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Absolute Electron Intensities in the Heart of the Earth's Outer Radiation Zone

B. J. O'Brien, J. A. Van Allen, C. D. Laughlin, and L. A. Frank

Department of Physics and Astronomy
State University of Iowa, Iowa City, Iowa

Previous estimates of the intensities of electrons in the heart of the earth's outer radiation zone have been derived largely from the observed response of detectors whose minimum wall thicknesses were of the order of 1 gram per square centimeter of intermediate Z material. On the assumptions that the response of such a detector was due dominantly to the bremsstrahlung of nonpenetrating electrons (i.e., those of energy less than ~2 Mev) and that the effective energy of the electrons was of the order of 50 kev, *Van Allen and Frank* [1959] estimated the omnidirectional intensity J_0 of electrons of energy greater than 20 kev as $10^{11}(\text{cm}^2 \text{ sec})^{-1}$ on March 3, 1959, a day that followed a period of intense auroral activity.

Later estimates employing similar assumptions were in rough agreement [*Arnoldy, Hoffman, and Winckler,* 1960; *Fan, Meyer, and Simpson,* 1961; *Vernov, Chudakov, Vakulov, Logachev, and Nikolayev,* 1960]. However, Vernov and his co-workers found evidence in the data from the second Soviet cosmic rocket (Lunik II) for an intensity of $\sim 5 \times 10^5$ $(\text{cm}^2 \text{ sec})^{-1}$ of electrons in the energy range around $1 \sim 2$ Mev, a result that was not inconsistent with certain upper limits provided by the data from Pioneer III and Pioneer IV, viz: $J_0 < 1 \times 10^8(\text{cm}^2 \text{ sec})^{-1}$ for $E > 200$ kev and $J_0 < 1 \times 10^6(\text{cm}^2 \text{ sec})^{-1}$ for $E > 2.5$ Mev, the latter number corresponding to the assumption that the response of the detector was due dominantly to penetrating electrons [*Van Allen and Frank,* 1959; see also *Rosen and Farley,* 1961]. A critical review of the evidence on the intensity of electrons in the outer zone has been given by *Dessler* [1960].

The present note gives an analysis of preliminary data from the array of SUI detectors on Explorer XII (1961ϵ). It is found that the omnidirectional intensity of electrons of energy greater than 40 kev is typically of order $10^8(\text{cm}^2 \text{ sec})^{-1}$ and of energy between 1.6 and 5 Mev, 2×10^5 $(\text{cm}^2 \text{ sec})^{-1}$. Hence, the response of lightly shielded ($\sim$ 1 g/cm^2) detectors is largely due to direct penetration of the primary electrons, and our 1959 assumptions for the tentative interpretation of Pioneer III and IV observations in the outer zone are seen to be invalid.

Explorer XII was launched at 0321 UT on August 16, 1961, into an orbit with apogee altitude 77,300 km, perigee altitude 300 km, inclination 33° and period 26 hours. The payload was built by the Goddard Space Flight Center of the National Aeronautics and Space Administration and carries five detector modules designed, built, and calibrated at SUI, with characteristics as listed in Table 1.

The 302 GM is similar to those flown by the Iowa group in Explorer IV, Pioneers III and IV, and Explorer VII, and by the Minnesota group in Pioneer V and Explorer VI. It has characteristics, shown in Figure 1, applicable to within a factor of 2 to 3 to those flown previously by the Iowa group. Note in particular from Figure 1 how essential it is to know the relative proportions of penetrating and nonpenetrating electrons (Frank, 1961, unpublished).

The electron spectrometer consists of three Anton-type 213 Geiger-Mueller tubes inside a lead cylinder 3.5 g cm^{-2} thick. Electrons between about 45 and 60 kev are magnetically focused into one tube through its thin ($\sim$ 1.2 mg cm^{-2}) mica window to give the low-energy passband (Sp L). A similar arrangement for electrons between about 80 and 110 kev gives the high-energy passband (Sp H). 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

TABLE 1. SUI Detector Characteristics on Explorer XII

Detector	Symbol	Omnidirectional Characteristics			Directional Characteristics		
		Shielding	Directly Detectable Particles	Geometric Factor, cm^2	Shielding	Directly Detectable Particles	Geometric Factor, cm^2 sterad
Anton type 302 Geiger-Mueller 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	$\sim$0.75	...	...	...
Magnetic Spectrometer Channels	Sp L	3.5 g cm^{-2} of Pb	Electrons $\geq$5 Mev	(0.14 $\pm$ 0.06)	1.2 mg cm^{-2} of mica	Electrons 45 $\leq$ E $\leq$60 kev	10^{-5}
	Sp H		Protons $\geq$50 Mev		1.2 mg cm^{-2} of mica	Electrons 90 $\leq$ E $\leq$110 kev	10^{-5}
	Sp B				...	...	...
Cadmium Sulphide Modules	CdS TE	2.6 g cm^{-2} of Pb over $\sim$12 sterad and	Electrons $\geq$4 Mev Protons $\geq$40 Mev and	...	None	Electrons $\geq$100 ev Protons $\geq$1 kev	
	CdS B				None	Electrons $\geq$500 kev Protons $\geq$ 1 kev	3 $\times$ 10^{-4}
	CdS Opt.	$\sim$0.5 g cm^{-2} of Mg over $\sim$0.6 sterad	Electrons $\geq$1 Mev Protons $\geq$20 Mev		...	...	

kev of the energies at 1 per cent of peak transmission. The third 213 GM in the cylinder (Sp B) is completely shielded and determines the background correction for the other two channels due to penetrating particles and bremsstrahlung (Laughlin, 1960, unpublished).

The other SUI modules contain crystals of cadmium sulphide, whose conductivity varies with the energy loss within them (Freeman, 1961, unpublished). Their characteristics are also listed in Table 1. The first is the total-energy detector CdS TE, which is open over 10^{-3} sterad, shielded by $\sim$0.5 g cm^{-2} of magnesium over about 0.6 sterad, and by $\sim$2.6 g cm^{-2} of lead over the remaining solid angle. The second module CdS B has similar shielding, but is fitted with a magnet to serve as a broom which sweeps out electrons of $\sim$500 kev before they hit its crystal. The third module is the 'optical monitor' CdS Opt which is similar to CdS TE except that over the aperture of 10^{-3} sterad a plate of quartz 0.2 mm thick provides a minimum shielding of some 0.5 g cm^{-2} (Freeman, private communication).

The Explorer XII data studied thus far have come from reception and real-time decoding by one of the NASA receiving stations. The data discussed herein are for passes in which the satellite is approaching the earth from apogee, and specifically for the period during which the 302 GM rate exhibits its highest value in the region of space usually referred to as the outer zone.

We show in Table 2 the counting rates of 302 GM and the spectrometer channels at these maxima. We then show in Figure 2 the variation in counting rates of the detectors during the pass when 302 GM reached the highest counting rate observed in the data reduced to date.

The differences in the various peak counting rates shown in Table 2 arise in part because the orbital cuts through the outer zone occur at different geomagnetic latitudes as well as at

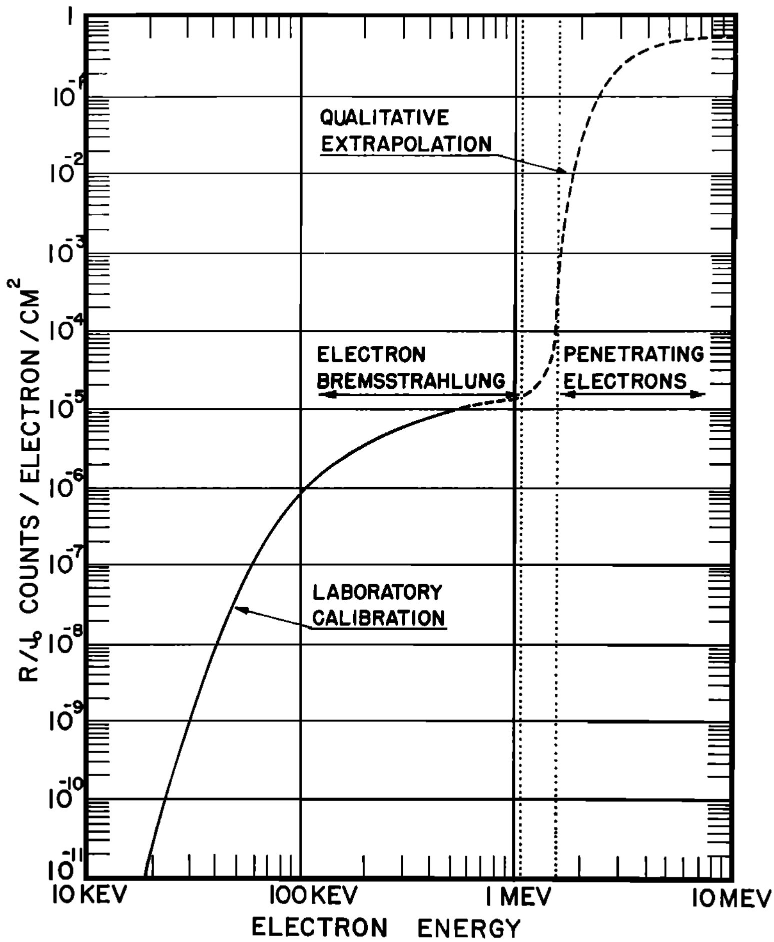

Fig. 1. Efficiency of the Explorer XII 302 GM as a function of electron energy. R is the counting rate for an omnidirectional intensity J_0 of monoenergetic electrons $(cm^2\ sec)^{-1}$. For electron energy less than 120 kev the curve is from detailed laboratory calibrations with an electron gun, and for energy between 120 kev and 500 kev it is a theoretical extrapolation. Above 500 kev the curve is essentially qualitative.

different times. They should not be interpreted as purely temporal variations.

We have converted Sp L and Sp H rates in Table 2 to electron intensities in the following manner. First assume that the counting rates of Sp L, Sp H, and Sp B due to sea-level cosmic rays give us their relative geometric factors 0.4, 0.6, and 1, respectively. Then subtract from the raw Sp L and Sp H rates in Table 2 the values of 0.4 Sp B rate, and 0.6 Sp B rate, respectively, so as to correct in-flight rates for the contribution by penetrating particles and/or bremsstrahlung. We consider this correction relatively crude, and will refine it using apogee cosmic ray counting rates to give the relative geometric factors. Note however, that even if we assume Sp L and Sp H rates to be completely uncontaminated by background, the intensity estimates would be less than twice their corrected values.

A more important uncertainty in making intensity estimates from Sp L and Sp H rates arises because Explorer XII is spinning at 30 rpm and the telemetered information is the number of counts a given detector has accumulated in 10.24 seconds. In this period the directional detectors, whose axes are at right angles to the spin axis, cut through the peak

TABLE 2. Explorer XII Data at Times of Maximum 302 GM Rate on Selected Passes

UT Date 1961	302 GM Apparent counts/sec	302 GM True counts/sec	Sp L counts/sec	Sp L Corrected counts/sec	Sp L J_0†	Sp H counts/sec	Sp H Corrected counts/sec	Sp H J_0†	Sp B* counts/sec SpB_L	Sp B* counts/sec SpB_H
Aug. 24	5,030±20	5.6×10^3	9.8±0.6	6.7	7	12.3±0.6	7.7	8	7.4±0.5	7.3±0.5
Sept. 1	15,900±40	4×10^4	93.5±2	62	60	101±2	59	60	74±2	67±2
Sept. 3	19,900±40	1.0×10^5	122±2	74	70	140±2	71	70	114±2	109±2
Sept. 5	21,090±40	1.5×10^5	153±2	91	90	165±3	79	80	145±2	136±3
Sept. 13	4,330±15	4.7×10^3	12.2±0.6	8.2	8	16.2±0.7	10.7	10	9.3±0.5	8.8±0.6
Sept. 15	2,680±20	2.8×10^3	15.1±0.7	12.2	10	36.7±1	32	30	6.8±0.5	7.5±0.6
Aug. 19‡	195±6	195	40.8±1	40.4	40	21.3±0.8	20.6	20	1.0±0.2	1.1±0.2

* The Sp B rates denoted by Sp B_L and Sp B_H are the rates of the background counter in the spectrometer at the moments of maximum Sp L and Sp H rates respectively (usually slightly different).

† The omnidirectional intensities J_0 listed under Sp L and Sp H are in units of 10^6 (cm^2 sec)$^{-1}$ within the respective pass bands of the spectrometer.

‡ The data for the Aug. 19 pass are included solely to illustrate the occasional soft nature of the electron spectrum. On this pass there was no clear maximum in 302 GM rate.

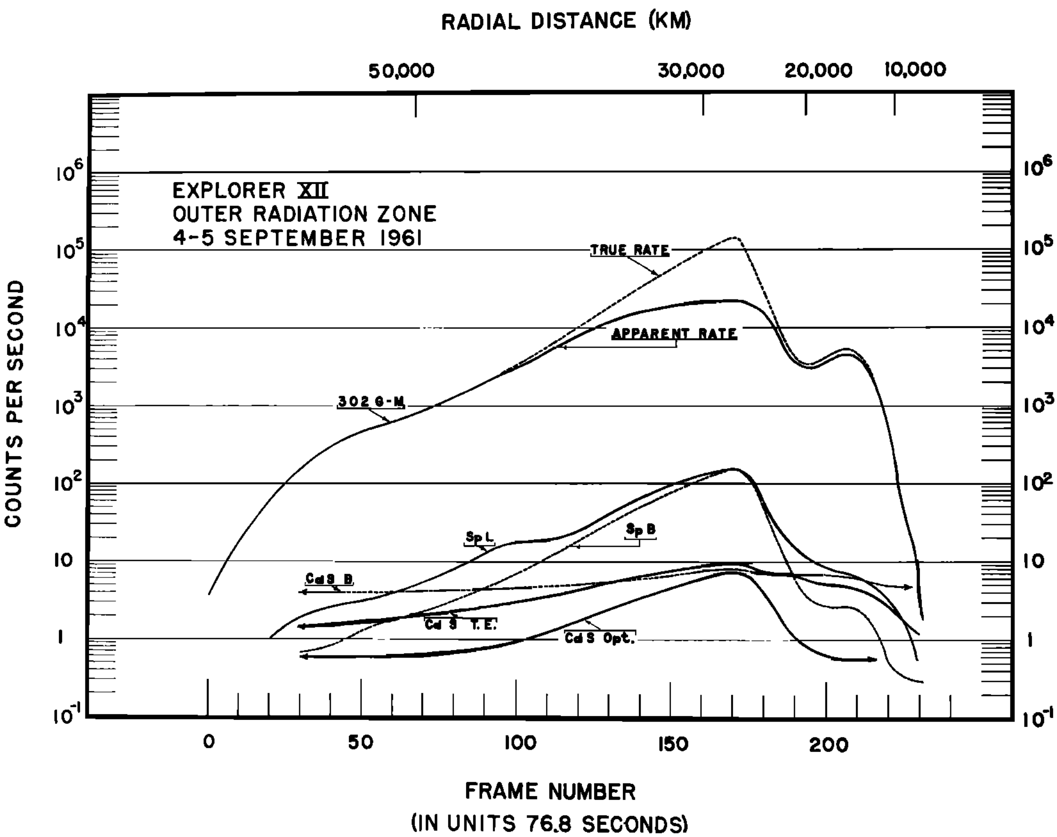

Fig. 2. Counting rates of the detectors as Explorer XII approached the earth on September 4–5, 1961. The rate of Sp H is very nearly the same as that of Sp L and is not plotted separately. The principal peak in the 302 GM rate occurs at a radial distance of 27,000 km and at a geomagnetic latitude of 15°. The secondary peak also occurs in the outer zone.

directional flux some 10 times. For this note, we take the directional intensity calculated directly from counting rates and the directional geometric factors (see Table 1), and then multiply this number by 10 so as to estimate the omnidirectional intensity in particles $(cm^2 sec)^{-1}$.

It is probable that 10 is an upper limit to the ratio of omnidirectional intensity to time-averaged unidirectional intensity; an improved value of this ratio will be obtained later from detailed study of the relationship of the spin axis of the payload to the magnetic field vector and of the actual angular distribution of the unidirectional intensity at the position of the observations.

We see from Table 2 that in the pass on September 4-5, 1961, the 302 GM true counting rate was about 1.5×10^5 counts per second. This is to be compared with peak rates of similar detectors on Explorer VI and Pioneer III of some 10^4 counts per second, and with the peak rate of order 10^5 counts per second on Pioneer IV. We conclude from this and from the preliminary trajectory data that this pass yields a typical sample of the heart of the outer zone during an intense period.

In previous work such rates were interpreted as being due to intensities of order 10^{10} to 10^{11} particles $(cm^2 sec)^{-1}$ of electrons mainly in the

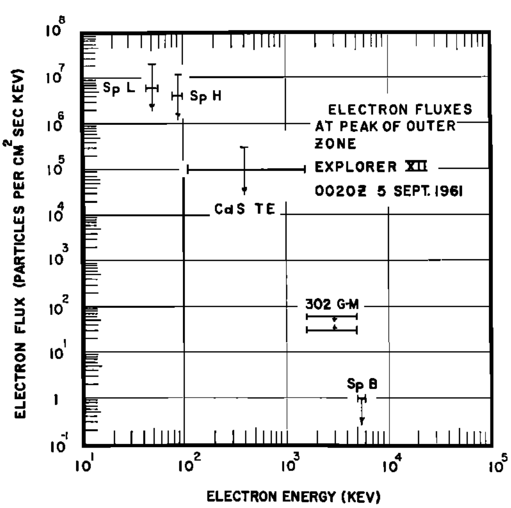

Fig. 3. Absolute differential number-energy spectrum for the omnidirectional electron intensity in the heart of the outer zone. The upward- and downward-drawn arrows signify lower and upper limits, respectively.

energy range of a few tens to a few hundreds of kev. However, we see from the spectrometer data of Table 2 and Figure 2 that the intensity of electrons in this energy range was only of order 10^8 particles $(cm^2 sec)^{-1}$. Also we see from Figure 1 that this latter intensity would give only some 100 counts per second in the 302 GM. (Indirect confirmation of this estimate from in-flight data is given by the pass on August 19, 1961 listed in Table 2.) Explorer XII is the first satellite or space probe to provide a conclusive measurement of the intensity of $\sim$ 50 kev electrons in the heart of the outer zone.

There remain three possible causes for the 1.5×10^5 counts per second of the 302 GM: (1) bremsstrahlung from an intensity of electrons of energy below $\sim$ 40 kev of order 10^{14} particles $(cm^2 sec)^{-1}$ at say 30 kev (see Fig. 1); (2) bremsstrahlung from an intensity of electrons of energy above $\sim$ 110 kev (but below 1.6 Mev) of order 10^{10} particles $(cm^2 sec)^{-1}$ at say 500 kev (see Fig. 1), or (3) direct counting of penetrating electrons of order 10^5 particles $(cm^2 sec)^{-1}$ having energies above about 1.6 Mev but below about 5 Mev (the energy of an electron which will penetrate the shielding of Sp B).

It is possible to choose which of these possibilities existed during this pass by making use of the measurement of energy flux by the CdS detectors. The method is as follows: first, take the raw CdS TE rate and assume it is due solely to particles entering through the aperture of 10^{-2} sterad. This yields an omnidirectional energy flux of 300 ergs $(cm^2 sec)^{-1}$ which is certainly an extreme upper limit, but which nevertheless is equivalent to only about 6×10^9 particles $(cm^2 sec)^{-1}$ at 30 kev, or to about 3×10^8 particles $(cm^2 sec)^{-1}$ at 500 kev, and so is several orders of magnitude too low to permit either possibility (1) or (2).

We are therefore forced to conclude that most of the 302 GM counts are due to penetrating particles.

Once having drawn this conclusion, we are free to make more realistic estimates of the several causes of the counting rate of CdS TE. In particular, the high rate of CdS Opt (whose axis was more than 45° from the solar vector during this period) shows that many counts are caused by penetrating particles and/or bremsstrahlung entering over the 0.6 sterad which has only $\sim$ 0.5 g cm^{-2} shielding. By using X-ray calibration of the relative sensitivity of the two CdS crystals, we are left with about 5 counts per second in CdS TE which can be attributed to electrons entering through the 10^{-2} sterad aperture. This corresponds to a flux of electrons of order 100 ergs $(cm^2 \sec)^{-1}$.

The electrons between 40 and 110 kev would contribute about 10 per cent of this energy flux. In order to estimate an upper limit to the intensity of electrons between 110 kev and $\sim$ 1.6 Mev, we assume that such electrons alone, with an average energy of 500 kev, gave the remaining energy flux. Thus we find an upper limit of 10^8 particles $(cm^2 \sec)^{-1}$ of $\sim$ 500 kev energy. This is certainly an upper limit since we have ignored the energy carried by any electrons between $\sim$ 1 kev and 40 kev.

When further calibrations of Sp B are made, we will know how effective bremsstrahlung from $\sim$ 2 Mev electrons is in causing Sp B to count. In the meantime, we may use the Sp B rate to place an extreme upper limit of $\sim 10^8$ particles $(cm^2 \sec)^{-1}$ to the intensity of (penetrating) electrons of energy above $\sim$ 5 Mev.

We plot a differential number-energy spectrum from these data in Figure 3, and summarize our analysis of the electron intensities in the heart of the outer zone at 0200 UT on September 5, 1961, as follows:

(*a*) The intensity of electrons between about 45 and 60 kev was $\left(9 \begin{smallmatrix} +16 \\ -6 \end{smallmatrix}\right) \times 10^7$ particles $(cm^2 \sec)^{-1}$.

(*b*) The intensity of electrons between about 80 and 110 kev was $\left(8 \begin{smallmatrix} +16 \\ -5 \end{smallmatrix}\right) \times 10^7$ particles $(cm^2 \sec)^{-1}$.

(*c*) The intensity of electrons between 110 kev and about 1.6 Mev was less than 10^8 particles $(cm^2 \sec)^{-1}$.

(*d*) The intensity of electrons between about 1.6 and 5 Mev was $(2 \pm 1) \times 10^6$ particles $(cm^2 \sec)^{-1}$.

(*e*) The intensity of electrons above $\sim$ 5 Mev was less than 10^8 particles $(cm^2 \sec)^{-1}$.

We conclude that the omnidirectional intensity of electrons above about 40 kev was of order 10^8 particles $(cm^2 \sec)^{-1}$.

We find that the raw data of previous experiments, when reinterpreted in the light of our present findings, are generally compatible with them. From these considerations and from the high rate of the 302 GM on this pass, we conclude that the estimate of $\sim 10^8$ particles $(cm^2 \sec)^{-1}$ may be more or less typical of high intensity conditions in the heart of the outer zone as seen since 1958.

It is of particular importance to note that the characteristics of the 302 GM as shown in Figure 1 or of similar detectors, when combined with such an electron spectrum as found in Figure 3, make it possible for very great changes in counting rate to be produced by small changes in the form of the spectrum at high energies. We are examining this aspect in more detail to determine how responsible it may be for the reported temporal and spatial changes in the outer zone.

Note that the corrected rates from Sp L and Sp H must be due to electrons and not to protons. If there are protons present, the electron spectrum of Figure 3 would be modified only for electron energies above $\sim$ 110 kev in the following manner. If there are low-energy (nonpenetrating) protons present in appreciable fluxes, the total number of particles as estimated from Cd S TE data will be less than shown, because a single nonpenetrating proton may lose several Mev in the crystal. If there are high-energy (penetrating) protons present in appreciable fluxes, their energy spectrum would have to be extraordinarily steep to account for all the counts of 302 GM and Sp B. Furthermore, *Fan, Meyer, and Simpson* [1961] showed conclusively that the intensity of penetrating protons with energy greater than $\sim$ 75 Mev was less than cosmic-ray intensity. Thus our conclusion that there are no more than 10^8 electrons $(cm^2 \sec)$ with energy above $\sim$ 40 kev in the heart of the outer zone holds true irrespective of whether protons are present or not.

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