The high-altitude nuclear explosion over the Pacific on July 9, 1962, created an artificial radiation belt of considerable intensity. The characteristics of this belt, as determined by particle detectors on several satellites, are presented here.

The Artificial Radiation Belt

G. F. Pieper

On July 9, 1962, at 0900 UT (Universal Time) a nuclear device of 1.4-megatons yield was detonated at 400 km above Johnston Island in the Pacific Ocean. Since the explosion took place in the trapping region of the magnetosphere, an artificial radiation belt of considerable intensity was produced. The possible sources of the radiation belt were: (1) beta-decay electrons from the fission fragments created in the explosion; (2) protons and electrons from the decay of neutrons produced in the explosion; and (3) a large-scale redistribution in space of naturally-occurring trapped particles. Of these possible sources, only the fission fragment electrons contributed significantly to the most intense part of the artificial radiation belt. There is some evidence for a redistribution of mirror points of naturally-occurring electrons in the outer radiation zone, probably the result of a hydromagnetic disturbance propagated outward from the explosion, while the neutron decay products are spread over an immense region of space and can be shown to produce fluxes smaller than the natural ones.

The fission fragments themselves form a relatively localized source function from a geophysical point of view. Their decay electrons are trapped by the earth's magnetic field; they spiral around the field lines, oscillate between northern and southern mirror points, and drift longitudinally eastward to form a radiation belt around the earth. Radiation detection devices on several satellites—Ariel, Injun, Telstar, and TRAAC—showed large particle fluxes shortly after the explosion. Rapid degradation of the power systems of Ariel, Transit 4B, and TRAAC[1] was also observed.

The first preliminary report concerning the nature and extent of the artificial radiation belt was made by O'Brien, Laughlin, and Van Allen,[2] using data from the Injun satellite. Later, at the suggestion of W. N. Hess, Chief of the Theoretical Division of the Goddard Space Flight Center, experimenters having particle detectors on several satellites compiled their data to obtain the most complete picture possible of the new radiation belt. In addition to Hess, those involved have been R. F. Boyd, A. P. Willmore, and J. Quenby (Ariel); B. J. O'Brien, C. D. Laughlin, and J. A. Van Allen (Injun); W. L. Brown and J. Gabbe (Telstar); and G. F. Pieper and L. A. Frank (TRAAC). We will describe briefly the results of

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[1] R. E. Fischell, "The TRAAC Satellite," *APL Technical Digest*, **1**, Jan.–Feb., 1962, 2–9.

[2] B. J. O'Brien, C. D. Laughlin, and J. A. Van Allen, "Geomagnetically Trapped Radiation Produced by a High-Altitude Nuclear Explosion on July 9, 1962," *Nature*, **195**, 1962, 939–943.

this compilation.*

It is also possible to use the observed satellite solar-cell damage as an integral measurement of the trapped electron flux. This work, especially the results from Transit 4B and TRAAC, is described elsewhere in this issue by R. E. Fischell.

Satellite Radiation Detectors

Some of the earliest data concerning the enhanced trapped particle fluxes after the July 9 detonation came from the Ariel X-ray detector. This device was not designed to count charged particles and its efficiency for them is uncertain. The data are useful, however, in studying the time decay of the trapped particles and establishing contours of constant flux.

The Injun satellite[3] contains 14 radiation detectors, only one of which has an essentially omnidirectional character. This detector, denoted SpB, was originally designed to monitor the background of penetrating particles that must be subtracted from the counting rates of two open channels of a magnetic electron spectrometer. The SpB is now being used to give quantitative information and has been calibrated after the fact. It is shielded by 3.5 gm/cm^2 of lead and about 1 gm/cm^2 of counter wall and miscellaneous material; it has a geometric factor (counting cross section) of 0.11 cm^2.

Telstar carries a solid state *p-n* junction detector with pulse height analysis to select electrons in four energy ranges between 0.2 and 1.0 Mev. The detector is directional, with an aperture half angle of 10° looking out normal to the satellite's spin axis. The fluxes are converted to omnidirectional by multiplying by an appropriate solid-angle-area factor and then using a correction factor between 0.7 and 1.8 to account for the anisotropy of the electron flux.

Among the several charged-particle detectors on the TRAAC satellite[4] is an omnidirectional-type 302 Geiger counter supplied by L. A. Frank of the State University of Iowa. The counter has a wall thickness of 400 mg/cm^2 of stainless steel and is shielded by 265 mg/cm^2 of magnesium, an aggregate corresponding to an extrapolated range for electrons of ~1.6 Mev and to the range of protons of 23 Mev. The detector has a geometric factor of 0.75 cm^2 and subtends a solid angle on the satellite of $\sim 3\pi$ steradians. Omnidirectional fluxes are obtained with these constants, correcting for counter saturation at high counting rates.

Analysis of the Data

The source of the artificial radiation belt is the electrons emitted by the fission fragments produced in the nuclear detonation. The fission electron energy spectrum is known as a function of time after the fission occurs. It contains relatively more high-energy particles at early times than at later times. Thus, the energy spectrum introduced at a particular point in space depends on when the particles were injected after the detonation and may be different on one field line than on another. Furthermore, natural acceleration processes (almost certainly present in some regions of space but not well understood) may alter the spectrum as time goes on. Probably none of these qualifications changes the general picture drastically, so for lack of better knowledge the fission spectrum shown in Fig. 1, curve A, was assumed.

This assumption of a definite electron energy spectrum allows the results from the different detectors on the different satellites to be compared to determine whether they are in agreement. Calibration of an alternate unit of the Telstar detector at Los Alamos in a fission electron beam showed that the 240–340-kev energy channel counts 1/2.8 of all the electrons under curve A of

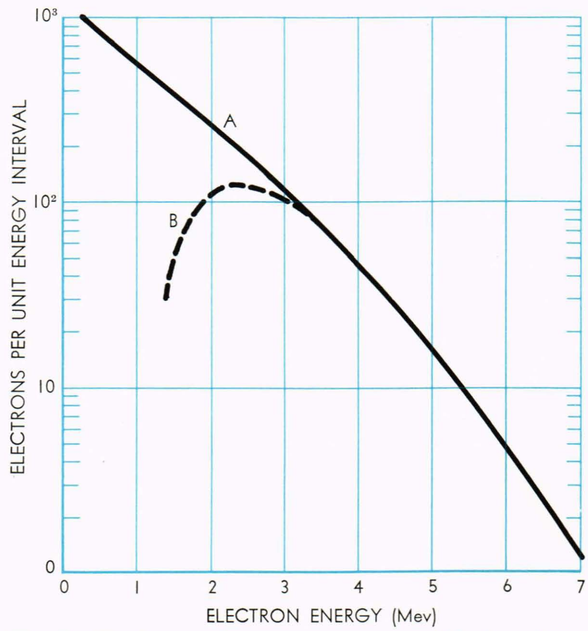

Fig. 1—(A) Assumed energy spectrum of fission electrons, and (B) energy spectrum of fission electrons counted by the 302 Geiger counter in the TRAAC satellite.

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* Portions of this paper are based on a report of this compilation by Dr. W. N. Hess. We are indebted to Dr. Hess for supplying Figs. 1–4.

[3] G. F. Pieper, "Injun, A Radiation Research Satellite," *APL Technical Digest*, **1**, Sept.-Oct., 1961, 3-7.

[4] C. O. Bostrom, D. J. Williams, and G. F. Pieper, "Charged-Particle Detection Experiments in the TRAAC Satellite," *J. Geophys. Research*, **67**, 1962, 3543.

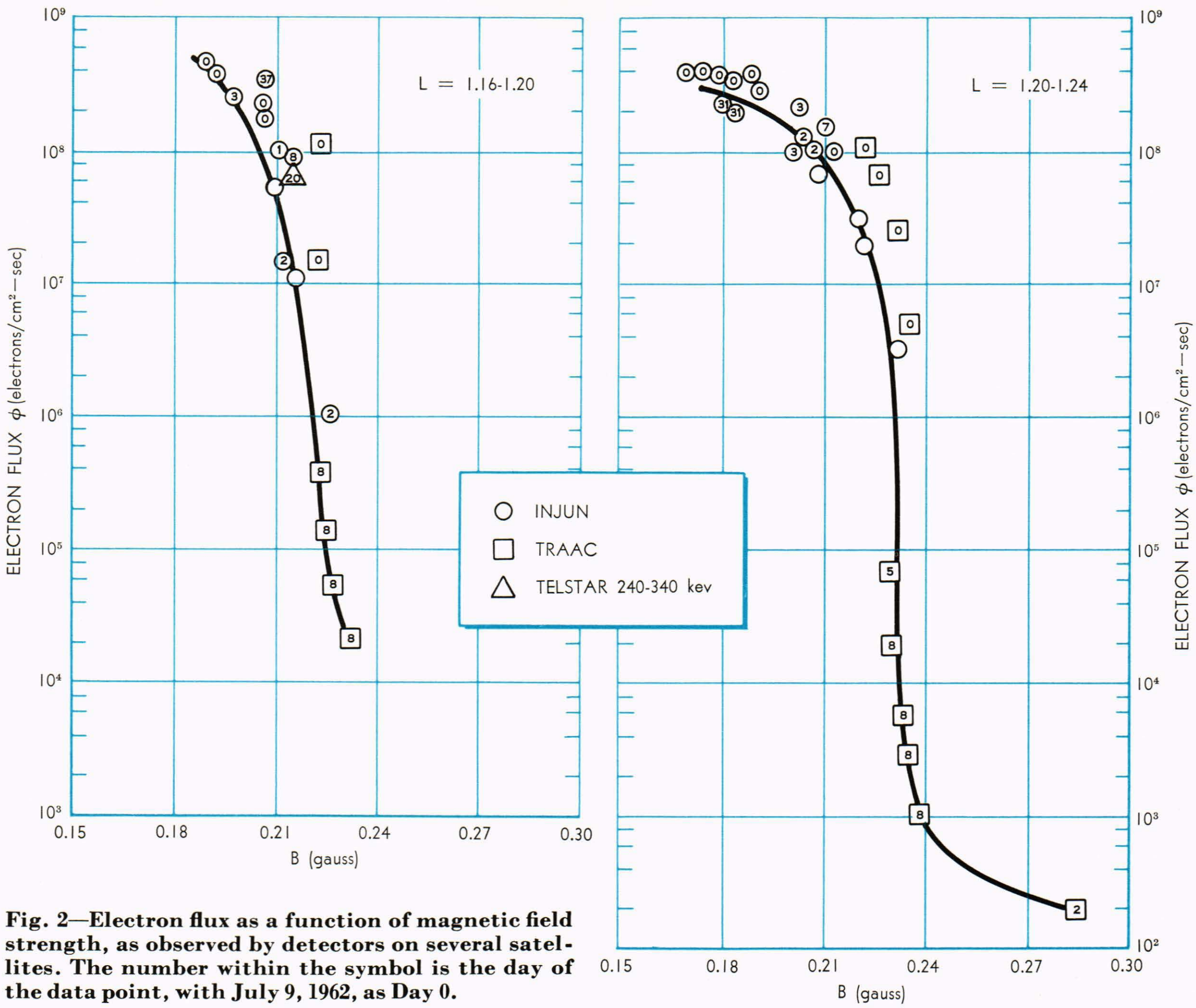

Fig. 2—Electron flux as a function of magnetic field strength, as observed by detectors on several satellites. The number within the symbol is the day of the data point, with July 9, 1962, as Day 0.

Fig. 1, while the 440–680-kev channel counts 1/6 of them. Similar calibration of an alternate unit of the Injun detector showed that it counts ~1/4000 of all the fission electrons. The factor for the TRAAC 302 counter was determined considering the penetration of electrons through the counter wall and detector shield. Using the range straggling data of Marshall and Ward,[5] one can determine the fraction of electrons that penetrate a particular thickness of material. In this way, the electron transmission spectrum for the TRAAC counter, curve B of Fig. 1, was obtained. The integral under the curve shows that the 302 counter detects 1/5.5 of all the fission electrons.

Using the above factors for the various detectors, the total flux of fission electrons can be obtained for each point in space seen by a detector. In order to compare the different detectors, Hess and coworkers have plotted the total flux along several field lines (actually narrow ranges of *L*, the magnetic shell parameter in earth radii, as a function of *B*, the magnetic field strength in gauss). These plots (samples shown in Fig. 2) show that the different detectors agree quite well, generally to a factor of two, with Telstar usually higher than Injun and TRAAC, for data taken after the day of the explosion (labeled by the number 0 inside the symbols on the plots). The data also show a quite reasonable trend in flux as a function of *B*.

This agreement among the detectors probably means that they are all working properly and that the assumption that the electrons have a fission energy spectrum is correct. It is possible, of course, that the electrons do *not* have a fission energy spectrum and that the detectors disagree, but an unlikely combination of such effects would be necessary to give the agreement observed here. One important area of disagreement between Injun and Telstar is discussed below.

[5] J. S. Marshall and A. G. Ward, "Absorption Curves and Rays for Homogeneous β-Rays," *Can. J. Research*, **A15**, 1937, 39.

Flux Plots

The data from the several satellites may now be combined to construct a composite flux map for the artificial radiation belt. McIlwain's coordinate system,[6] consisting of B and L (previously defined), is the natural one in which to express the results. The magnetic shell parameter is constant along a magnetic field line in space and, for a dipole, measures the distance from the center of the earth to the point where the field line crosses the equatorial plane. The L value thus labels a magnetic shell on which a charged particle drifts in longitude. In practice, higher-order terms in the earth's magnetic field are taken into account by calculating L from real values of the field.

The composite flux map so obtained by Hess is shown in Fig. 3. It pertains to the situation in space about one week after the explosion. Data

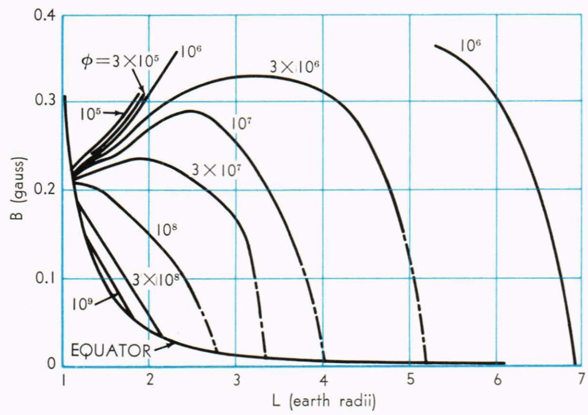

Fig. 3—Flux contours in B-L space for the artificial radiation belt, as drawn by Hess; ϕ refers to the omnidirectional flux in units of electrons/cm²-sec.

from all three satellites, Injun, TRAAC, and Telstar, contribute to the region $B > 0.15$ gauss and $L < 2.0$ earth radii. Outside this region the data are essentially all from Telstar. The same data can be replotted in an R-Λ (radial distance and invariant latitude*) coordinate system to get a more-easily-visualized picture of the situation in space, as shown in Fig. 4. This equivalent dipole representation of the earth's field is obtained from the transformation equations[6]

$$R = L \cos^2\Lambda, \quad \text{and} \quad B = \frac{M}{R^3}\left(4 - \frac{3R^{1/2}}{L}\right),$$

where M is the earth's dipole moment.

The maximum electron flux is about 3×10^9 particles/cm²-sec. Integrating to get the total number of electrons stored in the field, we find $\sim 2 \times 10^{26}$ electrons, about 60% of which lie within the 3×10^8 contour. According to this picture, the artificial belt blends into the natural radiation belt somewhere in the vicinity of the 10^7 contour; just where is uncertain, however.

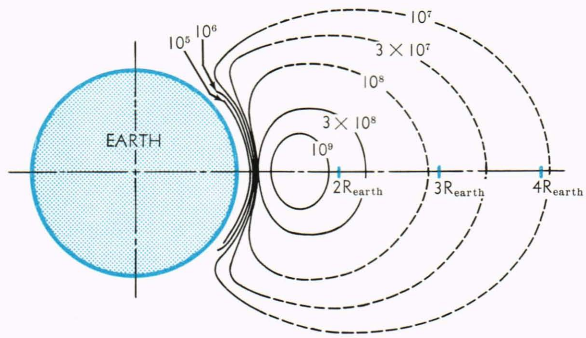

Fig. 4—Flux contours for the artificial radiation belt in R-Λ space obtained by transformation from Fig. 3.

The Injun-Telstar Controversy

At the time of this writing the flux contours shown in Figs. 3 and 4 cannot be considered firmly established. In particular, Injun data* indicate that the most intense region may terminate at a much lower altitude than shown in Fig. 4. Van Allen's 3×10^8 particles/cm²-sec contour crosses the equator at 1.18 and 1.23 earth radii and extends to invariant latitudes of $\sim 10°$ north and south. The total number of electrons stored in the field in this case would be $\sim 10^{24}$, rather than the 2×10^{26} found by Hess. Study of the matter is still proceeding actively at this time, with a possible resolution of the problem being that Telstar is seeing naturally-occurring electron fluxes at higher L's. The Telstar data that establish the 10^9 contour in Fig. 3 are two clusters of points near the ends of the line, with none in the middle. Possibly this contour is really two: an inner, artificial, high-intensity region also seen by Injun, and an outer, natural region. The same situation may pertain to the 3×10^8 contour. Detailed measurements of the electron energy spectrum in these two (?) regions may (or may not) be able to distinguish between their sources.

Time Behavior of the Artificial Radiation Belt

A major question concerning the artificial radiation belt is how long it will last in space. The

[6] C. E. McIlwain, "Coordinates for Mapping the Distribution of Magnetically Trapped Particles," *J. Geophys. Research*, **66**, 1961, 3681–3692.

* A mathematical latitude which, over North America, is within 2° of magnetic latitude.

* Private communication from J. A. Van Allen.

answer depends upon what point in space is under consideration. The values at low altitudes, e. g., $L < 1.20$ and $B > 0.22$, decayed by several orders of magnitude in a few days. Van Allen has observed a decay in intensity of a factor of 2 in 1000 hours at $L = 1.20$ on the magnetic equator. If his concept of the structure of the artificial radiation belt as described above is correct, it would decay in intensity by a factor of about 500 in a year and become unobservable. If the Telstar version is correct, the belt at somewhat higher altitudes near the magnetic equator may well last several years. A further interesting observation recently deduced from Telstar* has been that of a quite fast decay—an order of magnitude in a few days—of the flux in the L range 2 to 3.5. This decay includes the equatorial flux, its cause being unknown at this time. In view of this new information, the flux contours of Figs. 3 and 4, drawn earlier by Hess, may require substantial modification beyond $L = 2$.

The Second Artificial Radiation Belt

In addition to the major artificial radiation belt described above and shown in Figs. 3 and 4, a second, lower-altitude, much-less-intense belt was discovered by the writer using data from the TRAAC Geiger counter. This radiation zone was observed to exist over the region from longitude ~180°E to ~230° for several days following the July 9 event. The second belt had its maximum intensity on the magnetic shell $L = 1.16$ earth radii and corresponded, a few days after the detonation, to fluxes of maximum intensity $\gtrsim 10^4$ electrons/cm²-sec of energy > 1.6 Mev.

Although the second belt was observed to blend into the primary artificial belt over the geomagnetic equator, the two could be clearly distinguished on radius vectors from the magnetic center of the earth at invariant latitudes between 11° and 16°. Flux contours of the second radiation belt in B-L space are shown in Fig. 5. An R-Λ grid is superposed to aid in visualizing the radiation region. It will be noted that the region of B-L space shown in Fig. 5 is only a very small part of that shown in Fig. 3 and that the second belt was thus only a minor perturbation on the primary one. Nevertheless, a detailed study has shown that the circumstances of the origin and behavior of the second belt make it a matter of some interest.

The source of the second artificial belt is decay electrons from fission fragments that fell back onto the top of the atmosphere after the detonation.

* Private communication from W. L. Brown, Bell Telephone Laboratories.

On the basis of reasonable assumptions concerning the behavior of such fragments, it can be shown that they remain a fairly compact source of electrons from the geomagnetic point of view. Perhaps 10% of the electrons emitted from this source are successfully injected into the radiation belt where they oscillate between their northern and southern mirror points and drift eastward longitudinally. Because the belt is centered on the $L = 1.16$ shell, a considerable fraction of the electrons are lost by absorption over South America where this shell drops to an altitude of ~600 km at the magnetic equator and where typical electron mirror points (Λ ~12°) get down to an altitude of ~200 km.

The data indicate that newly-injected particles will last only a few revolutions around the earth at most and that about half the total flux in the second radiation belt in the region of TRAAC

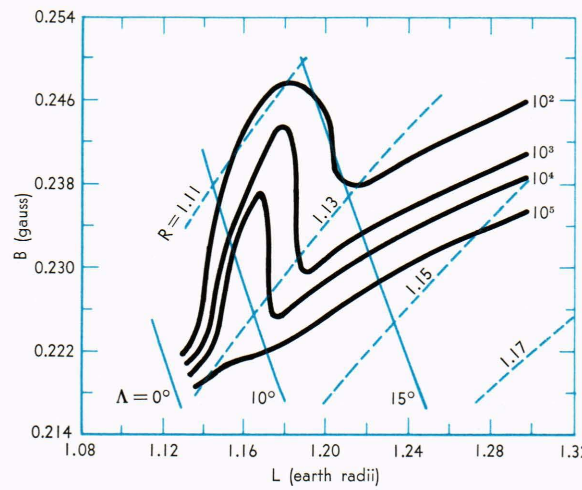

Fig. 5—Flux contours in B-L space determined by the TRAAC 302 Geiger counter from Days 192 to 199, longitude region ~180°E to ~230°E. Contours refer to omnidirectional flux of electrons of energy >1.6 Mev in particles/cm²-sec. Also shown is a grid in R-Λ space to aid in visualizing the second artificial radiation belt created by the July 9 nuclear burst.

observations at any time is due to new particles that have never circled the earth. In this circumstance, the belt's intensity as a function of time is governed primarily by the behavior of its source. Although TRAAC data concerning the time decay of the second radiation belt are fragmentary, they indicate that the belt decayed by a factor of ~5 in a five-day period beginning three days after the explosion. This result is about as expected from the known $t^{-1.2}$ behavior of a fission fragment electron source strength.