Discovering Earth’s radiation belts

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Six decades after the belts' discovery in 1958, scientists are still finding mysterious features.

HOLDING A MODEL OF *EXPLORER 1* overhead (left to right), William Pickering, James Van Allen, and Wernher von Braun celebrate the successful launch at a press conference on 31 January 1958 at the National Academy of Sciences. (Courtesy of NASA/JPL-Caltech.)

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The year 2017 marks the 60th anniversary of the dawn of the space age. On 4 October 1957, our planet's first artificial satellite, *Sputnik 1* (Russian for "companion"), was launched into low-Earth orbit by the Soviet Union. Although little more than a radio beacon, it showed the world that intercontinental ballistic missiles (ICBMs), at the core of Cold War military arsenals, could also place satellites into space. A mere month later, on 3 November, Soviet scientists launched a much larger and more sophisticated spacecraft—*Sputnik 2*, the second satellite sent into orbit and the first with a live animal; a model with a doll stand-in is pictured in figure 1. The event was timed to coincide with the eve of the 40th anniversary of the Bolshevik Revolution; the Soviets loved to celebrate their holidays with "labor" achievements.

In addition to the biological experiments aboard *Sputnik 2*, Soviet scientists under the leadership of Moscow State University's (MSU's) Sergei Vernov (shown in box 1) placed a Geiger–Müller (G–M) tube on board to measure radiation the satellite encountered.[1] For many years before World War II, Vernov had studied cosmic rays with ground-based and balloon instruments. So it was natural for him to want to measure primary cosmic-ray particles from the depths of the galaxy before they interact with Earth's atmosphere. (See the article by Per Carlson, Physics Today, February 2012, page 30.)

Officially, the Sputniks were launched in the framework of the International Geophysical Year (IGY) of 1957–58. Even so, the US was stunned by the achievement (see the article by Fae Korsmo, Physics Today, July 2007, page 38). Following the launch of the two Russian satellites, the US Army Ballistic Missile Agency was told to launch a satellite of its own using the Jupiter C rocket, which was under the direction of Wernher von Braun of the US Army Redstone Arsenal. William Pickering of the Jet Propulsion Laboratory led the effort to design, build, and operate the satellite—the 14 kg, torpedo-shaped *Explorer 1*. And James Van Allen and his team at the University of Iowa designed, built, and tested the radiation detectors installed on it. On 31 January 1958, less than three months after *Sputnik 2* had launched, *Explorer 1* made orbit.

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FIGURE 1. *SPUTNIK 2* WAS A 4-METER-TALL, CONE-SHAPED CAPSULE designed to remain attached to the rocket that launched it into orbit on 3 November 1957. It held radio transmitters, a telemetry system, a Geiger counter, and a temperature-control system for the cabin, which carried the dog Laika. The model shown here is now at the Polytechnical Museum in Moscow.

Like Vernov's team, Van Allen's group had installed G–M tubes[2,3] aboard *Explorer 1*. Also like Vernov, Van Allen had studied cosmic radiation with the help of rockets and balloons over many years before the planning and launch of the first US satellites. The first measurements obtained and analyzed by those pioneers were truly epochal. No one had predicted the existence of Earth's radiation belts—nested tori of energetic particles trapped by the planet's magnetic field. And the belts' discovery heralded a new science: space physics. However, the path to discovery was difficult and dramatic.

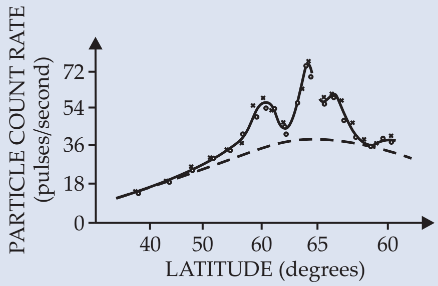
A problem of interpretation

When Vernov and his staff first saw the data from *Sputnik 2*, they noticed significant fluctuations, shown in box 1, in the count rates of their G–M tube. Knowing that the Sun had recently emitted a small flare, they incorrectly interpreted the fluctuations as due to the arrival of energetic solar particles. In fact, *Sputnik 2* was sampling regions threaded by the geomagnetic field, and the fluctuations were evidence of the radiation belts. The problem was that Soviet scientists could not get access to satellite data when the spacecraft's trajectory took it outside Soviet territory. The total secrecy that existed in Soviet science made it impossible to negotiate with other nations that picked up the satellite's transmission at ground receiving stations abroad. Australian scientists recorded *Sputnik 2* data

Box 1. Sergei Vernov

Sergei Vernov (1910–82), shown here circa 1957 at Moscow State University, began his space odyssey with an experiment on *Sputnik 2*. But his cosmic-ray research had started much earlier. Even before World War II, he used ground installations and balloon experiments in the atmosphere to detect the ionizing radiation. He continued the research with captured German rockets designed by Wernher von Braun and eventually expanded the work to missiles produced by Sergei Korolev, chief designer of the first Soviet satellites and rockets. Vernov understood that only experiments outside the atmosphere could reveal the nature of primary cosmic rays.

In 1956 the Soviet Academy of Sciences began to intensively discuss proposals for experiments in space, and Vernov and his staff had prepared their instruments for cosmic-ray measurements by the time *Sputnik 1* was launched in October 1957. But the satellite took off without those instruments. To their great frustration, Vernov's team and other Soviet scientists, along with much of the world, learned about the event from newspaper reports.



Just after the first *Sputnik* launch, Vernov convinced Korolev to install his Geiger–Müller tube on *Sputnik 2*, which launched a month later. The Geiger counter operated 10 days in orbit and gave Vernov and his team members—Naum Grigorov, Aleksandr Chudakov, and Yuri Logachev—their first information about space radiation: unexpected fluctuations in particle flux (data points on the solid line) above the expected intensity of galactic cosmic rays (dashed line), plotted here as a function of the latitudinal trajectory of the satellite. Vernov and Chudakov published the fluctuations[1] nearly two and a half years after they were first observed on 7 November 1957.

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from apogee passes over Australia and asked for the code to interpret it. The Soviets refused. And when the Soviets demanded the data from the Australians, the Australians refused. Thus the Soviet science was stymied by secrecy.

Van Allen and his team, pictured in figure 2, realized much sooner than Vernov and colleagues that what they were seeing from *Explorer 1* was a new natural phenomenon.[4] Early on, however, even Van Allen misinterpreted the data. During the first few minutes of *Explorer 1*'s ascent into space, its G–M counter behaved understandably. But subsequent data were confusing: There were periods during which the count rate matched that expected for cosmic rays, other periods during which it was far higher, and still other times when it fell to zero. The interpretation of those data was complicated by the frequent dropout of the signal—satellite power transmission was weak by today's standards—and the difficulty of computing the satellite's orbital trajectory. Van Allen initially thought they were detecting low-energy particles responsible for the generation of auroras.

When the team was puzzling over why the cosmic-ray count rate would fall so abruptly, graduate student Carl McIlwain pointed out that the particle flux might be so high in places that it would drive the G–M tube into saturation, such that it would be unable to distinguish discrete pulses and would stop counting entirely. That insight turned out to be key, and McIlwain confirmed the possibility by exposing a prototype G–M tube to an intense x-ray source in the lab. After he and colleague Ernie Ray saw the results of the exposure, Ray left his now famous "SPACE IS RADIOACTIVE" note on Van Allen's door.

Of course, neither researcher believed space was radioactive; the phrase captured their excitement and belief that the instrument was working properly. The only possible interpretation of the data from *Explorer 1* and *Explorer 3* (launched just before the researchers' pathbreaking analysis in April 1958) was that the satellites were encountering extremely high fluxes of particles at certain orbits—fluxes at least a thousand times the expected rate from cosmic rays.[4] In May Van Allen announced the discovery at a meeting of the American Geophysical Union.

Inner and outer

The Soviet scientists launched *Sputnik 3* the same month as the US announcement. Its satellite payload contained large, complex scientific instruments that allowed the Soviets to study in greater spatial detail the nature of particles trapped in Earth's magnetic field. It also allowed them to detect the presence of an outer zone of intense radiation separated from the inner zone. Only later did it become clear that the gap—or "slot" in today's parlance—was a region free of trapped particles that separated two quite different radiation belts: an inner belt dominated by high-energy (typically tens of MeV or higher) protons and an outer belt composed largely of energetic (typically 1–10 MeV) electrons, with each type of charged particle being locally accelerated by different physical processes in Earth's magnetosphere.

Among space physicists, a standing joke emerged many years later: It's completely understandable why US scientists discovered the inner radiation belt and the Soviets the outer one. It could not be otherwise: During the Cold War era, a demilitarized zone existed to separate the American inner zone and Soviet outer zone!

FIGURE 2. JAMES VAN ALLEN (1914–2006; center, in the dark suit) is surrounded by his team—graduate students Carl McIlwain (left) and George Ludwig (right) and assistant professor Ernie Ray (far right). They are looking over particle flux data detected by the team's Geiger counter aboard the *Explorer 1* satellite. (Courtesy of the James A. Van Allen Papers, University of Iowa Libraries.)

In fact, because *Sputnik 2* was launched from a high latitude in Russia, its orbital trajectory likely sampled parts of the outer belt, which resides at altitudes roughly between 3 and 10 Earth radii; the Explorer satellites launched into a more equatorial orbit and would have sampled regions in the lower-altitude inner belt, which extends from above the atmosphere out to about 2.5 Earth radii.

Since properly interpreting the data from the Explorer and Sputnik satellites, scientists have wondered about the radiation belts' origins. It was obvious that cosmic rays themselves had too much momentum to become trapped. Soviet scientists Vernov and Alexander Lebedinsky of MSU proposed that when cosmic rays bombard Earth's atmosphere, they could produce nuclear reactions that create neutrons, which subsequently decay into electrons and protons that are then trapped by the planet's magnetic field. The proposal was the first physical model to explain the nature of the radiation belts. Vernov and Lebedinsky announced the neutron-decay mechanism in July 1958, only a few months after the belts' discovery. Just two weeks later, US scientist Fred Singer independently published a description of a similar mechanism.[5]

Researchers subsequently realized that although the neutron-decay mechanism can explain the inner Van Allen belt of stably trapped protons, the outer belt of trapped electrons is much more variable in radial extent, overall intensity, and energy range. Those outer belt properties depend on how strongly the solar wind buffets the magnetosphere and thereby forces the acceleration and transport of the electrons. Understanding the outer belt acceleration, transport, and loss became a dominant goal of radiation-belt studies for much of the 1960s and 1970s.

Nuclear bombs in space

Even in the late 1950s, before it was known that radiation belts naturally existed, researchers from the Atomic Energy Commission's Livermore Laboratory in California were speculating that Earth's magnetic field could confine huge fluxes of high-energy electrons.[6] The researchers, led by Nicholas Christofilos, suggested that if it were true, then a defensive screen might be established to guard against ICBM attacks. The Livermore researchers proposed exploding nuclear weapons at high altitudes to entrain fission-produced MeV electrons in vast clouds surrounding Earth. They envisioned that the intense radiation would disable any missiles that might be launched through those clouds.

Van Allen and his team were drawn almost immediately into the classified realm of nuclear explosions in space. Around May of 1958, he and his coworkers endeavored to untangle human-induced particle populations from natural radiation-belt particles after a series of US low-yield, high-atmosphere nuclear tests.[7] In July 1962 a hugely powerful—equivalent to the yield from 1.4 megatons of TNT—and strategically placed US nuclear weapon code-named Starfish Prime was exploded at about a 400 km altitude over Johnston Island in the South Pacific Ocean.[8] That explosion and three similar-sized Soviet tests just outside Earth's atmosphere three months later altered the inner Van Allen belt dramatically and placed on geomagnetic field lines MeV electrons that would reside there for years. Those electrons made the radiation belts at least a million times more intense and hostile to satellites. Between late 1962 and early 1963, at least a dozen scientific satellites were killed by the powerful manmade radiation. Interestingly, for some time after Van Allen's discovery of the radiation belts, US scientists discussed whether the belts might be the result of earlier Soviet nuclear explosions.

Clearly, the ecology of near-Earth space was altered for years by military activities in the 1960s. And yet those activities also served as experimental tests for basic science and helped scientists check their models of radiation trapping. The man-made explosions also confirmed the idea that the injection of fresh particles inside Earth's magnetic field can create stable trapped fluxes of particles around the planet.

Today we know that besides cosmic rays, several other significant sources of matter make up the belts. They include solar plasma that penetrates the magnetosphere and ionospheric particles that are injected into trapping regions during magnetic storms. Among other, more exotic sources are so-called anomalous cosmic rays produced in the outer solar system. There are also particles of interplanetary matter that escape from Jupiter's magnetosphere and travel along interplanetary magnetic field lines toward Earth.

After the pioneering work of Van Allen and coworkers in the US and their counterparts in the Soviet Union, interest in the use of space for society grew enormously. In just a few years between the late 1950s and early 1960s, space hardware went from technological demonstration and scientific curiosity to practical and routine implementation. Earth satellites have been launched for communication, weather observations, geopositioning, remote Earth sensing, military reconnaissance, and countless other purposes. Our planet is virtually encased in a cocoon of spacecraft that orbit from distances just above the sensible atmosphere to tens of thousands of kilometers above Earth's surface (see the article by David Wright, PHYSICS TODAY, October 2007, page 35). Because the radiation belts constitute the main space-weather threat to those satellites,[9] understanding their detailed behavior is essential. Radiation-belt measurements have been performed by nearly every space

Box 2. A third radiation belt

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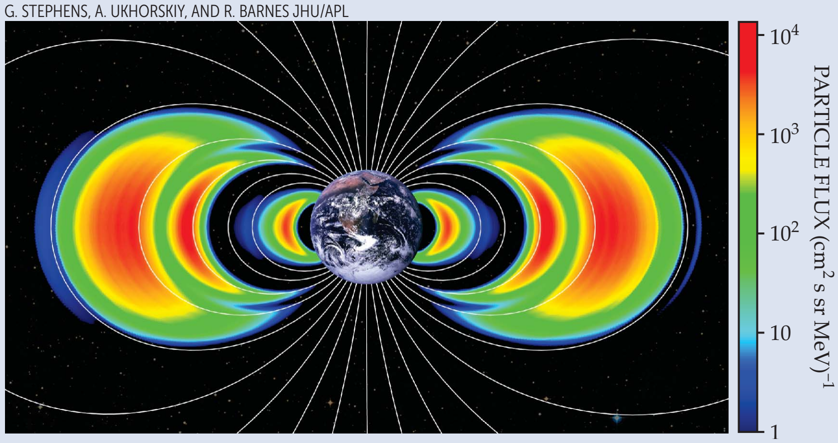

Most of the particles that make up the Van Allen belts ultimately come from the solar wind that buffets Earth's magnetosphere. Variations in the wind intensity cause the belts to wax and wane in spatial extent and trapped-particle population. Occasionally, our Sun releases billions of tons of hot plasma at several million kilometers per hour in dramatic expulsions known as coronal mass ejections (CMEs) that can pump up the belts to such intensities that they become immensely more dangerous for days to weeks afterward. To understand those changes in space weather and their satellite-killing effects, NASA began developing a program called "living with a star" about a decade ago. A key component of the program was dubbed the Radiation Belt Storm Probe (RBSP) mission, whose goal was to fly two identical Earth-orbiting spacecraft through the inner and outer belts.

Launched on 30 August 2012 into a highly elliptical orbit, the twin spacecraft (also known as the Van Allen Probes) traversed the same trajectory at different times. Within days of the launch, the RBSP sensors showed that during and after major solar-induced geomagnetic storms, a distinct and persistent population of electrons with energies greater than 2 MeV can appear in the space between the inner and outer belts. (The energy range among particles reached more than 10 MeV on occasion.) For nearly six decades, the existence of inner and outer Van Allen zones with an empty slot between them had been a well-accepted and reasonably well-understood feature in space physics. The appearance of a third belt, or population, of ultrarelativistic electrons was a fascinating surprise, and understanding it requires a mechanism for how the electrons that compose it can be emplaced and accelerated deep inside the magnetosphere.

Once accelerated, the electrons were found to circle Earth for weeks or months on magnetic drift paths without significant loss of energy or intensity, only to be abruptly lost when a shock wave from another powerful CME hit Earth and sufficiently distorted the magnetosphere. In the figure, which illustrates the flux of 4.2 MeV particles in cross section, the third Van Allen belt appears sandwiched between the inner belt's population of mostly protons and the outer belt's population of mostly electrons.

The Van Allen Probes have also detected a seemingly impenetrable barrier to the radial diffusion of electrons into the inner part of Earth's magnetosphere.[12] In fact, over the entire five-year lifetime of the spacecraft, sensors have observed no significant fluxes of electrons with energies greater than about 1 MeV inside a geocentric radial distance of 2.5 Earth radii. Whereas lower-energy electrons and protons readily move into the inner Van Allen zone, high-energy electrons appear—at least under recently observed geomagnetic conditions—completely unable to do so. Like the third belt, that feature has never been previously observed and poses interesting theoretical questions.

One intriguing aspect of the barrier is that the innermost extent of the energetic electrons seems to correspond closely to the outermost extent of a persistent Earth-shrouding "bubble" of strong, low-frequency, electromagnetic radiation detected by the Van Allen Probes. Those very low frequency (VLF) electromagnetic waves result from atmospheric lightning, leak through the ionosphere, and energize the charged particles that are entrained along magnetic field lines around the planet. But the highest proportion of wave energy in the VLF bubble appears to emanate from ground-based transmitters that communicate with submarines. Human activity may thus be sculpting the inner edge of the outer Van Allen zone.[12]

Box 3. Vernov's legacy at Moscow State University

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For many years after the launch of *Sputnik 2*, radiation and cosmic rays became the main research topics of space physics in the Soviet Union. Sergei Vernov and other scientists from Moscow State University (MSU) took the lead in those areas. Since 1957, MSU scientists have initiated and conducted numerous experiments in space. They developed individual instruments for cosmic-ray and other space radiation measurements and complex instruments to study those and related phenomena, such as electromagnetic waves, magnetic fields, and plasmas in near-Earth space.

A series of four satellites collectively called *Electron*, and whose instruments MSU scientists developed, were launched in the late 1960s to study the radiation belts. Multipurpose space experiments followed in the early 1970s to study auroral radiation using the Cosmos 900 satellites. And experiments to test solar–terrestrial interactions in Prognoz missions followed in the late 1970s and 1980s. MSU scientists developed instruments to study the radiation environment in all space missions exploring the Moon, Mars, and Venus during the Soviet era. Even before Yuri Gagarin's first manned flight into space in 1961, MSU instruments were installed aboard the robotic Vostok vehicles to provide environmental information that improved the safety of later human spaceflight.

Cosmic-radiation studies continue today in Russia. Satellites *Vernov* (2014) and *Lomonosov* (2016, shown here) were launched to answer fundamental questions about the nature of certain radiation fields in space and their influence on Earth's atmosphere. An important objective of experiments conducted on those satellites is to monitor the current hazards posed by the radiation belts and to forecast the danger level in the context of complex dynamic processes associated with the variable activity of the Sun and its effect on Earth's magnetic field.

satellite and by virtually all spacefaring nations over the past six decades.

From the late 1970s well into the 1990s, spacecraft such as the *Combined Release and Radiation Effects Satellite* and NASA's *Solar Anomalous and Magnetospheric Particle Explorer* found fascinating examples of rapid particle acceleration, abrupt and profound loss of particles from the belts, and high-energy events (greater than 10 MeV) produced by solar-induced shock waves hitting our magnetosphere. By the early 2000s, it became clear that new, advanced satellite missions were needed to solve the puzzles produced by those and other phenomena.

Recent missions

In 2012 NASA launched the Radiation Belt Storm Probes mission. Later renamed the Van Allen Probes, the dual-spacecraft mission was designed to explore the spatial structure and dynamics of the radiation environment. Almost immediately after launch, the satellites' instruments discovered a new phenomenon: the presence of a third distinct population of energetic particles—in effect, a third belt.[10] Discussed in box 2, the newly found region of ultrarelativistic electrons has intrigued both observers and theorists. Soviet satellites and others had detected relativistic electrons in the slot region between the two main belts during 1970s-era missions, but the Van Allen Probes offered the first comprehensive and detailed spatial patterns. The dynamics found by the twin satellites flying in that region during magnetic storms have revealed how MeV particles are accelerated and suddenly lost from the belt.

Two years after the Van Allen Probes began collecting data, Russia launched a satellite called *Vernov*, which is now also studying the third belt and has clarified some details of the phenomenon. Spacecraft recently launched by Russia, the US, and other nations have found even more features of Earth's radiation belts, such as a remarkably sharp apparent barrier to the transport of charged particles from the outer to the inner belt, changes in the populations of extremely high-energy protons, and the presence of electric fields that modulate the flow of radiation-belt particles.[11]

In April and December 2016, two new satellites—*Arase* from Japan and *Lomonosov* from Russia—were launched to continue space-environment studies. *Lomonosov* has special relevance for this anniversary article. That satellite, pictured in box 3 and named after the founder of MSU, Mikhail Lomonosov (see the article by Vladimir Shiltsev, PHYSICS TODAY, February 2012, page 40), is the latest in a series of satellites initiated and launched by MSU scientists—a series that started with Vernov's work on *Sputnik 2*. It's unlikely that MSU's interest and involvement (or that of dozens of other institutes and space agencies) in such studies will wane anytime soon. Radiation-belt features have been found around every magnetized planet in our solar system.

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