OSO II prior to launch. The pointable sail is mounted on a nine-sided base approximately 44 inches across. Balls on arms contain pressurized gas to orient satellite in space.*



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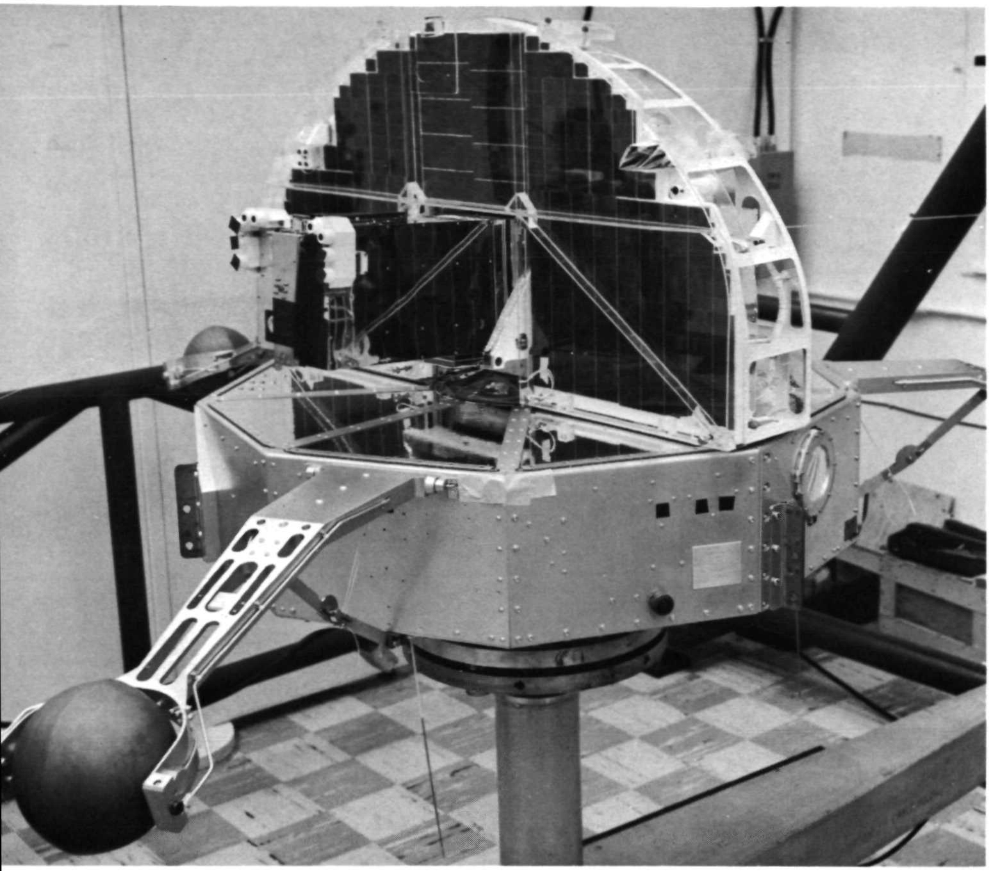
Although many NASA satellites have carried various instruments for studying the Sun, the series of Orbiting Solar Observatories (OSOs) have been the most productive. The great utility of the OSOs derives from the fact that one section of the satellite (the sail) continuously points at the Sun while another part (the wheel) spins, stabilizing the satellite and permitting other instruments to scan a large sector of space. Furthermore, the pointed sail section includes a scanning platform that gives instruments the opportunity to map the Sun's face by sweeping zig-zag fashion across it.

The first of several OSOs was launched on March 7, 1962. They carry a tremendous variety of optical instrumentation—mostly designed to detect X-rays and the far ultraviolet portion of the spectrum. Spectrographs have been employed to examine the far ultraviolet spectrum. Going a step farther, spectroheliographs scan the Sun's surface, like a TV camera, giving us images of the Sun in different wavelengths. When a scientist wants to look only at the Sun's gaseous envelope, the corona, he flies a coronagraph, which blots out the Sun's bright central disk. In short, dozens of different satellite instruments have been monitoring and scanning the Sun since 1962.

What has all this instrumentation discovered? Most of the new knowledge of the sun involves: (1) Identification of highly ionized atoms of various elements on the Sun, (2) Better understanding of solar flares through analysis of X-rays and other short wavelength radiations they emit, and (3) Correlation of these radiations with geomagnetic disturbances and the eruption of plasma from the Sun's surface. In essence, we now understand our nearest star better. To illustrate, scientists are now confident they can forecast the development of a solar flare and thus give astronauts out in space plenty of time to take shelter before they are hit by bursts of solar radiation.



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Dust From The Sky

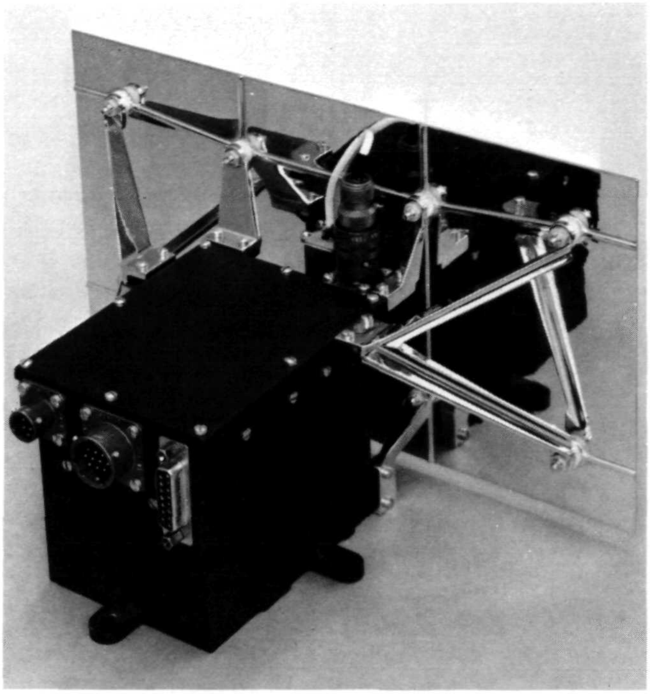
Roughly 1000 tons of meteoric dust sifts down through our atmosphere every day. Where it all comes from no one knows. In fact, one of the other big surprises in space physics has been the discovery that the Earth may swing around the Sun surrounded by a cloud of dust.

Meteorites* were ignored for a long time by organized science because it was manifestly impossible for stones to fall from the sky. Only after the little French town of L'Aigle was bombarded by a volley of several thousands of such stones on April 26, 1803, did science finally come around and admit the existence of meteorites. The meteorites that fall to Earth, however, are millions of times larger than the particles in the Earth's halo of dust.

Spaceship designers, from the early dreamers like Jules Verne to engineers now building manned spacecraft, have worried about these interplanetary projectiles puncturing the walls of their vehicles. In the 1940s and 1950s, a number of engineers calculated the probability of a spaceship being perforated by a meteoroid. They based their estimates upon the numbers of meteor streaks seen high in the Earth's atmosphere and rockets that collected meteoric dust at high altitudes with flytrap devices. When they evaluated these data, engineers

** In space a bit of meteoric material is called a meteoroid. If it is very small, it is a micrometeoroid. If it lands on the Earth, it is a meteorite. Meteors are shooting stars.*

20 *Acoustic sounding boards, such as this one built for Mariner II, have flown on many satellites.*



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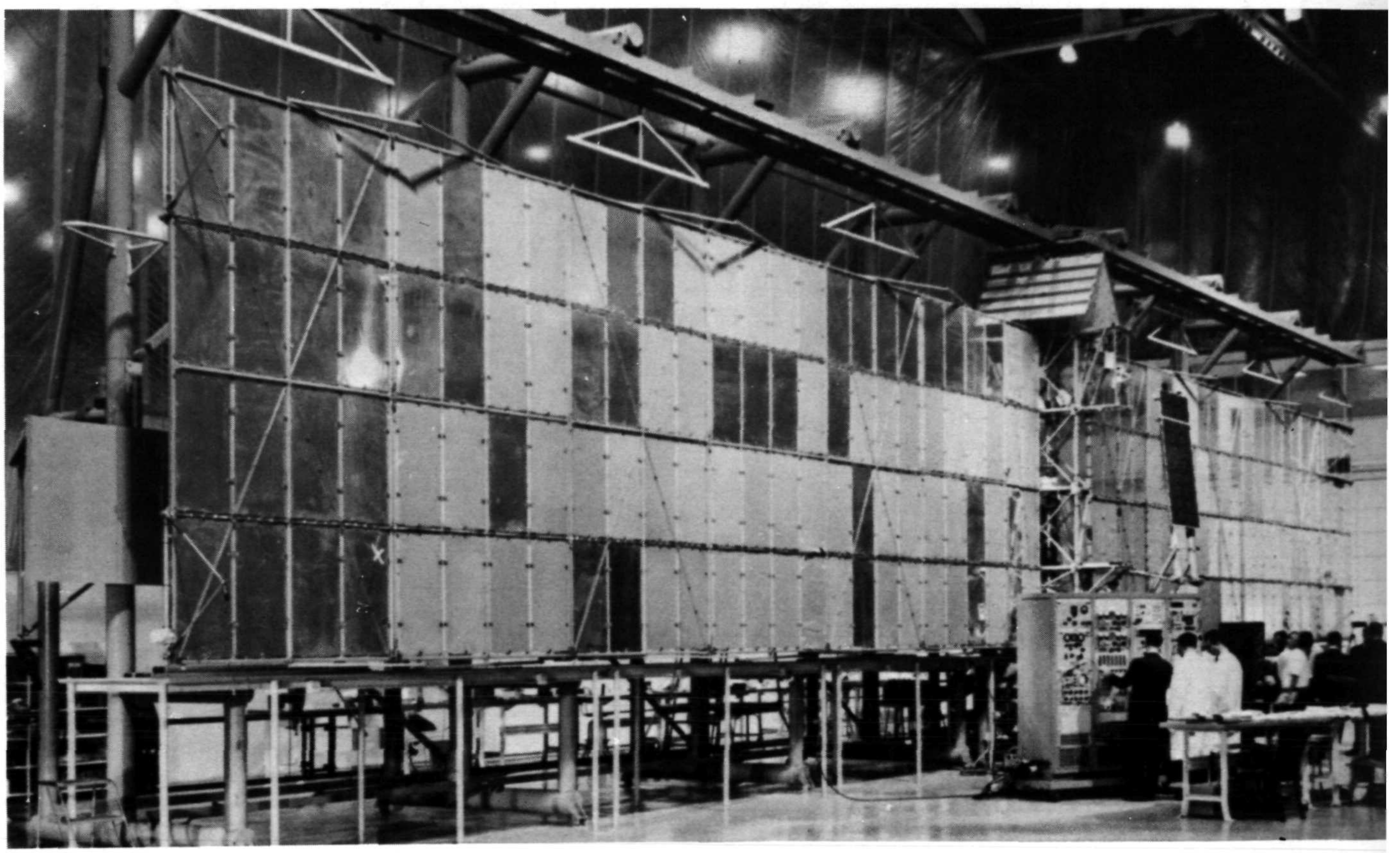
became concerned about the practicality of manned space flight. Consequently, many of the early satellites carried a wide array of instruments to record meteoroid impacts as well as their penetrating power.

A simple, straightforward way to check on the meteoroid hazard is to orbit thin-walled, pressurized bottles that send back signals when they lose pressure. Satellites such as Explorers XIII, XVI, and XXIII carried such pressurized cells. The first U.S. satellite, Explorer I, included two different micrometeoroid detectors; a closely wound wire card that would signal an open electrical circuit if hit by a meteoroid, and a piezoelectric microphone that listened for impacts. The latter instrument has been very popular on many satellites and deep space probes. Such sounding boards mounted on the Mariner probes to Venus and Mars reported a density of micro-meteoroids between the planets of some 10,000 times less than what they reported near the Earth.

21 *Huge "wing" of a Pegasus satellite, flown as a byproduct of Saturn I launch vehicle tests, to make micrometeoroid measurements. The wings were deployed in orbit to expose capacitor-type micrometeoroid detectors.*



Although the existence of a dust cloud around the Earth has been inferred from experiment, the nature of the dust, the size of the particles, and the dust's origin remain unknown. One trouble is that we do not know whether this dust is fluffy or composed of hard sphericles, such as those we find so common in deep sea sediments. Until recently, we knew very little about so-called hypervelocity impact because we could not duplicate meteoroid speeds (up to 50 miles per second) here on the Earth.

Micrometeoroid data have accumulated from our many diverse instruments, from various orbits at different times of the year. The major conclusions reached over the past ten years of space research are: (1) The danger to astronauts in spacecraft or walking in space is very small, and (2) a dust cloud seems to hover around the Earth. In other words, there is a local population of tiny dust particles and a separate, less dense population of interplanetary meteoroids.

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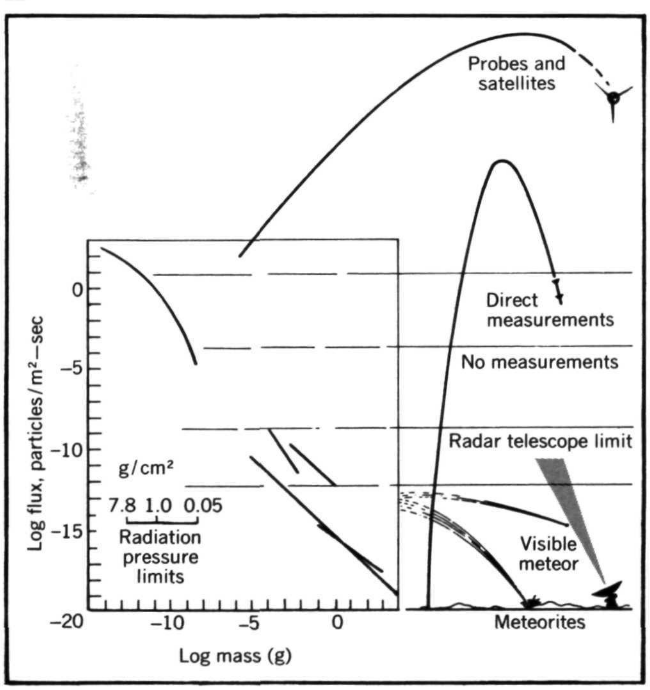


22 *Summary of micrometeoroid measurements made near Earth. Flux at left is cumulative in the sense that any point includes all meteoroids larger than the value on the abcissa. Dust cloud around Earth was discovered when deep space probes left Earth's gravitational field.*

Cosmic Rays

Around the turn of this century, early experimenters with radiation and radioactivity discovered that their instruments recorded some radiation no matter how much shielding they placed around them. At first, they thought it was due to natural radioactivity in the walls of their laboratories. After many vigorous and occasionally unscientific confrontations, the scientific world recognized the existence of a very penetrating form of radiation, which like meteorites could not come from outer space, but nevertheless did. Although we know a lot more about this cosmic radiation* today, we still do not know where it comes from and where charged particles get all their energy.

One of the key early cosmic ray experiments was carried out by the Austrian-American physicist, Victor F. Hess in 1911 when he carried radiation detection instruments to high altitudes in a balloon. His results were as surprising to the scientists of his time as the discovery of the Van Allen belts was to 1958 scientists. Hess found that cosmic ray intensity first decreased then increased, indicating an extraterrestrial rather than Earthly origin.

This discovery was contrary to expectations because this radiation was thought to originate in terrestrial materials. Since Hess' time, experimenters have been taking radiation instruments as high as they could get them—on mountains, in rockets and satellites—or as low as they could get them—in deep mine shafts.

** Cosmic radiation is not the same as the solar wind or the radiation in the Van Allen belts. It is far more penetrating than either.*

The high and deep approaches reveal some basic facts about cosmic rays. Cosmic ray researchers want to get high above our atmosphere on long-life satellites to escape the influence of the atmosphere. A few cosmic rays—the so-called primaries—zip right through the atmosphere into waiting instruments, but most of the incoming cosmic ray particles (mostly protons) smash into atoms in the air. The pieces of subatomic debris go on to cause more nuclear reactions, continuing until there is a shower of secondary cosmic rays. Scientists want to know what the unadulterated primary cosmic ray flux looks like.

In the 1920s and 1930s, it was fashionable to go down as well as up with cosmic ray instrumentation. The cosmic rays had great penetrating power, piercing a yard of lead almost as if it did not exist. Since many scientists thought that cosmic rays must come from well-defined sources in the heavens, they made their instruments directionally sensitive by using deep mine shafts for telescopes. As the Earth turned, the telescope would sweep out sectors of the sky; cosmic rays arriving from directions other than straight up would be mostly absorbed in the Earth walls of the telescope.

One of the major missions of NASA's sounding rockets, satellites, and balloons is to see if cosmic rays come from specific regions of the heavens. Hundreds of rocket flights and scores of satellites, such as the Energetic Particles Explorers and the Interplanetary Monitoring Platforms, have transported cosmic ray telescopes well out beyond the atmosphere. First, of course, electronic ingenuity had to replace Nature's unflyable telescopes with arrays of detectors connected in coincidence so that signals would be recorded only when a particle zipped through several detectors arranged in a straight line.

One well-known source of energetic particle radiation is the Sun. Until 1942, when the gigantic solar flare of February 28 caused cosmic ray counters all over the world to click a little faster, scientists thought that the Sun contributed little if any to the cosmic ray flux. Now, satellites and deep space probes (the Mariners and Pioneers) intercept these high energy solar particles soon after they have been spit out by solar flares. The results seem to show that these particles tend to follow the Sun's spiral magnetic lines of force—after the fashion of the much lower energy plasma tongues. In general, the solar cosmic ray particles have been found to be much less energetic, on the average, than the galactic cosmic rays arriving from outside the solar system.

In the search for the origin of cosmic rays, scientists at the Naval Research Laboratory have searched the sky for discrete cosmic X-ray sources using detectors on high altitude rockets. As the rockets rolled in their flight above the atmosphere, their instruments scanned the sky and detected at least 30 separate sources. If the particulate cosmic rays also originate from discrete sources, scientists will have to explain how these sources can accelerate particles to energies as high as 10^{20} electron volts.* Some cosmologists—Geoffrey Burbridge, for example—suggests that cosmic rays may be born in radio galaxies and the fantastically powerful quasars (quasistellar objects) that have been discovered recently.

Mapping the cosmic ray flux as a function of time has uncovered an unsuspected problem: as solar activity increases in its 11-year cycle, galactic cosmic ray intensity drops. The supposition is that the active Sun spews out more plasma and, in effect, builds a magnetic bottle around the whole solar system, deflecting cosmic rays and causing a Forbush decrease for the entire solar system. If this is true, we will not understand the true primary cosmic rays until we send interstellar probes well beyond the Sun's influence.

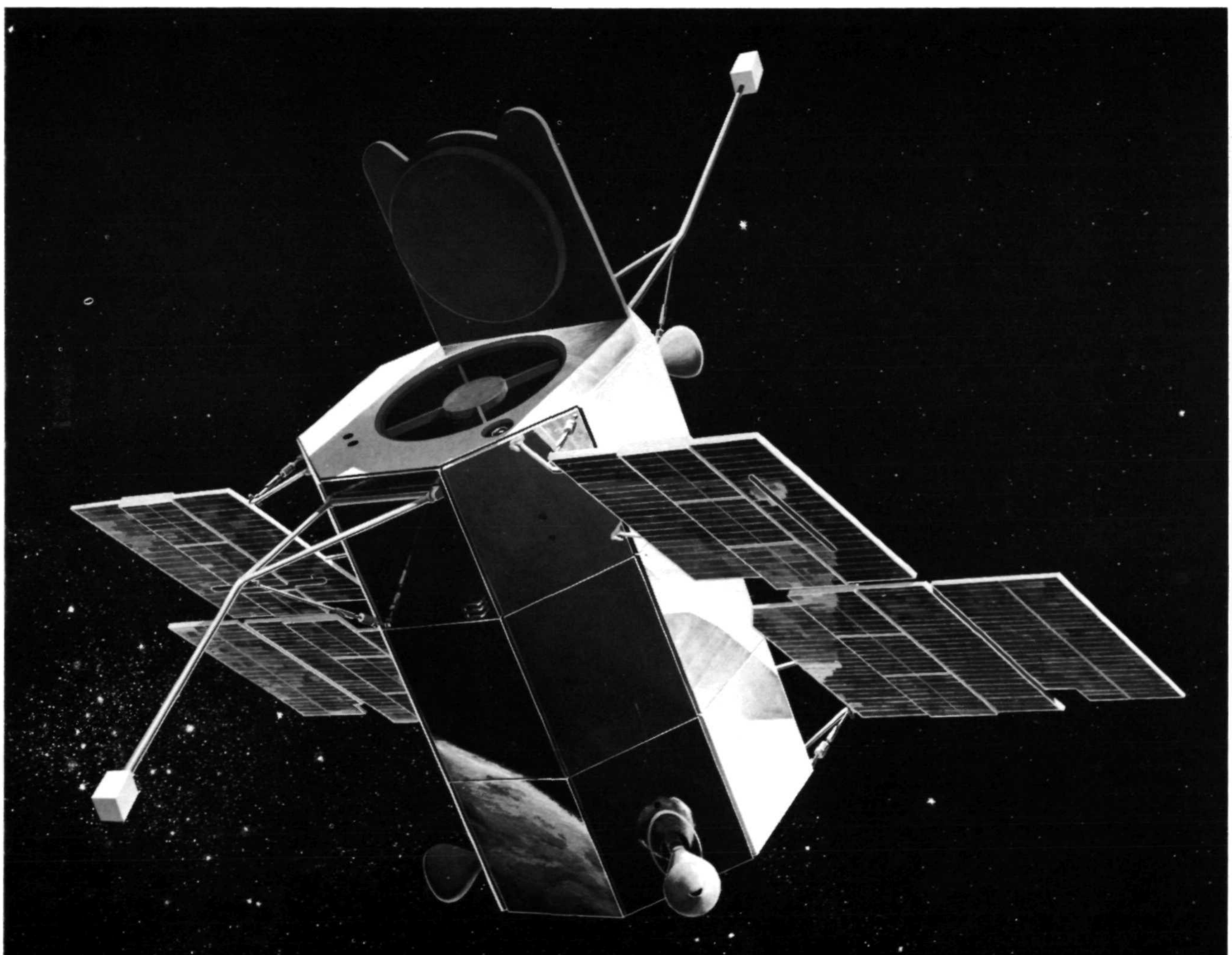
** Terrestrial atom smashers can achieve only about 10^{10} electron volts.*

23 *This artist's concept of the OAO (Orbiting Astronomical Observatory) illustrates the octagonal body containing a telescope and the large solar cell paddles. Body is just over five feet long.*

Robot Star Gazers

What does astronomy have to gain from space vehicles? The answer is the same as it was for solar physics. New dimensions of seeing: the X-ray and far ultraviolet regions of the spectrum and radio waves below about 20 MHz. There is, however, a basic difference between stellar astronomy and solar physics; the Sun is a single, big target, whereas the stars seem countless and it is difficult for unmanned satellites to find specific ones by remote control. The technical difficulties of stellar astronomy from space vehicles has caused this field to lag behind the other space sciences described earlier. Nevertheless, progress has been made with high altitude rockets and a few satellite experiments.

The study of cosmic X-ray sources is included in the category of space astronomy because there must be some astronomical object out there (not necessarily visible) that generates the X-rays. Actually, cosmic X-ray sources were reported as early as 1962 by R. Giacconi and his associates, who flew X-ray detectors in a rocket from White Sands, New Mexico. More rocket flights by other experi-



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menters have extended the list of sources to the point where scientists suspect that there are well over one thousand such cosmic X-ray machines. Just what these machines really are remains a mystery.

Some rockets have been equipped with ultraviolet instruments to see what stars look like at these wavelengths. T. A. Chubb and E. T. Byram have found that many stars seem strangely deficient in ultraviolet radiation. If one extrapolates the visible flux into the ultraviolet region, far more ultraviolet radiation is predicted than actually observed. This problem can be best approached by using a satellite with a stabilized telescope capable of making a large-scale survey of the heavens in the ultraviolet region of the spectrum. This is one of the major tasks of the Orbiting Astronomical Observatory (OAO) program.

Immense dish antennas are employed by Earth-bound radio astronomers to explore the sky at very long wavelengths. Radio astronomers, though, have always been frustrated by the ionosphere in their desire to pick up radio signals below 20 MHz. The first small satellites obviously could not carry dish antennas the size of a tennis court into orbit; but they did find room for small nondirectional radio receivers, which could listen to cosmic radio noise below 20 MHz. The U.S.-Canadian Alouettes, the Soviet Elektrons, Explorer XX, and many high altitude rockets listened at these low frequencies. Because they looked in all directions at once, these experiments could not pick out individual sources of noise. A general radio noise background was found for the cosmos. In addition, the Earth's ionosphere was found to be unexpectedly noisy. Beyond observations like these, the big discoveries in radio astronomy below 20 MHz will have to wait until highly direction-sensitive antennas can be placed in orbit.

NASA's initial answer to the problem of antenna directivity is the Radio Astronomy Explorer (RAE) which has ascended to orbit and deployed four straight antennas, each about 750 feet long. The antennas were made from beryllium-copper tape, which is rolled up prior to deployment. As the metal tape is paid out by a motor, it curls up into a long cylinder, which gives it rigidity. As the RAE orbits around the Earth, the directional antenna pattern sweeps the sky, picking up the low frequency signals that are absorbed by the ionosphere.

Our New View of the Universe

The great discoveries of space science; the Van Allen belts, the Earth's dust cloud, the magnetosphere, and the subtle and not-so-subtle influences of the Sun on the Earth were all made easier by the fact that rockets and satellites could carry instruments above the atmosphere. Eventually scientists might have been able to deduce the existence of these phenomena from purely terrestrial observations, but it might have taken decades longer. The sights and sounds of interplanetary space are so muffled by our atmosphere, ionosphere, and magnetic shell, that we have had to extend our senses with instrumented spacecraft to discover what really exists "out there." We have found a different universe, a universe more dynamic than we expected, one that seems rather alien at first. We have increased our understanding of the cosmos, and that is a prime purpose of science. Further, as we understand more about the forces affecting the solar system and the Earth, we are learning more about man's immediate environment and how to predict and control many of the forces which affect human life.

Additional Reading

For titles of books and teaching aids related to the subjects discussed in this booklet, see NASA's educational publication EP-48, Aerospace Bibliography, Fourth Edition.

Information concerning other educational publications of the National Aeronautics and Space Administration may be obtained from the Educational Programs Division, Code FE, Office of Public Affairs, NASA, Washington, D. C., 20546.

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Space Physics and Astronomy

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