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Chapter 6

The Origins of Magnetospheric Physics[1]

James A. Van Allen[2]

As of 1981, magnetospheric physics is a massive and flourishing science which engages the efforts of over a thousand investigators in at least twenty different countries. The current rate of publication in this field is on the order of two or three original research papers per day. The scientific heritage of the subject lies principally in the areas of geomagnetism, aurorae, geomagnetic storms, and the geophysical aspects of cosmic rays and solar corpuscular streams. This heritage is well represented by a wide body of important scientific literature.[3]

The general magnetic field of the Earth is essential to the existence of its magnetosphere. Indeed the magnetosphere of the Earth or of any other celestial body may be defined as that region surrounding the body within which its magnetic field, however distorted by external currents, controls the motion of electrically charged particles. The magnetosphere of the Earth encompasses a huge population of such particles—electrons, protons, and other ions—whose source and gross dynamics are traceable principally, but

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[1] Presented at the Fifteenth History Symposium of the International Academy of Astronautics, Rome, Italy, 1981.

[2] Department of Physics, University of Iowa, Iowa City, Iowa, U.S.A. I am very grateful for a Regents' Fellowship of the Smithsonian Institution for the period January-August 1981. During this time I was in residence at the National Air and Space Museum in Washington, D.C., writing a monograph entitled "Origins of Magnetospheric Physics." The present paper is an abridgement of a portion of that monograph.

[3] S. Chapman, and J. Bartels, *Geomagnetism* (Oxford, England: The Clarendon Press, 1940, 2 vols.); L. Jánossy, *Cosmic Rays* (Oxford, England: The Clarendon Press, 1948); S. K. Mitra, *The Upper Atmosphere* (Calcutta, India: The Asiatic Society, 1952 ed.); D. J. X. Montgomery, *Cosmic Ray Physics* (Princeton, NJ: Princeton University Press, 1949); C. Störmer, *The Polar Aurora* (Oxford, England: The Clarendon Press, 1955); H. Alfvén, *Cosmical Electrodynamics* (Oxford, England: The Clarendon Press, 1950).

not wholly, to the solar wind, a magnetized, ionized gas emitted by the Sun and flowing outward through the solar system.

On the one hand, magnetospheric physics is closely related to laboratory plasma physics, and, on the other, it is presumably applicable to natural phenomena in planetary and astrophysical systems throughout the universe. The theory of ionized gases in magnetic and electric fields provides the unifying principles of the subject over a vast range of physical scale. The present sophistication of magnetospheric physics stands in stark contrast to its primitive beginnings.

Precursory Work

During the period 1946-1957, a large number of investigations were conducted in the upper atmosphere of the Earth with scientific instruments on rockets flown more or less vertically to altitudes of up to 390 kilometers by research workers in the United States, the Soviet Union, the United Kingdom, Australia, France, and Japan.[4] Some of these flights were devoted to the study of the intensity and nature of the cosmic radiation above the appreciable atmosphere. Such measurements were extended over the latitude range 77° North to 71° South by an inexpensive balloon-launched rocket technique during the latter part of this period.[5] This series of flights from ships at sea also resulted in the first direct observations of the primary auroral radiation.[6]

Experience in conducting scientific measurements with rocket-borne instruments, *and* the rapid development of high performance rockets following World War II, made it realistic to plan scientific work with Earth orbiting satellites as part of the 1957-1958 International Geophysical Year. The first flight of an artificial satellite of the Earth, *Sputnik I*, was achieved by the Soviet Union on 4 October 1957. The radio signals from *Sputnik I*, at 20.005 and 40.002 MHz, were received by stations throughout the world. The distinctive—beep-beep-beep—modulation of these signals heralded the beginning of a new scientific epoch. *Sputnik II*, launched on 3 November 1957, carried the first detectors of energetic charged particles to be flown on a satellite. Two shielded (10 g cm^{-2}) Geiger tubes (gas-discharged counters 10 cm in length and 1.8 cm in diameter) in this payload were intended to provide a geographically comprehensive survey of the cosmic ray intensity above the atmosphere. This flight obtained observations over the Soviet Union for a period of about seven days in the altitude range 225 to 700 km, the latitude

[4] Homer E. Newell, Jr., *High Altitude Rocket Research* (New York: Academic Press, 1953).

[5] James A. Van Allen, "Balloon-Launched Rockets for High-Altitude Research," in Homer E. Newell, Jr., ed., *Sounding Rockets* (New York: McGraw-Hill Book Co., 1959); James A. Van Allen and M. B. Gottlieb, "The Inexpensive Attainment of High Altitudes with Balloon-Launched Rockets," in R. L. F. Boyd and M. V. Seaton, eds., *Rocket Exploration of the Upper Atmosphere* (London, England: Pergamon Press, 1954).

[6] L. H. Meredith, M. B. Gottlieb, and James A. Van Allen, "Direct Detection of Soft Radiation Above 50 Kilometers in the Auroral Zone," *Physics Review*, 97 (1955): pp. 201-205; James A. Van Allen, "Direct Detection of Auroral Radiation with Rocket Equipment," *Proceedings of the National Academy of Sciences*, 43 (1957): pp. 57-62.

range 40° to 65° North and the longitude range 25° to 143° East. Reliable data were obtained on the latitude and altitude dependence of cosmic ray intensity. On a particular pass on 7 November 1957 a brief series of "bursts" of substantially greater (~50 percent) than average intensity was observed coherently by the two detectors at latitudes greater than 58° North (Figure 1). This effect was termed a "cosmic-ray burst," but no physical interpretation was suggested. Otherwise the *Sputnik II* data exhibited a smooth dependence of previous rocket measurements at lower altitudes.[7]

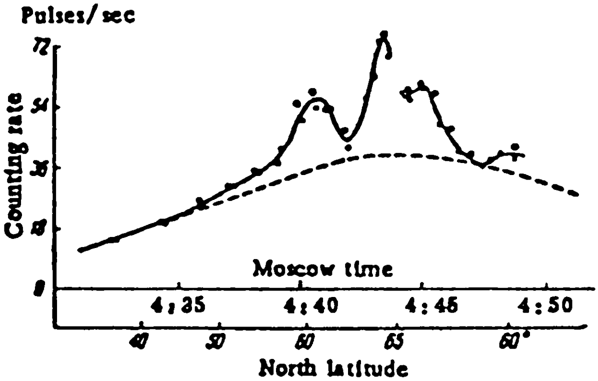

Figure 1 Time dependence of the counting rate of a Geiger tube on *Sputnik II*. The dashed curve shows the usual case and the points and solid curve show the occurrence of an unusual "cosmic ray burst" on 7 November 1957 (See S. N. Vernov, N. L. Grigorov, Iu. I. Logachev, and A. E. Chudakov, "Cosmic Radiation Measured on the Second Artificial Satellite," *Doklady Academii Nauk, U.S.S.R.*, 120 (1958): 1231-1233, also published in English, *Soviet Physics Doklady*, 3 (1958): 617-619.

Discovery of the Inner Radiation Belt of the Earth

In anticipation of the opportunity for extending our sparse geographical survey with rockets of the cosmic ray intensity above the atmosphere, I had proposed the flight of a simple radiation detector on an early U.S. Earth satellite.[8] The instrumentation prepared for this purpose at the University of Iowa had a single, lightly-shielded (1.5 g cm^{-2}) Geiger tube (10.2 cm length and 2.0 cm diameter) as the basic detector. One such instrument was a part of the payload (Figure 2) of the first U. S. satellite, *Explorer I*, launched on 1 February 1958 (UT), 31 January, EST from Cape Canaveral, Florida, into an orbit inclined at 33° to the equator with perigee and apogee altitudes of 360 and 2550 km, respectively. A similar instrument was flown in *Explorer III*, launched on 26 March

[7] S. N. Vernov, N. L. Grigorov, Iu. I. Logachev, and A. E. Chudakov, "Cosmic Radiation Measured on the Second Artificial Satellite," *Doklady Academii Nauk, USSR*, 120 (1958): pp. 1231-1233, also published in English, *Soviet Physics Doklady*, 3 (1958): pp. 617-619.

[8] James A. Van Allen, "Cosmic-Ray Observations in Earth Satellites," in James A. Van Allen, ed., *Scientific Uses of Earth Satellites* (Ann Arbor: University of Michigan Press, 1956), pp. 171-187.

1958 into an orbit of the same inclination with perigee and apogee altitudes of 188 and 2800 km, respectively.[9] The *Explorer III* instrument included the important addition of a miniature magnetic tape recorder which stored the counting rate data for 135 minutes (more than a complete orbital period) and then, on radio command, played back the stored data over the telemetry transmitter in six seconds while within the range of a single receiving station.[10]

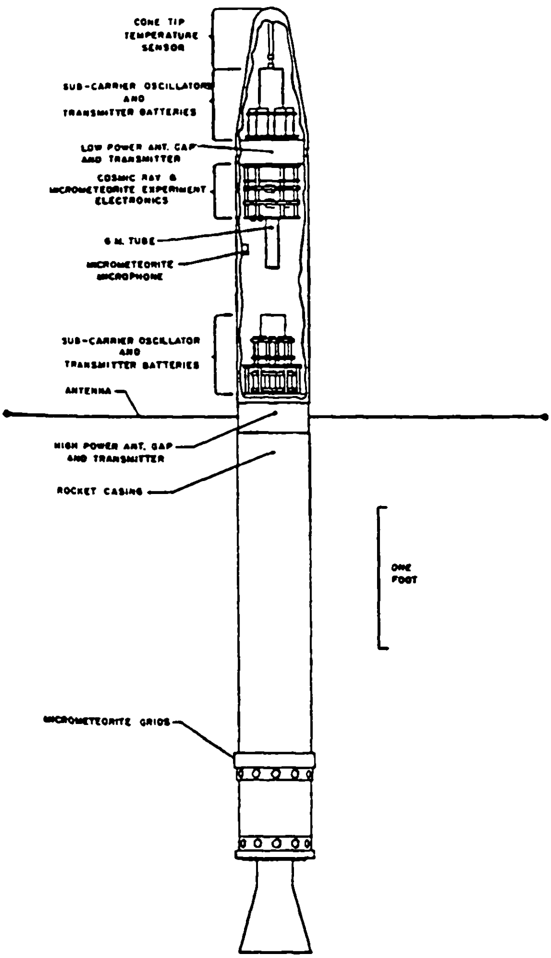

Figure 2 Outline drawing of the payload of *Explorer I* (1958 Alpha), as permanently attached to the fourth stage rocket of the propulsion system (See George H. Ludwig, "Cosmic-Ray Instrumentation in the First U.S. Earth Satellite," *Review of Scientific Instrumentation*, 30 (1959): 223-29).

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[9] George H. Ludwig, "Cosmic-Ray Instrumentation in the First U.S. Earth Satellite," *Review of Scientific Instrumentation*, 30 (1959): pp. 223-229.

[10] George H. Ludwig, "The Instrumentation in Earth Satellite 1958 Gamma," M. S. Thesis, University of Iowa Research Report 59-3, 1959. See also *Satellites 1958 Alpha and Gamma: High Intensity Radiation Research and Instrumentation*, IGY Satellite Report No. 13 (Washington, DC: National Academy of Sciences, 1961), pp. 31-93.

Within the first few weeks of *Explorer I*'s orbital flight, we had only a rather sparse set of data, consisting of segments of the order of one minute duration from many different and somewhat uncertain positions in latitude, longitude, and altitude. During some segments of data, the counting rate of our Geiger tube was of the order of 20 to 100 counts per second, generally within the range that we had expected for cosmic radiation, and the instrument appeared to be operating reliably. In other segments of data there were no counts observed for as long as two minutes. On one noteworthy pass the rate underwent a transition from zero to a reasonable value within about twenty seconds. There was no conceivable way in which the cosmic ray intensity could drop to zero at high altitudes. On the other hand, we had a high level of confidence in the Geiger tube and the associated tuning fork timer and electronic circuitry by virtue of conservative design and the rigorous thermal and mechanical conditions that it had survived in the pre-flight testing program. This puzzle hung over our heads as we tried to find if this strange effect had any systematic dependence on passing through the Earth's shadow, on payload temperature, or on altitude, latitude or longitude. Noise-free data accumulated slowly.

Throughout the few weeks following the launch of *Explorer I* we were heavily occupied in preparing *Explorer II* (lost in the launch failure of 5 March) and *Explorer III*; in developing data reduction and analysis techniques, to which we had given relatively little attention before flight; in formulating plans for subsequent flights; and in coping with a steady flow of telephone calls on practical arrangements and on inquiries concerning our progress. Our original plan was to accumulate a comprehensive body of data on the distribution of cosmic-ray intensity around the Earth on a leisurely basis. But the widespread interest in *Explorer I* produced an urgent demand for an immediate report of observational results.

Soon after the launching of *Explorer III*, I flew to Washington, D.C., to confer with Joseph Siry, John Mengel, and others at the Naval Research Laboratory (NRL) and pick up preliminary orbital data for *Explorer III*. Contrary to the implications of some popular accounts, the Vanguard group fully supported the Explorer program in many vital ways. The first successful launch of a Vanguard satellite had occurred on 17 March 1958, and the NRL team was operating on an around-the-clock basis, now handling the tracking and data acquisition for three satellites. From NRL, I returned to the Vanguard data center on Pennsylvania Avenue and picked up the complete record of a successful playback of data from our *Explorer III* tape recorder. The playback had been received at the San Diego minitrack station on 28 March 1958.

I put the record in my briefcase and returned to my room in the Dupont Plaza Hotel. There, with the aid of graph paper, my slide rule, and a ruler from a nearby Peoples Drug Store, I worked out the counting rates of our Geiger tube as a function of time for a full 102-minute period and plotted them (Figure 3). The data provided a beautiful confirmation and extension of the fragmentary data from *Explorer I*. The counting rate at low altitudes was in the expected range of 15 to 20 counts per second. There was then a very rapid increase to a rate exceeding 128 counts per second (the maximum recordable rate of our on-board storage system). A few minutes later the rate decreased rapidly to zero. Then after about fifteen minutes it rose rapidly from zero to greater than 128 counts per second again and remained high for forty-five minutes, then again decreased rapidly to 18 counts per second as the orbit around the Earth was nearly completed. At 3:00 a.m. I packed my work sheets and graph and turned in for the night with the conviction that our instruments on both *Explorers I* and *III* were working reliably and giving reproducible results, but that we were encountering a mysterious physical effect of a real nature.

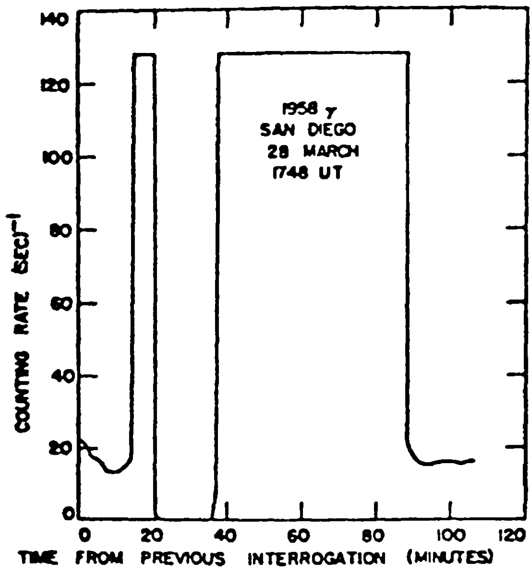

Figure 3 *Apparent* counting rate of the Geiger tube on *Explorer III* (1958 Gamma) as derived from a tape recording for one orbit around the Earth. Note that 128 count sec^{-1} is the saturation level of the recording system and that a zero *apparent* counting rate corresponds to a *true* counting rate greater than 25,000 count sec^{1} (James A. Van Allen, "Observations of High Intensity Radiation by Satellites 1958 Alpha and 1958 Gamma, *Satellites 1958 Alpha and Gamma: High Intensity Radiation Research and Instrumentation*, IGY Satellite Report No. 13 (Washington, DC: National Academy of Sciences, 1961), pp. 1-22.

Early the following day I flew back to Iowa City and proudly displayed my graph and my conviction to my colleagues, Earnest Ray and Carl McIlwain. Meanwhile, it had occurred to McIlwain that a sufficiently great intensity of radiation would overload our detection system and drive the "apparent" counting rate to zero, a fact that we all knew but had temporarily ignored, because of our predisposition to reject the possibility of such great intensities, and because of our apprehension about possible malfunctioning of the instrument. During the previous day, McIlwain made tests with our prototype Geiger tube system using a small x-ray machine and demonstrated that a true rate exceeding about 25,000 counts per second would indeed result in an apparent telemetered rate of zero. The conclusion was immediate: At altitudes of the order of 1200 km and greater the radiation intensity was at least a thousand times as great as that of cosmic radiation!

Ray's famous, though consciously inaccurate remark summarized the situation: "My God, space is radioactive!" Our realization that there was a very great intensity of radiation at high altitudes rationalized our entire body of data. George Ludwig returned from the Jet Propulsion Laboratory to the University of Iowa on the 11th of April 1958, and the four of us continued working feverishly in analyzing the data from *Explorers I* and *III* (using primitive hand methods) and organizing them by altitude, latitude, and longitude. The systematic, repetitive run of the data on successive orbits confirmed my earlier conclusion that both instruments were indeed operating reliably.

During mid-April we prepared graphs and a short written statement of our raw findings and I mulled over their meaning.[11] I entertained two quite different lines of thought: (a) that we might be detecting x rays or gamma rays, possibly from the Sun or (b) that the radiation at high altitudes might be akin to the auroral soft radiation which we had studied during the preceding several years with rockroom flights at high latitudes and most recently by McIlwain's rocket flights from Fort Churchill. We had identified the auroral radiations as being principally electrons having energies of the order of 10s of keV. I quickly rejected hypothesis (a) on the conclusive grounds that the high intensity radiation was present during both daylight and dark conditions, that it exhibited a latitude dependence, and that the extremely rapid increase in intensity with increasing altitude was impossible for any type of electromagnetic radiation. Specifically, the rate of increase of intensity was a factor of ten within an altitude range of less than 100 kilometers at an altitude of the order of 100km; the decrease in atmospheric "thickness" within that increment of altitude was totally negligible compared to the same 1.5 g cm^{-2} of material in the nose cone and wall of the detector. Such an increase could not be due to decreased absorption of x-rays or gamma rays of any wavelength. Hence, I concluded that the effect must be attributed to electrically charged particles, constrained by the Earth's external magnetic field from reaching lower altitudes.

Such particles could not be arriving directly from infinity because of the concentration of the effect near the geomagnetic equator, in complete defiance of C. Störmer's theory of the entrance of electrically charged particles from a distant source into the Earth's magnetic field. By virtue of my familiarity with a 1907 paper by Störmer on the bound motion of an electrically charged particle in a dipolar magnetic field, with magnetic field confinement of charged particles in laboratory machines during my 1953-1954 work building and operating an early version of a stellarator at Princeton University, and with an early 1958 suggestion of N. C. Christofilos (discussed later), I further concluded that the causative particles were present in trapped orbits in the geomagnetic field, moving in spiral paths back and forth between the northern and southern hemispheres and drifting slowly around the Earth.[12] The intensity of these trapped particles, whose mirror points were at low altitudes, would be diminished by atmospheric absorption. I called this population of particles geomagnetically trapped corpuscular radiation. Later it was termed the "radiation belt" of the Earth because of the toroidal form of the populated region, encircling the Earth like a belt.

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[11] James A. Van Allen, George H. Ludwig, Ernest C. Ray, and Carl E. McIlwain, "Observation of High Intensity Radiation of Satellites 1958 Alpha and Gamma," *Jet Propulsion*, September 1958, pp. 588-592; and "Radiation Observation with Satellite 1958 e," *Journal of Geophysical Research*, 64 (1958): pp. 271-286.

[12] C. Störmer, "Sur les trajectoires des corpuscles electrises dans l'espace sous l'action du magnetisme terrestre," Series IV, *Arch. Sci. Phys. Nat.*, 24 (1907): pp. 317-364.

The foregoing account of observations and interpretation is essentially the one that I gave in a special joint session of the American Physical Society and the National Academy of Sciences in the latter's auditorium on 1 May 1958. A large press conference was held following the lectures with me and other participants in the *Explorer I* and *Explorer III* program, and the results were reported extensively by news media on the following day. Fortunately, and unknown to me until more than a year later, a "Voice of America" tape recording was made of my lecture and of the ensuing question and answer period. A written transcription of this tape, together with copies of my illustrations, provided a documented, published record of this lecture, complete with grammatical errors and colloquial language.[13]

I had adopted at that time the working hypothesis that the trapped radiation consisted of "electrons and likely protons, energies of the order of 100 keV and down, mean energies probably about 30 keV." In this vein of thought, the response of our Geiger tube would be attributed to *bremsstrahlung* produced as the electrons bombarded the nose cone of the instrument. If this *bremsstrahlung* interpretation was correct, I estimated that an omnidirectional intensity of 10^8 to 10^9 $(cm^2\ sec)^{-1}$ of 40 keV electrons would be required to account for the counting rates at altitudes of ~ 1500 km over the equator. However, in my 1 May lecture, as well as in response to a question at the end, I emphasized that we had no definitive identification of particle species, and that the particles might be penetrating protons or electrons. I did, however, regard protons and electrons of energies necessary to penetrate the Geiger tube directly, namely $E_p > 35$ MeV and $E_e > 3$ MeV, as unlikely in view of our auroral zone measurements with rocket-borne equipment. Later in 1958 we found that this opinion was incorrect.

Of the some 1,500 real-time recordings of *Explorer I* telemetry signals in the period 1 February to 9 May 1958, 850 contained readable data. A much larger body of data was obtained from *Explorer III*. During its 44 days of useful life, the satellite completed 523 orbits around the Earth and 504 tape recorder play-backs were attempted. Of these attempts a total of 408, or 81 percent, were successful. The tape recorder operated perfectly throughout this period and never failed to respond to a command that was electronically successful.

Virtually all of the *Explorer I* data were reduced and analyzed (Figures 4 and 5).[14] But only some 10 percent of the *Explorer III* data were reduced. Even as of 1981, George Ludwig and I regret not having completed the reduction of the major part of both the real-time and stored data from *Explorer III*. In early 1958, however, we considered that we had gleaned the principal elements of the data and hardly felt it worthwhile to continue because of the limited dynamic range of the instrument and our preoccupation with follow-on satellite missions carrying detectors specifically designed for the then-known intensities and for particle species identification and other more revealing properties of the radiation.

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[13] James A. Van Allen, "Observations of High Intensity Radiation by Satellites 1958 Alpha and 1958 Gamma," in *Satellites 1958 Alpha and Gamma: High Intensity Radiation Research and Instrumentation*, IGY Satellite Report No. 13 (Washington, DC: National Academy of Sciences, 1961), pp. 1-22.

[14] S. Yoshida, George H. Ludwig, and James A. Van Allen, "Distribution of Trapped Radiation in the Geomagnetic Field," *Journal of Geophysical Research*, 65 (1960): pp. 807-813.

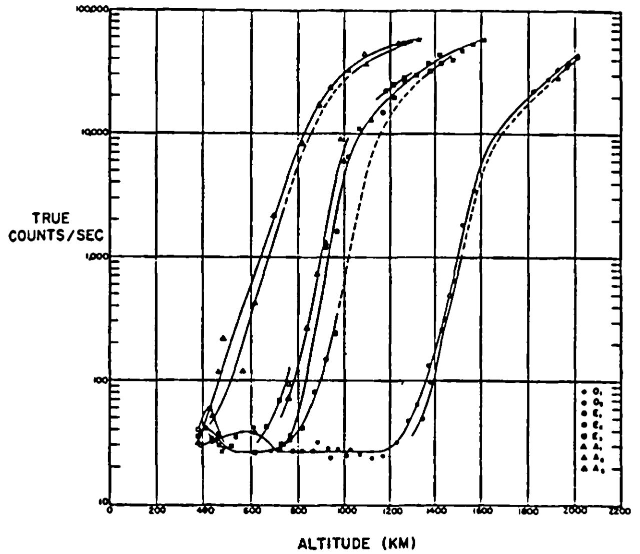

Figure 4 Altitude dependence of the *true* counting rate of the Geiger tube on *Explorer 1* as observed within 19° of the magnetic dip equator at different geographic longitudes approximately as follows: two curves on the left, 288° East; three curves in the center, 5° East; and two curves on the right 105° East (See S. Yoshida, George H. Ludwig, and James A. Van Allen "Distribution of Trapped Radiation in the Geomagnetic Field," *Journal of Geophysical Research*, 65 (1960): 807-813).

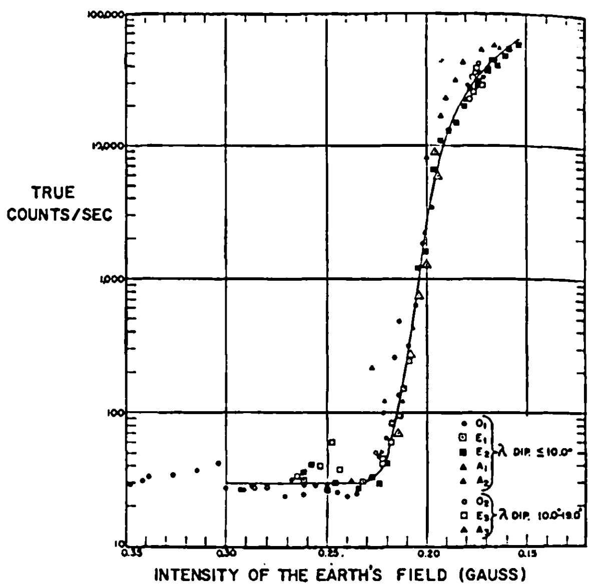

Figure 5 All of the counting rate data of Figure 4 replotted as a function of scalar magnetic field strength, illustrating the validity of the geomagnetic trapping hypothesis. (See S. Yoshida, George H. Ludwig, and James A. Van Allen "Distribution of Trapped Radiation in the Geomagnetic Field," *Journal of Geophysical Research*, 65 (1960): 807-813).

There is no evidence, so far as I can find, that Soviet scientists were aware of the existence of geomagnetically trapped radiation before my 1 May 1958 report of *Explorer I/III* observations. It may be noted that the high intensity radiation found by these two satellites was a part of what was later recognized as the *inner* of two major radiation belts.

Radiation Observations with Sputnik III

The third Soviet satellite, *Sputnik III*, was launched on 15 May 1958 into an orbit inclined at 65° to the equator. Its orbit, similar to that of *Sputnik II*, had perigee and apogee altitudes of 225 and 1,880 km, respectively. Among other equipment, *Sputnik III* carried a scintillation detector for the observation of photons and charged particles. The scintillator was a cylinder of crystalline NaI (T*l*) 4.0 by 3.9 cm in size, mounted on a photomultiplier tube whose photocathode had a diameter of 4.0 cm. The effective shielding of the detector was at least 1 g cm^{-2}. Three quantities were transmitted: (a) the counting rate of pulses corresponding to energy release in the crystal of 35 keV or more, (b) the anode current of the photomultiplier tube, and (c) the current to an intermediate dynode. A preliminary report of the observations with this instrument was made in a special lecture by S. N. Vernov at the Fifth General Assembly of CSAGI (Special Committee for the International Geophysical Year) in Moscow, 30 July-9 August 1958. Among U.S. delegates to this meeting were Ernest Ray of the Iowa group, who gave a preliminary report of *Explorer IV* results obtained during the first few days of its flight (see later section). The first written report (available in English) of *Sputnik III* observations that I have found was submitted to *Planetary and Space Science* on 17 January 1959 and published soon thereafter.[15] The stated intention of this investigation was "to obtain data on photons at high altitudes." The choice of detector and associated data handling system does not suggest any prior knowledge of the existence of geomagnetically trapped radiation, nor is there any hint of such prior knowledge in the text of the paper. Nonetheless, as with *Explorer I*, the principal results related to electrically charged particles (in part, via their *bremsstrahlung*).

Vernov and his colleagues distinguished two observed zones of high intensity radiation—a polar zone (latitudes 52° to 65° North) and an equatorial zone. In the section of their paper entitled "Electronic Component of Cosmic Rays in the Polar Region," the authors stated, in part:

> Comparing this increase of ionization and increase of the counting rate, one can estimate photon energy of the bremsstrahlung radiation and, consequently, the energy of electrons. The photon energy will be of the order of 100 keV or less. The sign "less" arises due to the fact that in some cases only a low limit of counting rate is known. However, the photon energy cannot be significantly lower than 100 keV, since the threshold is 35 keV. Thus, the most probable value of the energy of elec-

[15] The following quotes and my observations on the findings are from S. N. Vernov, A. E. Chudakov, E. V. Gorchakov, J. L. Logachev, and P. V. Vakulov, "Study of the Cosmic-Ray Soft Component by the 4th Soviet Earth Satellite," *Planetary and Space Sciences*, 1 (1959): pp. 86-93.

> trons responsible for the effect is about 100 keV. . . . Thus, the polar region is characterized by a permanent electron flux, the intensity of which varies in a wide range. Taking into account the efficiency of electron registration by the bremsstrahlung radiation, we estimate the electron flux as 10^3 to 10^4 particles (cm^2 sec sterad)$^{-1}$. . . .

The authors concluded this section of their paper as follows:

> At present it is difficult to give a complete interpretation of the electron component observed. It is not excluded that these electrons are accelerated near the Earth by electric fields similar to those assumed to be in the aurora. But it is possible also that the electron component comes from far away, for example, from the Sun; and penetrates, despite the small amount of energy of the particles, through the Earth's magnetic field due to the difference between the field and that of an ideal dipole.

On a purely observational basis the *Sputnik III* data represented discovery of the Earth's *outer* radiation belt, inasmuch as they were acquired before those of *Explorer IV* and *Pioneer III* (see later section). However, the interpretation of Vernov and his associates did not encompass the idea of geomagnetic trapping for what they called the "electron component of the cosmic rays in the polar region."

The next section of this important paper was entitled "Zone of High Intensity in the Equator Region." Therein the authors confirmed our *Explorers I/III* results and added significant detail on latitude and altitude dependence of intensity. They also found the radiation intensity in the equatorial region to have approximate north-south symmetry relative to the geomagnetic equator, and to be stable in time. The time stability at low latitudes was contrasted to the marked temporal variability at high latitudes. They estimated that the energy deposition rate in the NaI crystal was of the order of 5 erg sec^{-1} at an altitude of 1200 km near the geomagnetic equator. The authors remarked:

> Independently of the mechanism of production of particles in the equatorial zone, it is obvious that the main role in this effect is played by the factor of storing. This fact is proved by the concentration of particles in the equatorial zone where, at a sufficient altitude, they can oscillate for a very long period of time.

At the end of this section of the paper, the authors concluded as follows:

> It is possible now to make a hypothesis that the equatorial zone of high intensity is placed symmetrically to the Earth's magnetic field and is characterized by a strong concentration of the density of particle flux in the plane of magnetic equator. Such an equatorial zone provides, apparently, ideal conditions for particle oscillations in a magnetic field, and leakage is determined probably only by ionization losses and losses for radiation. In this case such a long lifetime of particles is possible (of the order of a year) that even such a weak mechanism of injection as the decay of neutrons leaving the atmosphere under the action of cosmic rays appears to be sufficient to explain the observed intensity.

The conclusion clearly embraced the concept of geomagnetic trapping as appropriate for the equatorial region and suggests that the decay of neutrons produced in the atmosphere by cosmic rays provides a possible source. However, no observational identification of the nature of the trapped particles was achieved nor was any information on intensity vs. range obtained. Also, it was not clear whether the authors were thinking of low energy or high energy neutrons or of electrons or protons or both as decay products thereof.

On *Sputnik III* there were two other detectors relevant to the present discussion. Each detector consisted of a fluorescent film of ZnS (Ag), 5 cm in diameter and 2×10^{-3} g cm^{-2} in thickness, deposited on the face of a photomultiplier tube. Aluminum foils of thickness 8×10^{-4} g cm^{-2} and 4×10^{-4} g cm^{-2} covered the fluorescent films of the respective detectors. The primary purpose of this instrument was to detect and measure corpuscular streams, especially those which cause aurorae and contribute to heating the upper atmosphere. Again the principal results related to geomagnetically trapped particles at relatively low latitudes. V. I. Krasovskii made a preliminary report on his investigation at the Fifth General Assembly of CSAGI in Moscow in 1958, including the concept of geomagnetic trapping.[16] In a 1961 full report of Krasovskii's team's findings they concluded that:

> . . . large currents of electrons with energies about 10 keV were detected at 1900 km above the southern part of the Pacific Ocean. The intensity of these currents was very high, and in the majority of cases the apparatus gave off-scale readings, since it was not expected that such high intensities would be present . . . . For all the off-scale readings, the energy flux of the electrons under investigation was in excess of 100 erg $(cm^2\ sec)^{-1}$ up to 1900 km from the Earth's surface. If electron currents of this intensity were capable of penetrating into the lower parts of the atmosphere, for example the F-layer of the ionosphere, then they could not have remained unnoticed, since they would appreciably increase the ionization of the upper atmospheres and would give rise to polar aurorae. Since such phenomena were not observed, the recorded currents were explained by an oscillatory motion of the electrons along the magnetic lines of force (July 1958, Fifth CSAGI Meeting, Moscow) . . . .
>
> The majority of the recorded electrons move near the plane perpendicular to the magnetic line of force, and the flux of electrons along the line of force in the direction toward the Earth (downward direction) is greater than in the opposite direction. Electrons moving toward Earth at small angles to the magnetic line of force were also recorded, and this suggests that particles which penetrate into the lower part of the atmosphere appear as a result of some processes occurring at distances in excess of 1900 km. It was established that the energy flux of electrons with a magnetic moment enabling penetration into the F-layer of the ionosphere can reach values of about 1 erg $(cm^2\ sec)^{-1}$.[17]

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[16] V. I Krasovskii, Yu. M. Kushnir, G. G. Bordovskii, G. F. Zakharov, and E. M. Sveltlitskii, "The Search for Corpuscles with the Help of the Third Artificial Satellite," in *Artificial Earth Satellites* (New York: Plenum Press, 1960); 2:75-77. This was also published in *Uspekhi Fiz. Nauk*, USSR, 64 (1958): 425.

[17] V. I. Krasovskii, I. S. Shklovskii, Yu. I. Galperin, E. M. Sveltlitskii, Yu. M. Kushnir, and G. A. Bordovskii, "Discovery of Approximately 10-kev Electrons in the Upper Atmosphere," in *Artificial Earth Satellites* (New York: Plenum Press, 1961), 6:137-155.

Follow on Investigations with Explorer IV and Pioneers I, II, and III

The next satellite to carry radiation instruments was *Explorer IV*, under the joint auspices of the U.S. National Committee for the International geophysical year and the Department of Defense. Its purpose was twofold: First, to follow up on the discoveries of *Explorers I/III* with a system of detectors of adequate dynamic range to cope with the then-known intensity of trapped radiation and of more discriminating properties than those used in *Explorers I/III*, and, second, to observe the effects of a planned series of high altitude atomic bomb tests. The bomb tests had been proposed in the Atomic Energy Commission by Nicholas Christofilos in late 1957 for the purpose of producing artificial radiation belts of electrons from the decay of radioactive fission products of the bombs.[18] The University of Iowa group was entrusted with preparing the package of radiation detectors. We settled on an array of four radiation detectors:

1. *Detector A:* A circular disc of plastic scintillator, thickness 0.178 cm, diameter 0.762 cm, cemented on the face of an end-window photomultiplier tube and covered by 0.14 cm^{-2} of aluminum (pulse counting).
2. *Detector B:* A circular disc of CsI (*Tl*) scintillating crystal, thickness 0.203 cm, diameter 0.762 cm, cemented on the face of an end-window photomultiplier tube, with the crystal coated with an evaporated layer of aluminum (0.2 mg cm^{-2}) and further shielded by a nickel foil of 0.8 mg cm^{-2} thickness (quasi-logarithmic electrometer for anode current).
3. *Detector C:* A miniature Geiger tube having a omnidirectional geometric factor of 0.14 cm^2 for 1.2 g cm^{-2} shielding and its full value of 0.705 cm^2 for about 5 g cm^{-2} shielding (pulse counting).
4. *Detector D:* A nearly identical Geiger tube, enclosed in an additional lead shield of 1.6 g cm^{-2} thickness so that its omnidirectional geometric factor was 0.14 cm^2 for 2.8 g cm^{-2} shielding and 0.823 cm^2 for 6 g cm^{-2} shielding (pulse counting).

Detectors A and B were clearly directional by virtue of physical collimators and the geometric shape of the sensitive elements; Detectors C and D were sensitive omnidirectionally, but there was an unavoidable variation of the shielding in different directions. Every effort was made to provide the necessary dynamic range to cope with the intensity of the natural radiation and the estimated intensity of that to be artificially injected.

Upgraded high speeds of the four-stage launching vehicle made it possible to plan an increase in the inclination of the satellite orbit, from the 33° orbits of *Explorers I* and *III*, to 50° in order to provide improved coverage in latitude. *Explorer IV* was launched from the east coast of the United states on 26 July 1958 into an orbit of 50° inclination to the equator, with perigee and apogee altitudes of 260 and 2200 km, respectively.

All the detectors operated properly and there was soon a large amount of fresh observational data available. The findings of *Explorers I/III* were massively confirmed, and major advances were made in knowledge of the distribution of intensity and the

[18] N. C. Christofilos, "The Argus Experiment," *J. of Geophysical Research* 64 (1959): pp. 869-875.

nature of the geomagnetically trapped radiation.[19] Energy fluxes as great as ~ 100 erg $(cm^2 \ sec \ sr)^{-1}$ were measured with Detector B at high altitudes near the geomagnetic equator and excellent angular distributions were obtained. Comparison of the rates of detectors C and D showed that the radiation near the geomagnetic equator was much more penetrating than at high latitudes and was not compatible with the *bremsstrahlung* interpretation that I had suggested earlier.

In agreement with the data from *Sputnik III*, the distribution of intensity as observed near the Earth was found to be bifurcated into a low latitude region and a high latitude region separated by a "slot" of lesser intensity at a geomagnetic latitude of about 48°. The angular distributions of directional intensity and the altitude distributions of omnidirectional intensity in *both* regions were characteristic of magnetically trapped radiation. This result for the high latitude region contradicted the 1958 interpretation of Vernov and his colleagues as quoted above. Contours of constant intensity turned away from the Earth at geomagnetic latitudes exceeding about 60°, suggesting that aurorae occur at or beyond the high latitude boundary of trapping. The diversity of detectors on *Explorer IV* also gave a parametric characterization of the radiation at each point along the orbit, but we were still unable to reach unique conclusions on the relative proportion of electrons and protons because of ignorance of their respective energy spectra. In a later paper I gave a variety of alternative interpretations.[20] Meanwhile, the U.S. Department of Defense had produced bursts of two 10-megaton yield atomic bombs, called *Teak* and *Orange* on 1 August and 12 August 1958, at approximate altitudes of 75 and 45 km, respectively, above Johnston Atoll in the North Pacific. Three Argus atomic bomb bursts (about 1.4 kiloton yield) were produced over the South Atlantic on 27 August, 30 August, and 6 September 1958 at altitudes of about 200, 250, and over 480 km, respectively.

We observed with *Explorer IV* the effects of all five nuclear bursts in populating the geomagnetic field with energetic electrons. Despite the large yields of *Teak* and *Orange*, the effects on the radiation belts were small and of only a few days' lifetime because of atmospheric absorption corresponding to the relatively low altitudes of ignition. The three Argus bursts produced clear and well observed effects and gave a great impetus to understanding geomagnetic trapping.[21] About three percent of the available electrons were injected into durably trapped orbits. The apparent mean life-time of the first two artificial radiation belts was about three weeks, and about a month for the third. In all three cases a well defined and durable shell of artificially injected electrons was produced. Worldwide study of these shells provided results of basic importance in giv-

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[19] James A. Van Allen, Carl E. McIlwain, and George H. Ludwig, "Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field," *Journal of Geophysical Research*, 64 (1959): pp. 272-286.

[20] James A. Van Allen, Carl E. McIlwain, and George H. Ludwig, "Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field," *Journal of Geophysical Research*, 64 (1959): pp. 877-891.

[21] *Scientific Effects of Artificially Introduced Radiations at High Altitudes—A Symposium*, Seven observational and theoretical papers by various authors, in the *Journal of Geophysical Research*, 64 (1959): pp. 865-938.

ing a full geometrical description of the locus of trapping by "labeled" particles, and in establishing an upper limit on the diffusion coefficient of the constituent electrons.[22]

During the remainder of 1958 there were three U.S. Moon shots, *Pioneers I, II,* and *III,* launched on 11 October, 8 November, and 6 December, respectively. The most successful of these was *Pioneer III,* which did not achieve Earth escape velocity but had its apogee at 17 R_E (geocentric). Radiation data were obtained along a full radial traversal of the radiation belt region for the first time—in fact, along two different paths, one outbound away from the Earth and one inbound toward the Earth. It was found that the outer boundary of geomagnetic trapping was at a radial distance of about 10 R_E. In addition, the combination of data from *Pioneer III* with the low altitude data from *Explorer IV* revealed for the first time the full geometrical form of the two distinctly different radiation belts, an *inner* and an *outer* one (Figure 6).[23]

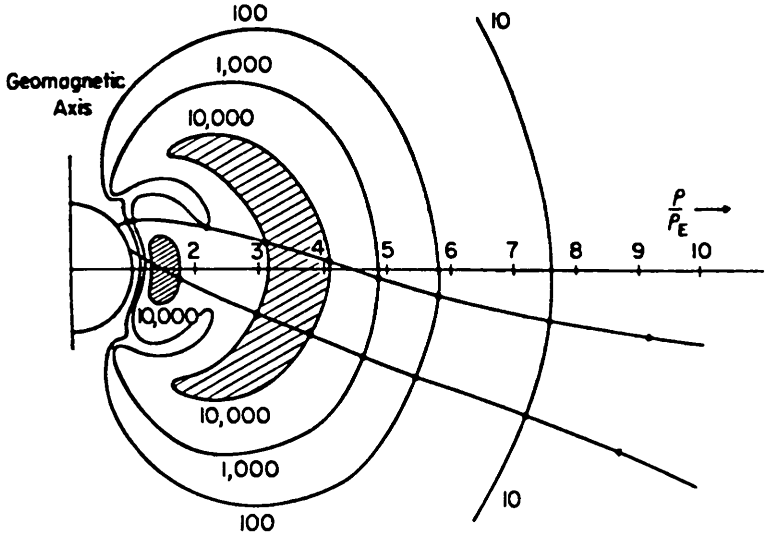

Figure 6 Intensity structure of the trapped radiation around the Earth. The diagram is a geomagnetic meridian section of a three-dimensional figure of revolution around the geomagnetic axis. Contours of constant intensity are labeled with number 10, 100, 1000, and 10,000. These numbers are the true counting rates of an Anton 302 Geiger tube carried by *Explorer IV* and *Pioneer III.* The linear scale of the diagram is relative to the radius of the Earth, 6371 km. The outbound and inbound legs of the trajectory of *Pioneer III* are shown by the slanting, undulating lines. The intensity structure is a function of detector characteristics (Van Allen and Frank, "Radiation Around the Earth to a Radial Distance of 107,400 km," as corrected in James A. Van Allen, "The Geomagnetically-Trapped Corpuscular Radiation," *Journal of geophysical Research,* 64 (1959): pp. 1683-1689.

[22] James A. Van Allen, Carl E. McIlwain, and George H. Ludwig, "Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field."

[23] James A. Van Allen and L. A. Frank, "Radiation Around the Earth to a Radial Distance of 107,400 km," *Nature,* 183 (1959): pp. 430-434.

Pioneer III completed the discovery phase in the study of the Earth's radiation belts, which were subsequently recognized as the distributions of the quite energetic components of the much greater population of (principally) lower energy particles constituting the full plasma physical system, later called the magnetosphere.