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Electrons in the Earth's Outer Radiation Zone

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Abstract. Preliminary results from Explorer 12 during August and September 1961 show that near the geomagnetic equatorial plane the omnidirectional intensity of 40–55 kev electrons is usually constant to a factor of 2 or 3 between radial distances of 25,000 and about 55,000 km; then it diminishes rapidly near the termination of the earth's magnetic field, which is generally at about 65,000 km. Typical midzone values for electrons between 40 and 55 kev are 10^6 to 10^7 electrons (cm^2 sec)$^{-1}$. The intensity of 80- to 100-kev electrons shows a similar radial dependence and a similar absolute value, but diminishes toward zero at a lesser radial distance. Hence the outer fringe of the outer zone at about 10 earth radii has a much steeper electron spectrum than the inner portion. The general structure of the outer zone as measured with a 302 Geiger tube by the staff members of this laboratory and other laboratories during the past four years is confirmed but is now shown to correspond to electrons of energy greater than 1.6 Mev in intensities of 10^3 to 10^5 (cm^2 sec)$^{-1}$ in the heart of the zone. Important spectral changes accompany geomagnetic storms.

Introduction. Early measurements of the radiation zones were carried out with detectors whose wall thicknesses were such as to exclude electrons of energy less than about 2 Mev and protons of energy less than 30 Mev. Such detectors revealed the existence of two distinct zones of high counting rates [*Van Allen and Frank*, 1959*a*]. In the inner zone the radiation was only mildly absorbed (30 per cent transmission) by an additional shield of 4 g/cm^2 of lead and 0.6 g/cm^2 of steel; but in the outer zone only 0.1 of 1 per cent of the radiation penetrated the additional shield [*Van Allen and Frank*, 1959*b*]. On the basis of the counting rate of the lightly shielded Geiger tube in Pioneer 4, of the preliminary knowledge of the spectrum of electrons in the outer zone [*Vernov et al.*, 1959], and of the above-quoted softness of the radiation there, it was regarded as likely that the counting rate of the detector was due primarily to the bremsstrahlung of nonpenetrating electrons. Employing this presumption and laboratory measurements of the efficiency of the detector for nonpenetrating electrons (see *Frank* [1962] for more thorough study of this matter), we concluded that the omnidirectional intensity of electrons of energy greater than 20 kev was of the order of 10^{11} (cm^2 sec)$^{-1}$. On the alternative interpretation that all of the counting rate was due to directly penetrating electrons, the upper limit of 10^8 (cm^2 sec)$^{-1}$ was placed on the omnidirectional intensity of electrons of energy greater than 2.5 Mev. The pertinent observations were obtained on March 3, 1959. Corresponding estimates based on the Pioneer 3 flight data of December 6, 1958, were less by a factor of 20.

We were eventually successful in flying a magnetic electron-spectrometer and several other detectors including a type 302 Geiger tube similar to the ones in Pioneers 3 and 4 through the outer zone on the NASA satellite Explorer 12. In a preliminary note, *O'Brien et al.* [1962] showed that in the heart of the outer zone the 302 Geiger tube rate was due primarily to penetrating electrons. From a study of data from the entire system of SUI detectors, they concluded that the omnidirectional intensity of electrons of energy greater than 40 kev was typically 10^8 (cm^2 sec)$^{-1}$ or less, and of energy between 1.6 and 5 Mev was of the order of 2×10^5 (cm^2 sec)$^{-1}$ or less.

The present paper is a more thorough-going analysis concentrating particularly on the spatial structure of the radiation zones. Since less than

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10 per cent of the transmitted data has been made available to us to date, the analysis is still a preliminary one.

SUI detectors on Explorer 12. Explorer 12 was launched at 0321 GMT on August 16, 1961, into an orbit with initial apogee altitude 77,300 km, perigee altitude 300 km, inclination 33°, and period 26 hours. At the time of launching the orbit of the satellite Explorer 12 was such that when it was at apogee the satellite was between the earth and the sun.

The characteristics of the SUI detectors on Explorer 12 are listed in Table 1. The shielded 302 GM was placed outside the main body of the satellite and was essentially an omnidirectional intensity detector, sensitive to electrons $E \geq 1.6$ Mev and protons $E \geq 20$ Mev, as well as to bremsstrahlung from electrons below the penetrability threshold of the shielding surrounding the detector. The characteristics of the 302 GM are given in Figure 1 of the paper by *O'Brien et al.* [1962].

The electron spectrometer consists of three Anton type 213 Geiger-Müller tubes inside a lead cylinder 3.5 g/cm² thick. Electrons between 40 and 55 kev are focused magnetically into one tube through its thin ($\sim$1.2 mg cm^{-2}) mica window to give the low-energy passband (SpL). A similar arrangement for electrons between 80 and 100 kev gives the high-energy passband (SpH). Both passbands have good resolution with steep sides, so that the energies at 50 per cent of peak transmission for each channel are within a few kev of the energies at 1 per cent of peak transmission. The third Geiger tube in the cylinder (SpB) is completely shielded and determines the background correction for the other two channels due to penetrating particles and bremsstrahlung. At apogee the satellite is outside the radiation zones, and, normally, the 302 GM counter responds only to galactic cosmic rays, the counting rate being 1.4 counts per second. At apogee, when the satellite is outside the geomagnetic cavity, the counters in the SpL, SpH, and SpB magnetic spectrometer channels also normally respond only to penetrating cosmic-ray particles. The counting rates of these three 213 GM counters at apogee are the same to within about 5 per cent and are equal to $\sim$0.4 c/s. This shows that the three counters have almost the same geometric factor for penetrating particles. Inside the radiation zones the actual SpB rates are subtracted from the raw SpL and SpH rates to allow for particles

TABLE 1. SUI Detectors on Explorer 12

		Omnidirectional Characteristics			Directional Characteristics		
Detector	Symbol	Shielding	Directly Detectable Particles	Geometric Factor, cm² ster	Shielding	Directly Detectable Particles	Geometric Factor, cm² ster
Anton type 302 Geiger-Müller tube	302 GM	265 mg cm^{-2} of Mg and 400 mg cm^{-2} of steel	Electrons $\geq$1.6 Mev Protons $\geq$ 20 Mev	0.6	...	...	...
Magnetic spectrometer channels	SpL	3.5 g cm^{-2} of Pb	Electrons $\geq$5 Mev		1.2 mg cm^{-2} of mica	Electrons $40 \geq E \geq 55$ kev	$(2 \pm 1) \times 10^{-5}$
	SpH		Protons $\geq$50 Mev	0.2	1.2 mg cm^{-2} of mica	Electrons $80 \geq E \geq 100$ kev	$(2 \pm 1) \times 10^{-5}$
	SpB		Electrons $\geq$4 Mev		...	...	...
Cadmium sulphide modules	CdSTE	2.6 g cm^{-2} of Pb over $\sim$12 ster	Protons $\geq$40 Mev	...	None	Electrons $\geq$100 ev Protons $\geq$1 kev	3×10^{-4}
	CdSB			...	None	Electrons $\geq$475 kev Protons $\geq$1 kev	3×10^{-4}
	CdSOM	0.5 g cm² over $\sim$0.6 ster	Electrons $\geq$1 Mev Protons $\geq$20 Mev	...	...	...	...

and bremsstrahlung penetrating the shielding around the counters.

The other SUI modules contain crystals of cadmium sulphide whose conductivity varies with the energy loss within them [*Freeman*, 1961]. Their characteristics are also listed in Table 1. The first is the total energy detector CdSTE, which is open over 10^{-2} ster, shielded by $\sim$0.5 g cm^{-2} of magnesium over about 0.6 ster, and by $\sim$2.6 g cm^{-2} of lead over the remaining solid angle. The second module CdSB has similar shielding but is fitted with a magnet to serve as a broom that sweeps out electrons of $E \geq 500$ kev before they hit the crystal. The third module is the 'optical monitor' CdSOM, which is similar to CdSTE except that over the aperture of 10^{-2} ster a plate of quartz 0.2 mm thick provides a minimum shielding of some 0.5 g cm^{-2}. The CdS detectors are also directional detectors pointing in a direction normal to the spin axis of the satellite.

Also relevant to the present work are the magnetometers built by Dr. Cahill of the University of New Hampshire. These magnetometers measure the strength and direction of the magnetic field in the vicinity of the satellite.

The inward pass of August 16–17, 1961. The inward pass of August 16–17, 1961, is chosen to illustrate the typical features of the outer radiation zone on a quiet day after a period of no pronounced geomagnetic activity. For this pass, the orbit of the satellite did not deviate by more than 7° from the quiet-day geomagnetic equatorial plane between apogee (83,500 km) and a radial distance of 24,000 km from the center of the earth. It is not necessary,

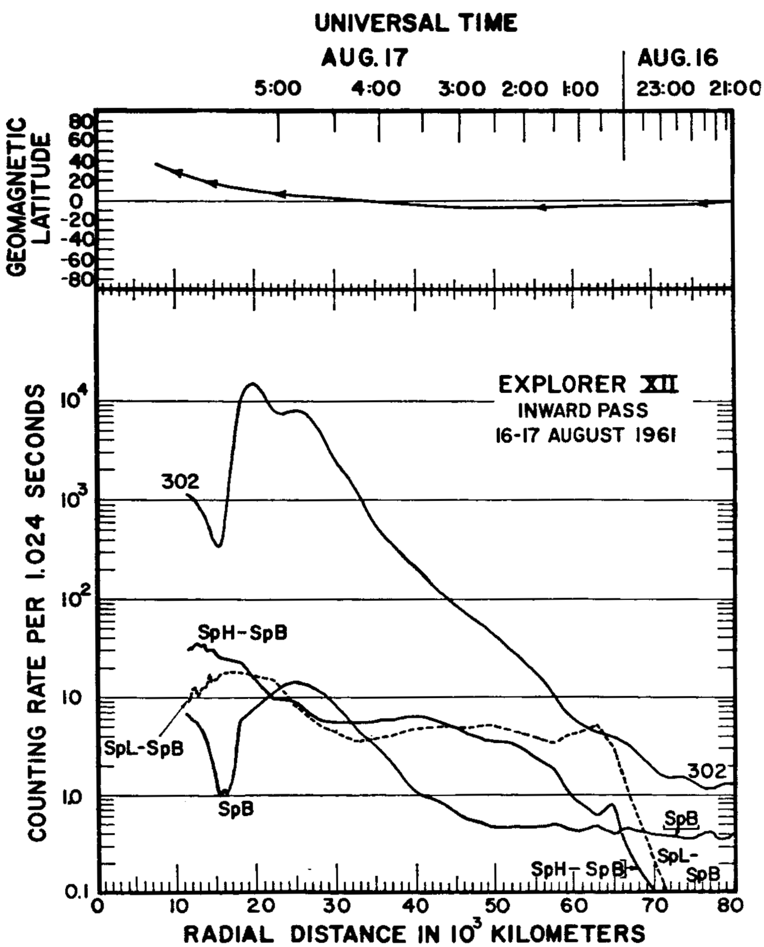

Fig. 1. Counting rates of the detectors as Explorer 12 approached the earth on August 16–17.

therefore, to discuss the variation of electron intensity with latitude, and it is not necessary to introduce the geomagnetic coordinates B and L in this region [*McIlwain*, 1961].

The data for the inward pass of August 16–17 are shown in Figure 1 where the SpL-SpB, SpH-SpB, 302 GM, and SpB counting rates are shown. At radial distances greater than 15,000 km the plotted counting rates SpL-SpB, SpH-SpB are mean values for counting times ~150 seconds; the values at smaller radial distances are mean values for 10.24-seconds counting times. The 302 GM rate for radial distances exceeding 37,000 km is the mean value for counting times ~150 seconds; for smaller radial distances it is the mean value for counting times of 10.24 seconds.

As the satellite comes in from apogee the SpL-SpB counting rate, caused by electrons in the energy range 40 to 55 kev, begins to rise very rapidly at a radial distance of ~70,000 km and reaches a fairly constant counting rate at radial distances less than 65,000 km. As the satellite comes in from apogee, the SpH-SpB counting rate rises at a slower rate than the SpL-SpB counting rate. The SpH-SpB counting rate eventually reaches a fairly constant value. The initial rise of the 302 GM coincides with the increase of the SpL-SpB counting rate. This initial increase in the 302 GM rate can be accounted for by bremsstrahlung from electrons of energies in the range 40 to 100 kev. For example, by means of Figure 1 of *O'Brien et al.* [1962], it can be seen that an omnidirectional intensity of 2×10^6 electrons $(cm^2 \ sec)^{-1}$ at 100 kev would give rise to ~2 c/s in the 302 GM. These values are comparable with the observed electron intensity in the energy range 40–100 kev and with the increase in the 302 GM counting rate between 70,000 and 60,000 km. As the satellite approaches the earth, the 302 GM rate continues to increase, but the SpL-SpB and SpH-SpB rates remain fairly constant. It will be shown later that the CdS detector rates prove that, for radial distances of 20,000 to 30,000 km, the 302 GM counting rate is not due mainly to the bremsstrahlung of an intense flux of electrons below the threshold of the 302 GM detector, but that the 302 GM is counting primarily penetrating electrons of energy greater than

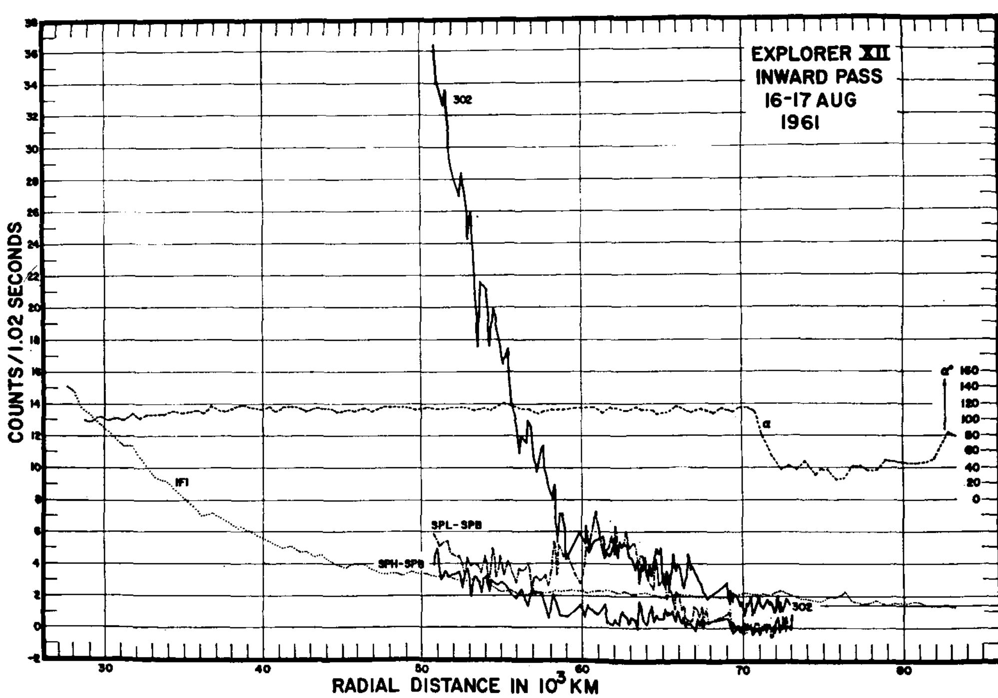

Fig. 2. Detailed plot of the counting rates near the outer boundary of the outer zone on August 17, 1961. Cahill's magnetometer results are also shown. It can be seen that electrons ~50 kev are trapped out to almost the full extent of the earth's magnetic field.

1.6 Mev. The 302 GM is also sensitive to protons of energy greater than 20 Mev. It was shown by *Davis and Williamson* [1962] that there is a proton flux that is typically of the order of 10^6 protons (cm^2 sec ster)$^{-1}$ of energy >250 kev in the outer radiation zone. Davis and Williamson found that the intensity of protons decreases exponentially with increasing proton energy. If their spectrum could be extrapolated to 20 Mev, the intensity of protons of energy greater than 20 Mev would be many orders of magnitude too low to account for the observed maximum 302 GM counting rate. The 302 rate increases by a factor 100 between 40,000 km and 25,000 km. Apart from bremsstrahlung, the SpB rate is due to electrons >5 Mev and protons >40 Mev. The SpB rate begins to rise at a smaller radial distance and at a slower rate than the less heavily shielded 302 counter. The 302 GM and SpB results suggest that the radial extent of trapping decreases with increasing electron energy. There is a hardening of the electron spectrum in the outer radiation zone, with decreasing radial distance from the center of the earth.

At one time it was suggested that the maximum 302 counting rate in the outer radiation zone was due to bremsstrahlung from a large flux of electrons >20 kev. To obtain the maximum 302 rate on August 17, 1961, in this way would require an omnidirectional intensity of the order of 10^{13} electrons/cm^2 sec each of energy 30 kev. Such a flux of electrons would be equivalent to an energy flux of $\sim 5 \times 10^5$ erg/cm^2 sec which would give $\sim 10^4$ counts per second in the CdSTE detector. This is several orders of magnitude greater than the maximum observed counting rate of 6 c/s. Thus the CdS results rule out bremsstrahlung from a large flux of electrons of energy less than 50 kev as the principal contribution to the 302 GM counting rate in the heart of the outer radiation zone.

The possibility remains that the observed 302 GM counting rate may be due to bremsstrahlung from electrons ~ 500 kev. To obtain the observed 302 GM counting rate of 2×10^4 counts per second at $R \sim 20{,}000$ km would require a flux of $\sim 2 \times 10^9$ particles/cm^2 sec of energy 500 kev. Such a flux of particles would give ~ 50 c/s in the CdSTE detector. This is an order of magnitude higher than the observed CdSTE counting rate. Sometimes, for example on September 29, 1961, the maximum 302 GM counting rate is as high as 2×10^5 c/s in the heart of the outer zone. If such a flux were due to the bremsstrahlung from electrons ~ 500 kev, the CdSTE should count at the rate of 500 c/s, whereas the maximum observed counting rate is always less than about 10 c/s. Thus it is safe to conclude that in the heart of the outer radiation zone, whenever the 302 GM counting rate exceeds 10^4 particles (cm^2 sec)$^{-1}$, most of the 302 GM counting rate is due to penetrating electrons. This finding of *O'Brien et al.* [1962] is sufficient of itself to resolve the early controversy about the number of electrons in the outer zone.

To obtain the directional intensities of electrons expressed as the number of electrons (cm^2 sec ster)$^{-1}$, the observed SpL-SpB and SpH-SpB counting rates must be divided by the product ϵG of the geometric factors of the spectrometers and the detection efficiencies of the 213 GM counters. It can be seen from Table 1 that ϵG is $\sim 2 \times 10^{-5}$ for both SpL and SpH.

Explorer 12 is spinning at 30 rpm, and the telemetered information is the number of counts a given detector has accumulated in 10.24 sec. The axes of the directional detectors SpL and SpH are parallel to each other and are at right angles to the spin axis. Thus the SpL-SpB and SpH-SpB counting rates observed in each 10.24-sec period represent averages over all directions normal to the spin axis of the satellite. The magnetic spectrometers SpH and SpL do not sample all directions in space. If α is the angle between the spin axis of the satellite and the magnetic field F, then θ, the angle between the detector direction and F, is given by

$$\cos\theta = \sin\alpha \cos\phi$$

where ϕ is the azimuthal angle between the detector direction and the plane containing F and the spin axis of the satellite. For a given value of α, the limits of θ are given by

$$\cos\theta = \pm\sin\alpha$$

According to the results of Cahill for the inward pass of August 16–17, shown in Figure 2, the angle α was just under 120°. Thus, the values of θ, the angle between the directional detectors and the magnetic field, varied between the limits given by

$$\cos\theta = \pm\sin 120^\circ = \pm\sqrt{3/2}$$

TABLE 2. Values of the Conversion Factor M

	Angular Distribution of Trapped Electrons				
α	$\sin^4 \theta$	$\sin^2 \theta$	Isotropic	$\cos^2 \theta$	$\cos^4 \theta$
0	6.7	8.4	4π	∞	∞
30	8.6	9.6	4π	33.6	107
45	11.2	11.1	4π	16.8	26.4
60	14.6	13.4	4π	11.1	13
90	17.6	16.8	4π	8.4	6.7

that is, θ varied between about 30° and about 150°. As the angular distributions of the trapped electrons are not known, the omnidirectional intensities cannot be calculated from the observed counting rates. For an isotropic angular distribution, the directional intensity expressed as the number of electrons $(\text{cm}^2 \text{ sec ster})^{-1}$ must be multiplied by a factor M equal to 4π (= 12.6) to obtain the omnidirectional intensity. The multiplication factor M for various values of α is given in Table 2 for various postulated angular distributions for the trapped electrons. For example, it can be seen that for a $\sin^4 \theta$ angular distribution the factor M may vary from 6.7 to 17.6, depending on α. Thus we must expect variations in spectrometer counting rates of up to a factor 3 or so owing to the different directions the spin axis of the satellite may have relative to the earth's magnetic field on various passes. For the inward pass of August 17, 1961, $\alpha = 120°$, so that the factor M varies from 11.1 to 14.6 for the angular distributions quoted in Table 2. For purposes of discussion, the directional intensities calculated from the counting rates, the directional geometric factors, and counter efficiencies are multiplied by 4π to obtain a rough estimate of the omnidirectional electron fluxes. (In practice the SpL-SpB and SpH-SpB counting rates were multiplied by 6.3×10^5 to obtain the quoted omnidirectional intensities.)

The 302 GM and SpB counting rates must be multiplied by 1.6 and 5.0, respectively, to obtain the omnidirectional intensities of electrons >1.6 Mev and electrons >5 Mev, respectively. These will represent upper limits to the number of penetrating electrons, since some of the counts in both detectors may be due to bremsstrahlung and penetrating protons.

The intensities of electrons calculated in this way at various radial distances are given in Table 3. The apogee counting rates are subtracted from the 302 and SpB rates. It can be seen that, for all radial distances inside the outer radiation zone, the intensity of electrons in the energy range 40–110 kev is far greater than the number of electrons capable of penetrating the shielding of the 302 GM counter. The large variation in 302 GM rate with radial distance is due predominately to the variation of the intensity of electrons >1.6 Mev. The 302 GM rate is not a

TABLE 3. Intensities of Electrons in the Outer Radiation Zone on August 17, 1961

Detector	c/s	Total Omnidirectional Intensity, $(\text{cm}^2 \text{ sec})^{-1}$	Omnidirectional Intensity per kev Interval, $(\text{cm}^2 \text{ sec})^{-1}$
65,000 km; $\lambda_m = -5°$; 00.15 UT			
SpL-SpB	2.9	1.8×10^6	1.2×10^5
SpH-SpB	0.8	5×10^5	2.5×10^4
302	2.4	5.4	···
SpB	0	0	···
302-SpB	···	5.4	$<1.5 \times 10^{-3}$
55,000 km; $\lambda_m = -7°$; 01.50 UT			
SpL-SpB	3.9	2.5×10^6	1.7×10^5
SpH-SpB	2.5	1.6×10^6	8×10^4
302	16	26	···
SpB	0.06	0.3	···
302-SpB	···	26	7.6×10^{-3}
45,000 km; $\lambda_m = -6°$; 03.05 UT			
SpL-SpB	5.0	3.1×10^6	2.1×10^5
SpH-SpB	4.7	2.9×10^6	1.5×10^5
302	86	1.3×10^2	···
SpB	0.28	1.4	···
302-SpB	···	1.3×10^2	3.8×10^{-2}
35,000 km; $\lambda_m = 0°$; 04.05 UT			
SpL-SpB	3.9	2.5×10^6	1.7×10^5
SpH-SpB	5.7	3.6×10^6	1.8×10^5
302	550	8.8×10^2	···
SpB	2.7	13.5	···
302-SpB	···	8.8×10^2	2.5×10^{-1}
25,000 km; $\lambda_m = +6°$; 04.50 UT			
SpL-SpB	8.4	5.3×10^6	3.5×10^5
SpH-SpB	8.8	5.6×10^6	2.8×10^5
302	8.1×10^3	1.3×10^4	···
SpB	13.6	68	···
302-SpB	···	1.3×10^4	3.8
15,000 km; $\lambda_m = +18°$; 05.30 UT			
SpL-SpB	15.5	1.0×10^7	6.7×10^5
SpH-SpB	29	1.8×10^7	9.0×10^5
302	360	5.8×10^2	···
SpB	1.0	5	···
302-SpB	···	5.8×10^2	1.7×10^{-1}

measure of the total intensity of particles in the outer radiation zone. The electron spectrometers give a better picture of this. The results show that on the inward pass of August 16–17, 1961, the omnidirectional intensity of electrons in the energy range 40–110 kev is of the order 10^7 electrons $(cm^2\ sec)^{-1}$ in the geomagnetic equatorial plane, and remains fairly constant (within an order of magnitude) throughout the outer radiation zone. The form of the electron spectrum can be obtained by converting the total omnidirectional intensities to the average omnidirectional intensities $(cm^2\ sec)^{-1}$ per kev energy interval. This can be done by dividing the total SpL-SpB and SpH-SpB omnidirectional intensities by the passbands of the electron spectrometers, which are 15 and 20 kev for SpL and SpH, respectively. The difference between the 302 GM and SpB total omnidirectional intensities is an upper limit to the omnidirectional electron intensity in the energy range 1.6 to 5 Mev. The 302 GM SpB omnidirectional intensity was divided by 3.4×10^3 to obtain the average omnidirectional intensity per kev interval in the energy range 1.5 to 5 Mev. The results for the inward pass August 16–17 are shown in Table 4. It can be seen that for most radial distances the omnidirectional intensity of electrons per kev interval is higher at 50 kev than it is at 100 kev. According to *Lenchek et al.* [1961], if the electrons in the outer radiation zone were due to electrons from the β decay of albedo neutrons, the electron intensity at 90 kev should be at least double the intensity at 50 kev. The electron intensity decreases very rapidly with increasing energy in the energy range 1.5 to 5 Mev. It has become fashionable to discuss energy spectrums in the radiation zones in terms of a power law of the form

$$dn/dE \sim E^{-\gamma} \qquad (1)$$

even though the exponent γ varies with energy. It will be assumed that the values for the omnidirectional intensity $(cm^2\ sec)^{-1}$ per kev interval in Table 3 are the values at the mean energy of the passband of the detectors, that is, 47.5 kev for SpL-SpB and 90 kev for SpH-SpB. Mean values for γ were calculated for the energy range 47.5 to 90 kev by substituting the values given in Table 3 into equation 1. The results are shown in Table 4. A decrease in γ represents a hardening of the spectrum.

The 302 GM counting rate gives an upper limit to the intensity of electrons of energy >1.6 Mev, and the SpB counting rate gives an upper limit to the intensity of electrons >5 Mev. The 302 and SpB results, given in Table 3, can be used to calculate the average integral energy spectrum, which can then be differentiated to obtain the differential energy spectrum of electrons in the energy range 1.6 to 5 Mev, if it is assumed that all the counts in both detectors are due only to penetrating electrons. Values of the exponent γ of the differential energy spectrum, calculated in this way, are given in Table 4. The results show that, for $R < 55{,}000$ km, γ is ~ 1 in the energy range 50–100 kev, showing that the energy spectrum is fairly flat in this region, whereas it is very steep in the energy range 1.6 to 5 Mev ($\gamma > 5$). Because of the thicker shielding around it, a higher proportion of the SpB counting rate is probably due to bremsstrahlung than of the 302 GM counting rate, so that the values of γ in the energy range 1.6 to 5 Mev are lower limits.

Since the preliminary publication by *O'Brien et al.* [1962], more precise measurements of the geometrical factors of SpL and SpH have been made. These new results show that previously the geometrical factor had been underestimated by a factor 2. Also, if we subtract the total SpB rates from the raw SpL and SpH rates, rather than 0.4 and 0.6 SpB, respectively, as O'Brien et al. did, then this reduces the estimated flux of electrons on September 5 that they gave. If the criteria adopted in the present paper are used, the values reported by O'Brien et al. at 47.5 kev and 90 kev in their Figure 3 must be reduced by factors of 17 and 5, respectively. The electron energy spectrum for the heart of the outer zone on September 5, 1961, is then also fairly flat

TABLE 4

Radial Distance, km	Mean Value of γ	
	40 kev to 100 kev	1.6 Mev to 5 Mev
65,000	2.4	∞
55,000	1.2	$\gg 5$
45,000	0.53	5.0
35,000	−0.09	4.7
25,000	0.35	5.7
15,000	−0.46	5.2

in the region 40 to 100 kev. The present results are consistent with their conclusion that the intensity of electrons greater than 40 kev is of the order of 10^8 (cm^2 sec)$^{-1}$ or less.

The inward pass of August 17 was chosen as typical of a pass following a period of no pronounced geomagnetic activity. The results for this pass show that electrons of energy ~50 kev are trapped out to almost the full extent of the earth's magnetic field. This is true for the other passes studied. This point will be discussed in more detail in the next section. Once trapping starts the SpL rate rises fairly rapidly and reaches a fairly constant value throughout the outer radiation zone. The SpH, 302, and SpB rates rise more slowly and begin to make significant contributions at smaller radial distances. This slower rise of the counting rate of these detectors with decreasing radial distance compared with SpL was observed in all the passes studied. *Fan et al.* [1961] observed a bifurcation of the outer zone. The SpL and SpH results on August 17, 1961, show that there is no bifurcation of the outer zone for electrons of energy 40 to 100 kev. The inner and outer radiation zones are generally defined in terms of the counting rate of the shielded 302 GM counter. The decrease of the 302 GM rate at $R < 20{,}000$ km ($L < 3.1$) in Figure 1 represents the inner boundary of the outer radiation zone. In this region the satellite entered the 'slot' region between the inner and outer radiation zones. It can be seen from Figure 1 that the counting rates of the electron spectrometers SpL-SpB and SpH-SpB did not decrease significantly in the 'slot' region. In fact, on this pass both the SpL-SpB and SpH-SpB rates increased in the region $R < 16{,}000$ km ($L < 2.9$), where the 302 GM counting rate was down by at least a factor of 10 compared with the maximum counting rate at $R \sim 20{,}000$ km. The increase in the 302 rate at $R < 15{,}000$ km is probably due to the satellite's passing through the outer edge of the inner zone.

Outer boundary of the outer radiation zone. It is now believed that on the side of the earth nearer the sun the earth's magnetic field generally terminates at a radial distance of ~70,000 km, owing to the pressure of the solar wind on the earth's magnetic field. The earth's magnetic field is pictured as a 'cavity' inside the interplanetary plasma. Cahill has measured the magnitude and direction of the magnetic field in the vicinity of Explorer 12. His results for the inward pass of August 16–17 are shown in Figure 2. The magnitude of the magnetic field is denoted by $|F|$, and α is the angle between the spin axis of the satellite and the direction of the magnetic field in the vicinity of the satellite. It can be seen that, for $R > 72{,}000$ km, α is about 40°. By the time the satellite reaches 70,000 km, α has changed to ~115°, and α then remains fairly constant. For radial distances less than 70,000 km the magnetic field is in a direction appropriate to the earth's magnetic field. The satellite does not deviate by more than 7° from the calculated geomagnetic equatorial plane from 70,000 to 24,000 km. Since the earth's magnetic field is normal to the geomagnetic equatorial plane, the angle α would be expected to remain fairly constant for this pass. There is no large change in $|F|$ at the interface for this particular pass. The SpL-SpB, SpH-SpB, and 302 GM rates are also shown in Figure 2. A linear scale is used for the ordinate in this instance. Each plotted point is the mean for 10.24-sec counting time, so that the statistical fluctuations are large. It can be seen from Figure 2 that the SpL-SpB and 302 GM counting rates begin to increase significantly at a radial distance ~69,000 km, that is, within ~1500 km of the interface between the geomagnetic field and the interplanetary field, showing that electrons ~50 kev are trapped out to almost the full radial extent of the earth's magnetic field.

Variations in the radial extent of trapping have been observed. For purposes of discussion, the outer boundary of the outer zone is defined as the radial distance at which the mean SpL counting rate is twice the mean background SpB counting rate. Typical results are shown in Table 5. The largest radial extent is 78,000 km for the inward pass of October 2, 1961, which was after the magnetic storm beginning at 2108 on September 30, 1960. This storm will be discussed in detail in a subsequent paper. For this pass *Cahill* [1962] did not observe a termination of the earth's magnetic field, so that it must have extended beyond 83,000 km.

The smallest observed radial extent of trapping was for the period September 11–13, 1961. The results for the inward pass of September 13 are shown in Figure 3.

Cahill observed a discontinuity in $|F|$ of $>50\ \gamma$ at ~52,000 km. The results of Freeman

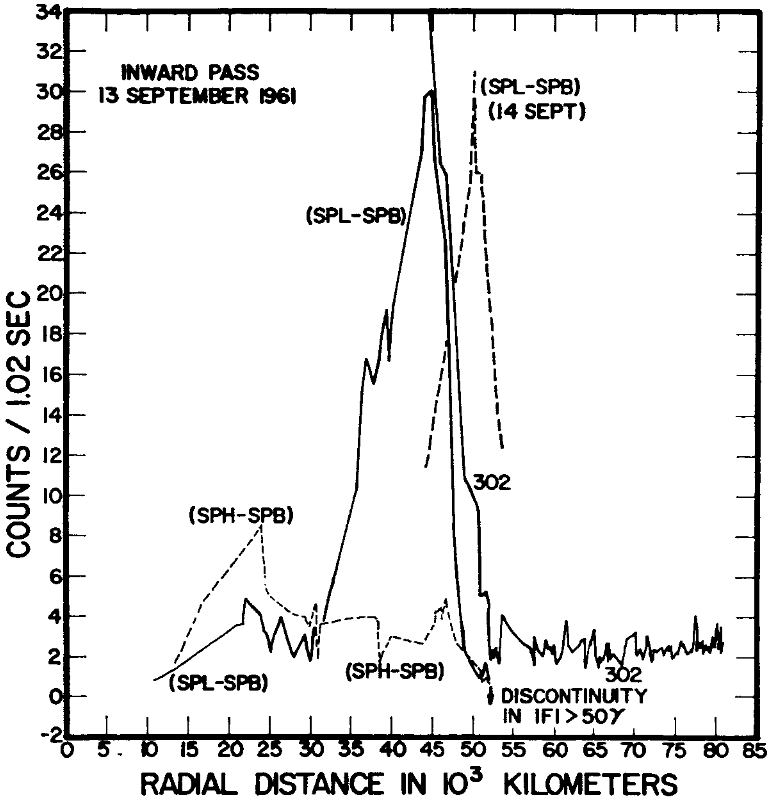

Fig. 3. Detailed plot of the counting rates near the outer boundary of the outer zone on September 13, 1961. Cahill observed a discontinuity in the magnitude of the magnetic field at 52,000 km. Trapping of electrons ~50 kev starts almost immediately after the satellite passes the magnetic field discontinuity.

(private communication) show that there was plasma of intensity ~20 ergs $(cm^2 \text{ sec ster})^{-1}$ outside the geomagnetic cavity between 52,000 and ~70,000 km. After the discontinuity in $|F|$ the geomagnetic field takes over, and it can be seen from Figure 3 that the trapping of electrons ~50 kev starts almost immediately. There is a large maximum in the SpL-SpB counting rate. For the inward pass of September 14, *Cahill* [1962] observed that the outer boundary of the geomagnetic field had moved out by ~5,000 km. The SpL-SpB counting rate for September 14 is also shown in Figure 3. The large peak in the SpL rate is still present, but it has moved out radially by about 5,000 km with the earth's field.

The results presented in this section illustrate how electrons ~50 kev are generally trapped out to almost the full radial extent of the earth's magnetic field. Once trapping starts, the SpL counting rate initially increases rapidly with decreasing radial distance. The higher-energy electron detectors always increase at a slower rate than SpL, showing that electrons of higher energy are only trapped (or accelerated or

TABLE 5. Outer Boundary of Outer Zone for 50-kev Electrons

	Position of Outer Boundary	
Date, 1961	R	λ_m
Aug. 17	69,000	−4°
Aug. 24	53,000	+9°
Aug. 29	64,500	−10°
Aug. 30	68,000	−11°
Sept. 3	64,500	−2.5°
Sept. 4	62,000	+6°
Sept. 12	61,500	+11°
Sept. 13	52,000	+8°
Oct. 2	>78,000	−5°

injected) efficiently at smaller radial distances than 50-kev electrons.

Time fluctuations. The inward pass of August 16–17 is typical of a quiet day after a period of no pronounced geomagnetic activity. Large variations in 302 counting rates have been observed after magnetic storms. It will be illustrated in a subsequent paper that the 302 rate may decrease by a factor of up to 1000 at a given L value following a magnetic storm. However, the maximum 302 GM counting rate always returns to the order of 10^5 c/s. Fluctuations of up to a factor of 50 have been observed in the intensity of electrons $\sim$50 kev. For example, between August 29 and 30, 1961, the electron intensity increased by a factor of 50 at $R = 60{,}000$ km, a factor of 35 at 40,000 km, and a factor of 45 at 30,000 km.

Note added in proof. Throughout this paper we have discussed the high energy portion of the electron spectrum in the outer zone as though the transmission of the shielding of the 302 and SpB detectors changed discontinuously from zero to unity at 'end point' energies of 1.6 Mev and 5 Mev respectively. A proper treatment of this matter will probably raise the quoted intensities of electrons of $E > 1.5$ Mev by at least an order of magnitude. Alternatively the quoted intensities might be regarded as those of electrons having E greater than an effective energy of perhaps 2.5 Mev. The poorly known spectral form in this energy region precludes a satisfactory discussion.

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