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A DISCUSSION AND BIBLIOGRAPHY OF CURRENT
LITERATURE CONCERNING VAN ALLEN BELTS
FOR USE IN
SNAP SPACE ENVIRONMENTAL STUDIES

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A DISCUSSION AND BIBLIOGRAPHY OF CURRENT
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By
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ABSTRACT

This report presents a bibliography of theoretical and experimental papers which concern the Van Allen trapped radiation belts. Also, a general discussion of past history and conclusions from some experimental and theoretical work are presented. This information is applicable to the evaluation of space radiation influences upon SNAP reactor systems. All results quoted are subject to change since additional information and improved instrumentation may provide new bases for the interpretation of experimental data.

I. INTRODUCTION

Within the very near future SNAP reactor systems will be orbited around the earth or sent on deep space probes. Missions of these types will subject the reactor systems to a radiation field that is independent of the neutron radiation emerging from the reactor vessel. This space radiation is composed of galactic cosmic rays, solar cosmic rays, and Van Allen trapped radiation. The latter source is the concern of this document.

Trapped radiation belts were first discovered in 1958 by J. A. Van Allen.^{(I-27)*} Before the discovery, theories had been advanced by Störmer^(V-13) and others concerning the possibility of the existence of trapped radiation enveloping the earth; this speculation was based upon theories of charged particles incident upon a dipole field. The only objection to their existence was the lack of a source needed to inject particles into this region.

The telemetered data from Explorer I showed an increase in counting rate with altitude (expected cosmic ray bombardment), and then a sharp decrease in counting rate. At first it was thought that this was a region of complete absence of radiation; however, later evaluation of the data suggested that what was being observed was the saturation of the counters. Therefore, the satellite was actually entering a region of extremely intense radiation which was orders of magnitude higher in counting rates than would be expected from galactic radiation.

Since the first measurements, many and various types of experiments have been undertaken. Satellites, sounding rockets, intercontinental ballistic missiles, and deep space probes have been employed. The instruments that have been used in the above experimental devices have been emulsion plates, scintillation counters, geiger counters, proportional counters, and spectrometers. Various shields have been used in connection with these counters and plates in order to ascertain the energy or the nature of the particles being observed.

In regard to display of experimental data, it is known that complications exist when using the standard coordinate system of radius, latitude, and longitude. In certain instances a 3% error in the calculation of the distance from the

*The reference system used in this article will be such that the Roman numerals (i. e., I, II, etc.) signify the Bibliography section and the Arabic numbers signify the position in that section.

center of the earth to the observation point could yield a change in intensity of a factor of 10; in addition, the earth's geomagnetic field differs from that of a dipole by more than 3%. It is evident that a more precise and representative coordinate system be employed to combine the data into a suitable map of the radiation field. It thus becomes convenient to introduce some basic theoretical relationships which can be used to describe this map of terrestrial radiation.

II. GENERAL THEORIES ON PARTICLE MOTION

The work of Störmer was originally undertaken to try and explain the auroral behavior by particles incident upon the earth's geomagnetic field. To simplify the necessary equations of motion and to try to find any constant of motion, Störmer used the dipole approximation to the earth's field as seen in Figure 1. Upon solution of the equations, a constant of integration, 2γ , must be introduced. The physical significance of this constant is that -2γ represents the angular momentum moment arm of the particle from the dipole center line. With a range of values of this constant, it is possible to obtain solutions for particle motion that have forbidden and allowed spatial regions surrounding the earth. Two such solutions are shown in Figure 2. Störmer then concluded that these allowed regions would not be populated because no suitable source mechanism was available. Alfven used this idea of allowed zones to predict trapped zones for the sun and its hypothesized dipole field. However, he did not apply the idea to the earth's magnetic field.

A fundamental description of motion of a particle in a magnetic field separates the particle's velocity into a component of motion parallel to the magnetic lines of force and a component of motion perpendicular to the force line. The component perpendicular to the field line will cause the particle to curve around this force line because of the Lorentz force. Since this force is directed normal to the velocity $V_{\perp}$, no work is being performed and thus energy is conserved. Therefore, the particle will move parallel to the magnetic line of force with magnitude of the component of the velocity in that direction, $V_{\parallel}$. As the particle enters a converging magnetic field, the Lorentz force, still normal to the line of force, has a component directed in the $-V_{\parallel}$ direction as seen in Figure 3. This component of the force causes the particle to reverse its direction along the line of force, resulting in reflection of that particle.

The same result can be obtained by investigating the magnetic moment μ , of the particle within the environment of no electric fields and a slowly converging magnetic field. Alfven^(IV-3) proved that the magnetic moment of the particle under the above conditions will be a constant of motion. This requirement necessitates the reflection of the particle at some position of magnetic field strength.

EXAGGERATED ACTUAL
GEOMAGNETIC FIELD

DIPOLE APPROXIMATED
GEOMAGNETIC FIELD

Figure 1. Representations of the Earth's Geomagnetic Field

Figure 2. Stormer Regions in R , z Coordinates for Two Specific γ Parameters

$$B_3 > B_2 > B_1$$

Figure 3. Magnetic Mirror System Showing Lorentz Force and Its Components

Because

$$\mu = \frac{\frac{1}{2} m V_{\perp}^2}{B} \quad \dots(1)$$

a relation can be obtained that has the form

$$B_0 \sin^2 \theta = B \sin^2 \theta_0 \quad \dots(2)$$

where B and B_0 are the magnetic fields anywhere along the line of force, and θ and θ_0 are the corresponding angles between the total velocity vector $\vec{V} = \vec{V}_{\perp} + \vec{V}_{\parallel}$ and the magnetic line of force. At the mirror point, the total velocity is the velocity perpendicular to the line of force; therefore, $\theta = 90^\circ$ and the relationship becomes $1 = (B/B_0) \sin^2 \theta_0$. For reference, θ_0 and B_0 are usually taken to be pitch angle and magnetic field at the geomagnetic equator. Equation 1 is called the first adiabatic invariant or transverse adiabatic invariant. A change in condition that destroys the constant value of μ also destroys the condition given by Equation 2.

The particle upon entering a converging field will perform a drift at right angles to the increasing field. This motion has been formulated by Alfvén^(IV-3) and is due to the gradient of the field changing the radius of curvature of the particle experiencing a Lorentz force. Alfvén showed that this gradient causes positive particles to drift to the west and negative particles to drift to the east in the earth's magnetic field. Rosenbluth and Longmire^(IV-32) used this relation to obtain the second or longitudinal adiabatic invariant. For a perfect dipole, the mirror points of the particles drift circularly on a surface around the axis. The equation calculating this surface represents the second invariant. The relation obtained is

$$J = \int_{\text{mirror point 2}}^{\text{mirror point 1}} V_{\parallel} d\ell \quad \dots(3)$$

where $d\ell$ is the line element and the integral is along the line of force between mirror points 1 and 2 and $V_{\parallel}$ is the velocity vector parallel to the force line.

The second invariant can be written in a simpler equation if the presence of electric fields is ignored. In this case, the magnitude of the total velocity is constant, and

$$J = v \int_{\text{mirror point 2}}^{\text{mirror point 1}} \left(1 - \frac{B}{B_m}\right)^{1/2} d\ell \quad \dots (4)$$

where v is the total velocity, B is the magnetic field at the position of $d\ell$ and B_m is the magnetic field at the mirror points. Therefore, under steady-state conditions, the particle will sweep out a surface, corresponding to the B_m and J at the mirror points and the field line connecting these mirror points.

It should be pointed out that even along the same field line, particles with different pitch angles and therefore different mirror points will define different J surfaces. This is because J is really only defined at the mirror points after integrating along the line of force between mirror points. The line of force connecting these points makes a surface as the particle drifts perpendicular to the converging field. Thus, particles that mirror nearer the earth's surface form so-called adiabatic surfaces that are numerically larger than those formed by higher altitude mirroring particles as seen in Figure 4.

Northrop and Teller^(IV-26) presented a third invariant which is known as the flux invariant and yields the result that during periods of time-dependent fields, a new condition can be employed (Figure 5). The condition is that ϕ , the flux of B inside the invariant surface J , be independent of time, or that is to say

$$\left\langle \frac{d\phi}{dt} \right\rangle = 0 \quad \dots (5)$$

This invariant is necessary during times of dynamic magnetic fields when μ and J are still invariants but are not enough to describe the particle's motion since the energy has been changed. If the rate of change of the field is slow enough, slow compared to the time needed for the particle to drift around the earth, ϕ can replace the energy as a constant.

Figure 4. Sketch of First and Second Adiabatic Invariants

Figure 5. Schematic Representation of the Third Adiabatic Invariant Showing Mirror Points for a Single Particle

Conditions for the destruction of these invariants are:

- 1) Destruction of ϕ requires the time of geomagnetic fluctuations to be comparable to the time needed for the particle to drift around the earth.
- 2) Destruction of J requires the time of geomagnetic fluctuations to be comparable to the time needed to go from one mirror point to the other.
- 3) Destruction of μ requires the time of geomagnetic fluctuations to be comparable to the gyration frequency.

With these invariants in mind, it is possible to visualize the dynamics of the trapped particles during times of geomagnetic storms. Prior to the storm commencement we can say that the particles are contained in their invariant shells and each shell is independent and separated from all the others. As the storm commences, a change in energy or change in spatial position of the invariant surface is witnessed by the particles and therefore these particles will go to different J value shells. This results in different energy spectra and spatial maps. After the storm and the consequent recovery phase, those particles that did not experience energy changes, or that returned to their initial energy will return to the shells containing the original lines of force; those that underwent an energy alteration will eventually end on different J shells.

Using these invariants, McIlwain^(II-18) obtained a coordinate system composed of B , the scalar magnetic field, and L , a parameter that retains most of the useful properties of J and is essentially constant along the magnetic field line.* Therefore, the invariant shell has essentially a unique value on its entire

The following is taken from McIlwain's article (II-18)

- 1) J can be represented by $J = R_o f_1(\lambda)$, where $R_o \equiv$ equatorial radial distance, $\lambda \equiv$ magnetic latitude, and $f_1(\lambda) \equiv$ a function of λ .
- 2) A dipole field has the familiar representation $B = (M/R_o^3 \cos^6 \lambda)(1 + 3 \sin^2 \lambda)^{1/2}$, where $M \equiv$ the dipole magnetic moment. Rearranging terms we get $R_o^3 B/M = f_2(\lambda)$, where $f_2(\lambda) \equiv$ another function of λ .
- 3) By combining these equations we obtain, $J^3 B/M = (R_o^3/M) f_1^3(\lambda) = (R_o^3 B/M) f_3(\lambda)$, or since λ can be expressed as a function of $R_o^3 B/M$, then $J^3 B/M = f_4(R_o^3 B/M)$ or rewritten as $R_o^3 B/M = F(J^3 B/M)$, where f_3 , f_4 , and F are separate functions of λ .
- 4) L is then defined by $L^3 B/M = F(J^3 B/M)$
- 5) All that remains to be done is to calculate the geomagnetic field B , the invariant for that field point J , the dipole moment of the earth M , and solve for F by fitting $\ln(L^3 B/M - 1)$ to a geometric expansion.

surface. For a dipole field L is the equatorial radius of the corresponding magnetic invariant shell. Sounding rockets and satellite data can thus be plotted easily with the changes in altitude, longitude, and latitude included. With these adiabatic invariants and a coordinate possibility in mind, it is now possible to go into some theories of particle belt formation and dynamics.

Experimental evidence thus far has established the fact that at least protons and electrons are the cause of the radiation belts. A schematic drawing of the belts is shown in Figure 6. The inner zone, whose peak intensity is located around 1.5 earth radii, is composed of protons and electrons. The outer zone, whose peak intensity is located around 3.75 earth radii, is composed almost exclusively of electrons. The trapped radiation has been observed out to about 15 earth radii.

Figure 6. Typical Representation of the Earth's Trapped Radiation

III. INNER BELT THEORY

The theories on source for the inner proton belt have been reduced to two modes. These two methods are not really entirely separate and independent, but seem to complement each other.

A. SOLAR COSMIC RAY INJECTION

One method of injection is to explain the particle source as a result of solar activity. It is known that during periods of quiet solar activity, a solar wind is impinging upon the earth's magnetosphere, but this is not intense enough to give a suitable source. However, solar flares inject particles of high intensity and energy into neighboring space. Thus a suitable source of protons and electrons would seem to be available in the flare phenomenon. Observations during magnetic disturbances would be expected to show large deviations in counting rates in the center of the inner zone; however, the early observations were essentially constant. Unfortunately, these observations were made during short observation time spans. Recently, Pizzella et al.^(I-21) reduced Explorer VII data and obtained long time observations of the belts and observed fluctuations in the inner zone of factors of 2 or 3. This doubling or tripling of intensity seems to be a composite of discrete increases during times of geomagnetic disturbances. They concluded that solar injection seems to be the cause of this increase and suggested two possible sources: temporary solar proton capture and perhaps a local acceleration of these particles and the subthreshold protons already in the belt, and neutron decay from bombardment of the polar caps by the solar plasma.

B. GALACTIC COSMIC RAY INJECTION

The other theory presented for the creation of the proton Van Allen belt is one of nuclear interaction of galactic cosmic rays with the upper levels of the earth's atmosphere. This interaction originally was thought to produce mesons and fairly light nuclei. These products, therefore, were the supposed cause of the radiation belts. However, decay rates and insufficient source strength ruled out these products. The next theorized products of the interaction were secondary protons and neutrons. Thus, if the protons were ejected with the proper orientation and energy they could be trapped; but the more favorable

mode would be for the neutrons to traverse outward to the heights needed for Van Allen belt observations and decay as

where

n = neutron

p = proton

β = electron

$\bar{\nu}$ = anti neutrino .

Since the neutron is not affected by the earth's magnetic field, these particles can reach the proper heights necessary for optimum trapping. Further investigation of the proposed theory based on neutron albedo, i. e., neutron leakage from the earth's atmosphere, yields results that fit experimental results in a certain energy region, with fast neutrons responsible for the proton portion of the belt, and slow neutrons responsible for the electrons in the inner and outer belt. It must be pointed out that the proton spectra from neutron decay does not satisfy the whole energy range of the observed spectra as will be discussed later. The electron portion of the decay has inconclusive experimental data at this time to base judgment on agreement with this theory.

To return to the proton inner belt, Freden and White^(I-7) proposed the theory, based upon suggestions of Singer^(II-23) and others^(II-13) for neutron albedo. To obtain a reasonable fit to experimental results, nuclear interaction and ionization losses must be included. Using the neutron differential spectrum taken from Hess's^(II-13) calculations, this theory fit experimental results over a broad range of ~ 75 Mev to ~ 300 Mev. Above and beneath this range, deviations from experimental results were observed. Lenchek and Singer^(II-15) obtained good agreement in the high energy portion of the differential spectrum by including an anisotropic distribution of neutrons emitted by the interaction in the atmosphere. Other possibilities for the deviation of experiment and theory at these high energies are nonadiabatic effects or hydromagnetic waves and errors in the postulated trapping probabilities. To explain the deviations at lower proton energies, Freden and White^(II-8) have postulated that the problem

is caused by a minimum in the albedo neutron spectrum. This minimum arises because of the peaking of the nonelastic cross sections of nitrogen and oxygen at about 20 Mev.

Relative peaks at the low energy end of the proton spectrum have been investigated experimentally by Nagle and Kniffen^(I-20) and theoretically by Lenchek^(II-16). The following hypothesis has been formed: solar protons impinge upon the polar regions of the earth and produce secondary neutrons with energies of order 10^3 less than those produced by galactic cosmic rays. By mapping these low energy neutrons and their position upon decay, the following result became manifest: only magnetic shells of L larger than ~ 1.7 earth radii are able to trap these low energy protons and electrons. Also, the trapping time is long compared to times between the injections. Thus, instead of transients, these low energy particles are equilibrium fluxes.

It is interesting to note that Lenchek and Singer calculated the rate of proton injection due to neutron albedo to be of the order of 10^{-14} protons/cm³-sec with energies above 50 Mev. Seward and Hess^(IV-33) calculate the loss rate of the electrons in the outer Van Allen belt is about 10^{-13} electrons/cm³-sec.

New experimental evidence indicates the possibility that neutron albedo is only part of the answer to the inner Van Allen proton belt. Part of this evidence is that already reported, the time variation of the proton belt intensity. Another bit of information that implies that albedo is not enough to explain the proton Van Allen belt was provided by Williams et al.^(I-30) who measured the neutron flux and obtained a value about six times more intense than would be expected from cosmic albedo.

IV. OUTER BELT THEORY

An attempt to explain the electrons in the outer belt by source injection from the sun and by neutron albedo has also been made. The solar injection theory was introduced because of the great changes in energy distribution, intensity, and spatial distribution observed during times of geomagnetic storms. In an attempt to explain dynamic outer belt changes, Coleman^(IV-4) calculated the change in integral spectrum of electrons due to a uniform slowly varying field and its subsequent betatron acceleration. Using reasonable magnetic field changes, he obtained the result that under the assumption of an initial integral spectra $N(>E) = KE^{-\gamma}$, γ varies little after the acceleration from its initial value. This agreed with many experiments made up to that time; however, Rosen and Farley^(III-23) made measurements with Explorer VI and could not explain the results by simple reversible betatron acceleration and deceleration. Therefore, a complex oscillation mechanism must be hypothesized. Because of these great variations in counting rates, magnetic field oscillations instead of particle intensity fluctuations have been speculated also by Dessler and Karplus.^(IV-10) They explained some of the observations by proposing a reversible process in which the outer belt is steady state and a ring current is located at 6 to 11 earth radii. This ring current theory is to be taken skeptically, since objections are still being raised and Explorer XII did not observe this ring current. However, this objection will be neglected in order to get a qualitative description of a model to explain dynamic changes in the outer belt. Dessler suggested that a plasma cloud would impinge upon the magnetosphere causing a diamagnetic ring current at around 3 to 5 earth radii. When this occurs, the particles beyond six earth radii will be lost because of the destruction of the earth's magnetic lines of force in that vicinity. During the time of the diamagnetic ring current, the magnetic field in the vicinity of 4 earth radii would decrease, therefore causing a deceleration of the particles and a subsequent decrease in the counting rates measured in this vicinity. However, this ring current supposedly decays in the time period of about one day. Therefore, as this current decays, an increase in the magnetic field takes place, that is, the geomagnetic field advances to its unrestricted value, and a subsequent betatron acceleration of the particles ensues. Final recovery from the magnetic storm is accomplished when the low energy particles are again trapped in the vicinity beyond 6 earth radii.

Walt and MacDonald^(IV-36) have calculated a neutron decay source for the outer belt. Interaction with the atmosphere by the electrons was accomplished by including a diffusion term and an energy loss mechanism in the basic equations of continuity. Upon comparison with experimental evidence of Cladis et al. ^(III-4) Walt et al. ^(III-38) it was concluded that either the outer belt did not arise from neutron decay, or the dominant loss is not Coulomb scattering. Hess and Killeen^(IV-17) suggested that the atmosphere model used by Walt et al. could be wrong and therefore yielded erroneous conclusions. Lenchek et al. ^(IV-22) did neutron decay calculations as a function of energy, pitch angle, and altitude. Their loss mechanisms were slowing down and pitch angle diffusion, both based upon Coulomb interactions. It should be noted that they concluded that slowing down is the dominant mode. Their major results were that the energy spectrum intensity peaks at about 200 kev and the omnidirectional integral intensity in the equatorial plane is approximately constant vs altitude. Further, only a small fraction of electrons can be accounted for by albedo, and this portion is that above 400 kev. Hess and Killeen use the neutron albedo model with small angle Coulomb scattering for changing the pitch angle and slowing down by collision with thermal electrons. Their results seem to agree with experimental results, allowing for errors in the experimental atmospheric model, for energies greater than about 50 kev. Hess and Poirier^(IV-16) calculated the electron spectrum from cosmic ray neutron albedo using loss methods of ionization energy loss, multiple scattering, and electron-electron scattering. Their conclusion is that no real straightforward decision can be made due to the scarcity of experimental information pertinent to checking the various theories.

Recently Farley and Sanders^(IV-12) evaluated the Explorer VI data and obtained pitch angle distributions. During their evaluation, they concluded that to explain their counter response, there must exist substantial fluxes of electrons with energy greater than 1 Mev. Therefore, some acceleration method must be introduced if neutron albedo is to be the source of the outer radiation belt. Various methods of trying to explain time variation of the belts and acceleration mechanics have been proposed. The belt variation in intensity has one method of explanation by use of the violation of the third adiabatic invariant. In

order to obtain these relativistic electrons, whistler radiation^{*} and its subsequent first adiabatic invariant violation have been proposed. Hydromagnetic waves have also been proposed to explain the observed fluctuations. It should be noted that Wentzel^(IV-38) has suggested that the hydromagnetic waves are sufficient to explain the dumping of the Argus electrons[†] through the mechanics of changing the magnetic moment within the period of one day.

Hydromagnetic waves and their influence on trapped charged particles have been investigated by Welch and Whitaker^(IV-37) with application to the trapped proton component. The experimental fact that caused the postulation of hydromagnetic waves was the absence of protons beyond ~ 6000 km. This was explained by hydromagnetic waves decreasing the magnetic moment of the protons and their consequent removal through lowering of the mirror points into the denser atmosphere. Lifetimes of trapped protons are a strong function of interaction methods. In the few hundred kilovolt energy region and below, charge exchange is the dominant interaction and the associated lifetime for protons of energy up to about 75 kev is of the order of one day. For protons of energies above 75 kev and up to 200 kev the lifetimes are in the order of a year. By comparison, a 1 Mev proton whose dominant loss mechanism is Coulomb scattering has a lifetime in the neighborhood of 25 yr. The above values were calculated by Liemohn^(II-17) for protons reflecting in the equatorial plane.

The concluding section will present some experimental results obtained and reported within the last few years. These references do not by any means include all the data reported, but are a fairly extensive list of pertinent data which is readily available. The data could possibly be presented in much simpler form if the geomagnetic field data used by McIlwain were used. However, access to that information is not available at the time of this writing. A careful evaluation must be made of all data since the latitude, longitude, altitude, and time are important factors in each experimental detection. As a result, the experimental results are varied and many of the conclusions derived are contradictory because of the difficulty of particle identification or detector saturation.

* Whistler radiation is electromagnetic waves of the audible frequency caused by lightning discharges.

† The Argus radiation belts were formed by fission bombs at ~ 480 km altitude in the Pacific during the summer of 1958.

V. EXPERIMENTAL RESULTS

Van Allen found that the radiation spatial distribution, which is a function of previous and present geomagnetic activity, had a peak in counting rate called the P_1 peak, at around 10×10^3 km from the center of the earth. This peak in intensity has been interpreted as the proton inner belt. Another peak was recorded at about 22×10^3 km and has been designated as the outer electron belt. Additional investigation has split the outer belt into peaks at $\sim 21.5 \times 10^3$ km called the E_3 peak, and $\sim 16 \times 10^3$ km called the E_2 peak. (See Figure 7.) It should be mentioned that these peaks are referenced to the energy region specified since different detectors locate the peaks at different altitudes. The minimum in the outer radiation zone $\sim 19 \times 10^3$ km has been investigated theoretically by numerous people. Dessler and Karplus^(IV-10) have attempted to explain this relative minimum in electron intensity on the grounds of the Capetown anomaly* in the geomagnetic field. Hoffman,^(III-12) however, has shown that if the geomagnetic field can be represented adequately with the data of Jensen, Murray, and Welch then the Capetown anomaly does not correspond with the field lines through the minimum. No adequate explanation has been given for this phenomenon of a minimum electron population.

Stolov^(III-28) investigated the geomagnetic lines of force through the outer zone and found that auroral arcs are at equal magnetic dip angles and this magnetic field line cuts the magnetic equator at $\sim 16,000$ km, the heart of the E_2 zone. Thus, the outer zone seems to be closely connected with the auroral displays.[†] Three theories concerning the observed relation have been presented. One is that the outer zone dumps the electrons down the field line, thereby producing the auroral arc. This is questioned because of the methods necessary to refill the outer zone in the necessary time. The second theory, proposed by O'Brien^(III-19) suggests that plasma from the sun causes the aurora and the

*The Capetown anomaly is an unusually weak magnetic field in the vicinity of Capetown on the southern tip of Africa.

†This has been explained somewhat by the observation of the $6300 \text{ \AA}$ aurora arc which is located about 900 km south of the visible auroral arcs. The postulation is that the E_3 zone, supposedly created by solar injection, moves into the E_2 zone, thought to be created by neutron decay, during magnetically disturbed periods, thus heating the E_2 zone and causing chemical reactions and subsequent emission of atomic oxygen $6300 \text{ \AA}$ red line. This chemical reaction is proposed since a collision process would excite the $5577 \text{ \AA}$ green line, which is absent under general intensity considerations.

Figure 7. Sketch of Van Allen Belt Flux in the Geomagnetic Equatorial Plane

outer zone fluctuations are merely catches of the excess solar plasma. O'Brien bases this theory on his observations with Injun I of actual dumping of electrons. Objections to this theory result from the measurements of decrease of outer zone intensity during magnetic storms, which is consistent with auroral dumping. The third theory by Akasofu and Chapman^(IV-1) suggested that the aurora polaris were caused by neutral magnetic points in the geomagnetic plane. These neutral points were formed by the geomagnetic and ring current field canceling.

Periods of magnetic activity have great effects upon the outer radiation belt. Rosen and Farley observed with Explorer VI three peaks in the outer belt at radial distances different from the usual two peaks first observed by Fan et al.^(III-5) During magnetic storm periods, the peak location of the outermost intensity was observed to move inwards from around 30.5×10^3 km to 25×10^3 km. The two theories as to the source of the fluctuation in the observed outer belt are the solar injection of particles and the magnetic acceleration or deceleration of the already trapped particles. The latter theory has been presented by Dessler and Karplus and observations by Explorer VII and Pioneer V seem to bear the theory out. In these two satellites, Explorer VII measured the electron flux for $E > 30$ kev near the earth and got counting rates of thousands of counts per second, while Pioneer V in interplanetary space never recorded over 3 cps during the same time. These two measurements, therefore, give an argument for local acceleration within a period of one day.

Fan et al. measured spatial fluctuations of the E_2 and E_3 peaks and observed fluctuations during times of magnetic disturbance of 10% of the total range from the dipole center. During this same time Argus observations only changed ~ 30 km; therefore, it seems that geomagnetic fluctuations are evident for regions beyond the Argus altitude, ~ 600 km. Observations of the E_3 spectrum showed that during the early part of the storm the spectrum remained the same even though the intensity increased by a factor of 6; however, later the γ in the differential spectrum fit $KE^{-\gamma}$ increased 25 to 50%.

The γ for the energy range of $10^2 \leq E \leq 10^3$ kev was of the order of 3 for altitude of the E_3 region of 22×10^3 km. The associated omnidirectional flux was found to be 8×10^8 electrons/cm²-sec for the same energy span. The E_2 data ($\sim 17 \times 10^3$ km) would fit more consistently with $\gamma = 5$. They also measured the proton flux of $E > 75$ Mev in the outer belt and obtained 0.0 ± 0.1 protons/cm²-sec. The conclusion obtained by the authors was that local acceleration is

the force behind the variations, since they could not detect sufficient density of preaccelerated electrons beyond the E_3 zone. An injection of low energy electrons $E < 50$ kev and their local acceleration does not seem feasible since the E_3 peak returned to its original altitude and the spectrum returned to its pre-storm value. Since the $E^{-\gamma}$ fit should be viewed with regard to conditions, O'Brien et al. (III-19) upon evaluation of Injun I data at ~ 1000 km, came to the conclusions that the intensity is 10^5 to 10^6 electrons/cm²-sec-ster up to latitude $\sim 75^\circ$ and $< 10^2$ for latitudes beyond 75° . The observed peak intensity was about 4×10^6 electrons/cm²-sec-ster for $E > 40$ kev and 10 ergs/cm²-sec-ster for electrons of $E > 1$ kev. The observed intensity was highly variable and changed by orders of magnitude within a few seconds, or few 10's of kilometers. Assuming a spectrum of $dN/dE = AE^{-\gamma}$, the experimental results vary in space and time in the region $40 \leq E \leq 120$ kev. Between 45 to 60° latitude, γ varies between 0 and 2, between 60° to 70° latitude, γ varies between 0 and 7.

When observing the experimental results, one must remember that the spectrum is a function of altitude. Singer^(II-27) has obtained an expression that states the maximum energy of the particle decreases with altitude because of the breakdown in the adiabatic invariants. Differential spectra for the proton and electron fluxes are shown in Figures 8 and 9 respectively. The spectra by the different observers have not been normalized; therefore, only the slope is the important feature. The simplicity of recording intensities by use of the L value of McIlwain is shown in Figures 10 and 11, in which the lines of constant count rate have been transformed from geographic coordinates into the B-L coordinates.

Upon evaluation of experimental data the fact should be kept in mind that along the field line, particles will decrease as the observation moves from the geomagnetic equator as seen in Figure 12. This is caused by the particles mirroring due to the pitch angle distribution changing along that line. A typical pitch angle distribution is shown in Figure 13, which is data obtained for two observations along the same field line. A presentation of typical integral data is displayed in Table I.

Figure 8. Differential Spectra for Proton Fluxes

Figure 9. Differential Spectra for Electron Fluxes

Figure 10. Explorer IV Results in Geographic Coordinates

Figure 11. Explorer IV Results in BL Coordinates

Figure 12. Particle Intensity Along the Field Line

Figure 13. Pitch Angle Distribution

TABLE I
INTEGRAL BELT FLUXES

Particle	Altitude	Latitude	Energy Span	Integral Flux	Units	Reference
β	heart of inner	-28°N	200 < E < 500 kev or	2×10^9	$\beta/\text{cm}^2\text{sec}$	I-13
β	heart of inner	-28°N	E > 500 kev	10^7	$\beta/\text{cm}^2\text{sec}$	I-13
β	22×10^3 km	0°	100 < E < 1000 kev	8×10^8	$\beta/\text{cm}^2\text{sec}$	III-5
β	17×10^3 km	0°	100 < E < 1000 kev	7×10^9	$\beta/\text{cm}^2\text{sec}$	III-5
p	2×10^3 km	-20°N	E > 1 Mev	0.27×10^5	$\text{p}/\text{cm}^2\text{sec ster}$	III-3
p	3×10^3 km	-20°N	E > 1 Mev	0.90×10^5	$\text{p}/\text{cm}^2\text{sec ster}$	III-3
p	4×10^3 km	-20°N	E > 1 Mev	2.02×10^5	$\text{p}/\text{cm}^2\text{sec ster}$	III-3
p	5×10^3 km	-20°N	E > 1 Mev	4.56×10^5	$\text{p}/\text{cm}^2\text{sec ster}$	III-3
p	heart P ₁	-	E = 2 Mev or	2.9×10^9	$\text{p}/\text{cm}^2\text{sec}$	III-23
p	heart P ₁	-	E = 10 Mev	1.5×10^7	$\text{p}/\text{cm}^2\text{sec}$	III-23
β	heart E ₂	-	E = 200 kev or	2.2×10^9	$\beta/\text{cm}^2\text{sec}$	III-23
β	heart E ₂	-	E = 500 kev	1.6×10^7	$\beta/\text{cm}^2\text{sec}$	III-23
β	heart E ₃	-	E = 200 kev or	2.7×10^7	$\beta/\text{cm}^2\text{sec}$	III-23
β	heart E ₃	-	E = 500 kev	2.0×10^7	$\beta/\text{cm}^2\text{sec}$	III-23
β	920 km	35°N	E > 50 kev	3.4×10^6	$\beta/\text{cm}^2\text{sec}$	III-4
β	1045 km	35°N	E > 50 kev	4.2×10^6	$\beta/\text{cm}^2\text{sec}$	III-4
p	920 km	35°N	E > 1 Mev	3.8×10^3	$\text{p}/\text{cm}^2\text{sec}$	III-4
β	heart of outer	-	E > 20 kev	10^9	$\beta/\text{cm}^2\text{sec ster}$	III-35
β	heart of outer	-	E > 1 Mev	10^5	$\beta/\text{cm}^2\text{sec ster}$	III-35

TABLE I (Continued)

Particle	Altitude	Latitude	Energy Span	Integral Flux	Units	Reference
β	3600 km	0°	E > 20 kev	2×10^9	$\beta/\text{cm}^2 \text{ sec ster}$	I-24
β	3600 km	0°	E > 600 kev	10^7	$\beta/\text{cm}^2 \text{ sec ster}$	I-24
p	3600 km	0°	E > 40 Mev	2×10^4	$p/\text{cm}^2 \text{ sec}$	I-24
β	16,000 km	0°	E > 20 kev	10^8	$\beta/\text{cm}^2 \text{ sec}$	I-24
β	16,000 km	0°	E > 200 kev	$\leq 10^8$	$\beta/\text{cm}^2 \text{ sec}$	I-24
p	16,000 km	0°	E > 60 Mev	$\leq 10^2$	$p/\text{cm}^2 \text{ sec}$	I-24
β	heart of outer	-	45 < E < 60 kev	9×10^7	$\beta/\text{cm}^2 \text{ sec}$	III-21
β	heart of outer	-	80 < E < 110 kev	8×10^7	$\beta/\text{cm}^2 \text{ sec}$	III-21
			110 kev < E < 1.6 Mev	10^8	$\beta/\text{cm}^2 \text{ sec}$	III-21
			1.6 < E < 5 Mev	2×10^5	$\beta/\text{cm}^2 \text{ sec}$	III-21
			E > 5 Mev	$< 10^3$	$\beta/\text{cm}^2 \text{ sec}$	III-21
β	heart of inner at 1000 km	-	E > 40 kev	5×10^6	$\beta/\text{cm}^2 \text{ sec ster}$	I-6
p	1000 km	-	E = 100 kev	3×10^8	$p/\text{cm}^2 \text{ sec ster}$	I-9
p	1000 km	30°	E > 31 Mev	10^3	$p/\text{cm}^2 \text{ sec}$	I-18

VI. CONCLUSION

Present and future SNAP systems must be evaluated for performance within the trapped radiation region discussed in this document. This radiation field will have characteristic effects upon the instrumentation, payload, and reactor core of SNAP flight systems. Possibilities are present to design reactor systems that make use of this radiation field as a reactor startup source. Whatever the benefits or liabilities of this radiation field, allowances must be made for its presence if top performance goals of long life, reliability, and steady-state operation are to be accomplished.

The bibliography is enclosed in Appendix A and is divided into five sections: I. Inner Radiation Belt (Experiment), II. Inner Radiation Belt (Theory), III. Outer Radiation Belt (Experiment), IV. Outer Radiation Belt (Theory), and V. General Papers on Van Allen Belts. Asterisks indicate papers that give a more general presentation of data or theory for faster access of information. Definitions and symbols used in this article are given in Appendix B.

APPENDIX A

BIBLIOGRAPHY

I. INNER RADIATION BELT (EXPERIMENT)

1. Armstrong, A. H., Harrison, F. B., Heckman, H. H., and Rosen, L., "Charged Particles in the Inner Van Allen Radiation Belt," J. G. R., Vol. 66, No. 2, 1961
2. Armstrong, A. H., Harrison, F. B., and Rosen, L., "Flux and Energy of Charged Particles at 300- and 600-Mile Altitude," Bull. Am. Phys. Society, 1959
3. Armstrong, A. H. and Heckman, H. H., "Flux and Spectrum of Charged Particles in the Lower Van Allen Belt," Bull. Am. Phys. Society, 1961
- *4. Arnoldy, R. L., Hoffman, R. A., and Winckler, J. R., "Observations of the Van Allen Radiation Regions During August and September 1959, Part I," J. G. R., Vol. 65, No. 5, 1960
- *5. Arnoldy, R., Hoffman, R., and Winckler, J. R., "Measurements of the Van Allen Radiation Belts During Geomagnetic Storms," Proceedings of the First International Space Science Symposium, 1960
6. Frank, L. A., Dennison, D. C., and Van Allen, J. A., "Electrons in the Earth's Inner Radiation Zone," American Geophysical Union, Forty-Third Annual Meeting, April, 1962
7. Freden, S. A., and White, R. S., "Spectrum of Trapped Particles in the Inner Radiation Belt," J. G. R., Vol. 65, No. 8, 1960
- *8. Freden, S. C. and White, R. S., "Protons in the Earth's Magnetic Field," Physical Review Letters, Vol. 3, No. 1, 1959
- *9. Freeman, J. W., "Detection of an Intense Flux of Low-Energy Protons or Ions Trapped in the Inner Radiation Zone," J. G. R., Vol. 67, No. 3, 1962
10. Gurtler, C. A., "Radiation Measurements in the Slot Between the Van Allen Belts to an Altitude of 1415 Kilometers," J. G. R., Vol. 66, No. 9, 1961
- *11. Heckman, H. H. and Armstrong, A. H., "Energy Spectrum of Geomagnetically Trapped Protons," J. G. R., Vol. 67, No. 4, April, 1962
12. Hoffman, R. A., "Proton Spectra and Fluxes of the Inner Van Allen Belt," American Geophysical Union, Los Angeles, California, December 27-29, 1961
13. Hoffman, R. A., Arnoldy, R. L., and Winckler, J. R., "Observations of the Van Allen Radiation Region During August and September 1959, 3. The Inner Belt," J. G. R., Vol. 67, No. 1, 1962
14. Holly, F. E. and Johnson, R. G., "Measurement of Radiation in the Lower Van Allen Belt," J. G. R., Vol. 65, No. 2, 1960
- *15. Holly, F. E., Allen Jr., L., and Johnson, R. G., "Radiation Measurements to 1500 Kilometers Altitude at Equatorial Latitudes," J. G. R., Vol. 66, No. 6, 1961

16. Imhof, W. L., Smith, R. V., and Fisher, P. C., "Proton Measurements in the Van Allen Belt," Bull Am Phys. Society, 1962
17. Korff, S. A. and Haymes, R. C., "High Neutron and Radiation Intensities at Balloon Altitudes During Auroral Display," J. G. R., Vol. 65, No. 10, 1960
- *18. Kniffen, D. A. and Naugle, J. E., "Proton Fluxes in the Inner Van Allen Belt," American Geophysical Union, Forty-Third Annual Meeting, April, 1962
- *19. Moffat, R. D., "Proton Intensity in the Van Allen Belt," IAS National Summer Meeting, Los Angeles, California, June 19-22, 1962
- *20. Naugle, J. E. and Kniffen, D. A., "Flux and Energy Spectra of the Protons in the Inner Van Allen Belt," P. R. L., Vol. 7, No. 1, 1961. 1961 Kyoto Conference on Cosmic Rays and the Earth Storm
- *21. Pizzella, G., McIlwain, C. E., and Van Allen, J. A., "Time Variations of Intensity in the Earth's Inner Radiation Zone," October 1959 through December 1960, J. G. R., Vol. 67, No. 4, April 1962
22. Reidy, W. P., Haymes, R. C., and Korff, S. A., "A Measurement of Slow Cosmic Ray Neutrons up to 200 Kilometers," J. G. R., Vol. 67, No. 2, 1962
23. Rothwell, P. and McIlwain, C. E., "Magnetic Storms and the Van Allen Radiation Belts: Observations from Satellite 1958 Epsilon (Explorer IV)," Proceedings of the First International Space Science Symposium, 1960
24. Van Allen, J. A., "The Geomagnetically Trapped Corpuscular Radiation," J. G. R., Vol. 64, No. 11, 1959
25. Van Allen, J. A., McIlwain, C. E., and Ludwig, G. H., "Radiation Observation with Satellite 1958E," J. G. R., Vol. 64, No. 3, 1959
- *26. Van Allen, J. A. and Frank, L. A., "Radiation Measurements to 658,300 Kilometers with Pioneer IV," S. U. I. 59-18, 1959
27. Van Allen, J. A., Ludwig, G. H., Ray, E. C., and McIlwain, C. E., "Observations of High Intensity Radiation by Satellite 1958 Alpha and Gamma," Jet Propulsion, Vol. 28, 1958
28. Van Allen, J. A., "Origin and Nature of the Geomagnetically Trapped Radiation," Proceedings of the First International Space Science Symposium, 1960
- *29. Vernov, S. N. and Chudakov, A. E., "Terrestrial Corpuscular Radiation and Cosmic Rays," Proceedings of the First International Space Science Symposium, 1960
30. Williams, D. J., Bostrom, C. O., and Pieper, G. F., "Neutron-Detection Experiment in the TRAAC Satellite," American Geophysical Union, Forty-Third Annual Meeting, April 1962

II. INNER RADIATION BELT (THEORY)

1. Alfvén, H., "Momentum Spectrum of the Van Allen Radiation," Physical Review Letters, Vol. 3, No. 10, 1959

2. Alfvén, H., "Solar Magnetic Field and Diurnal Variation of Cosmic Radiation," Physical Review 72, 1947
3. Avrett, E. H., "Particle Motion in the Equatorial Plane of a Dipole Magnetic Field," J. G. R., Vol. 67, No. 1, 1962
4. Chamberlain, J. W., "Physics of the Aurora and Airglow," Academic Press, New York, 1961
5. Davis, L. R., "Low Energy Trapped Protons," American Geophysical Union, Forty-Third Annual Meeting, April 1962
6. Dragt, A. J., "Effect of Hydromagnetic Waves on the Lifetime of Van Allen Radiation Protons," J. G. R., Vol. 66, No. 6, 1961
7. Dragt, A. J., "Effect of Hydromagnetic Waves on Van Allen Protons," J. G. R., Vol. 66, No. 8, 1961
- *8. Freden, S. C. and White, R. S., "Trapped Proton and Cosmic-Ray Albedo Neutron Fluxes," J. G. R., Vol. 67, No. 1, 1962
- *9. Freden, S. C. and White, R. S., "Particle Fluxes in the Inner Radiation Belt," J. G. R., Vol. 65, No. 5, 1960
10. Glasstone, S. and Loveberg, R. H., "Controlled Thermonuclear Reactions," Van Nostrand, New York, 1960
11. Gold, T., "Plasma and Magnetic Fields in the Solar System," J. G. R., Vol. 64, No. 11, 1959
- *12. Hess, W. N., "The Radiation Belt Produced by Neutrons Leaking out of the Atmosphere of the Earth," J. G. R., Vol. 65, No. 10, 1960
- *13. Hess, W. N., "Van Allen Belt Protons from Cosmic Ray Neutron Leakage," Physical Review Letters, Vol. 3, No. 1, 1959
- *14. Kellogg, P. J., "Electrons of the Van Allen Radiation," J. G. R., Vol. 65, No. 9, 1960
- *15. Lenchek, A. M. and Singer, S. F., "Geomagnetically Trapped Protons from Cosmic-Ray Albedo Neutrons," Journal of Geophysical Research, Vol. 67, No. 4, April 1962
16. Lenchek, A. M., "On the Anomalous Component of Low-Energy Geomagnetically Trapped Protons," J. G. R., Vol. 67, No. 1, 1962
17. Liemohn, H., "The Lifetime of Radiation Belt Protons with Energies Between 1 Kev and 1 Mev," J. G. R., Vol. 66, No. 10, 1961
- *18. McIlwain, C. E., "Coordinates for Mapping the Distribution of Magnetically Trapped Particles," J. G. R., Vol. 66, No. 11, 1961
19. Obayashi, T., "Physical State of Outer Atmosphere and the Origin of Radiation Belts," Proceedings of the First International Space Science Symposium, 1960
20. Parker, E., "Extension of the Solar Corona into Interplanetary Space," J. G. R., Vol. 64, No. 11, 1959
- *21. Ray, E. C., "On the Theory of Protons Trapped in the Earth's Magnetic Field," J. G. R., Vol. 65, No. 4, 1960

22. Singer, S. F. and Wentworth, R. C., "Cosmic Ray Measurements in the Vicinity of Planets and Some Applications," J. G. R., Vol. 64, No. 11, 1959
23. Singer, S. F., "Trapped Albedo Theory of the Radiation Belt," Physical Review Letters, Vol. 1, No. 5, 1958
24. Singer, S. F., "Radiation Belt and Trapped Cosmic Ray Albedo," Physical Review Letters, Vol. 1, No. 5, 1958
25. Singer, S. F., "Cause of the Minimum in the Earth's Radiation Belt," Physical Review Letters, Vol. 3, No. 4, 1959
- *26. Singer, S. F., "On the Nature and Origin of the Earth's Radiation Belts," Proceedings of the First International Space Science Symposium, 1960
- *27. Singer, S. F., "Latitude and Altitude Distribution of Geomagnetically Trapped Protons," Physical Review Letters, Vol. 5, No. 7, 1960
- *28. Spitzer, Jr., L., "Physics of Fully Ionized Gases," Interscience Publishers, New York, 1956
29. Wentzel, D. G., "Hydromagnetic Waves and the Trapped Radiation," J. G. R., Vol. 66, No. 2, 1961

III. OUTER RADIATION BELT (EXPERIMENT)

- *1. Anderson, K. A. and Enemark, D. C., "Balloon Observations of X-Rays in the Auroral Zone II," J. G. R., Vol. 65, No. 11, 1960
2. Arnoldy, R. L., "Electron Spectra and Fluxes in the Outer Zone," American Geophysical Union, Los Angeles, California, December 27-29, 1961
3. Bame, S. J., Conner, J. P., and Hill, H. H., "Protons in the Outer Van Allen Belt," American Geophysical Union, Los Angeles, California, December 27-29, 1961
- *4. Cladis, J. B., Chase, L. F., Imhof, W. L., and Knecht, D. J., "Energy Spectrum and Angular Distribution of Electrons Trapped in the Geomagnetic Field," J. G. R., Vol. 66, No. 8, 1961
5. Fan, C. Y., Meyer, P., and Simpson, J. A., "Dynamics and Structure of the Outer Radiation Belt," J. G. R., Vol. 66, No. 9, 1961
- *6. Fan, C. Y., Meyer, P., and Simpson, J. A., "Trapped and Cosmic Radiation Measurements from Explorer VI," Proceedings of the First International Space Science Symposium, 1960
- *7. Fan, C. Y., Meyer, P., and Simpson, J. A., "The Equatorial Pitch Angle Distributions of Electrons in the Outer Radiation Belt," Proceedings of the Second International Space Science Symposium, 1961
8. Farley, T. A. and Rosen, A., "Charged Particle Variations in the Outer Van Allen Zone During a Geomagnetic Storm," J. G. R., Vol. 65, No. 10, 1960
9. Forbush, S. E., Venkatesan, D., and McIlwain, C. E., "Intensity Variations in Outer Van Allen Radiation Belt," J. G. R., Vol. 66, No. 8, 1961

10. Gringauz, K. I., "Some Results of Experiments in Interplanetary Space by Means of Charged Particle Traps on Soviet Space Probes," Proceedings of the Second International Space Science Symposium, 1961
11. Hess, W. N., Killeen, J., Fan, C. Y., Meyer, P., and Simpson, J. A., "The Observed Outer Belt Electron Distribution and the Neutron Decay Hypothesis," J. G. R., Vol. 66, No. 8, 1961
12. Hoffman, R. A., 1. "Observations of the Van Allen Radiation Regions During August and September, 1959," 2. "The Capetown Anomaly and the Shape of the Outer Belt," J. G. R., Vol. 66, No. 12, 1961
13. Hoffman, R. A., Davis, L. R., and Williamson, J. M., "0.1 to 5 Mev Protons and 50 Kev Electrons at 12 Earth Radii During Sudden Commencement on September 30, 1961," American Geophysical Union, Forty-Third Annual Meeting, April 1962
14. Kurnosova, L. V., Logachev, V. I., Razorenov, L. A., and Fradkin, M. I., "Cosmic Ray Investigation By the Second Cosmic Rocket Landed on the Moon," Proceedings of the First International Space Science Symposium, 1960
15. McIlwain, C., "Evidence of High Fluxes of Electrons in the Inner Zone," American Geophysical Union, Los Angeles, California, December 27-29, 1961
16. McIlwain, C. E., "Direct Measurement of Protons and Electrons in Visible Auroral," Proceedings of the First International Space Science Symposium, 1960
17. O'Brien, B. J. and Ludwig, G. H., "Development of Multiple Radiation Zones on October 18, 1959," J. G. R., Vol. 65, No. 9, 1960
18. O'Brien, B. J., Van Allen, J. A., Roach, F. E., and Gartlein, C. W., "Correlation of an Auroral Arc and a Subvisible Monochromatic 6300 A Arc with Outer Zone Radiation on November 28, 1959," J. G. R., Vol. 65, No. 9, 1960
19. O'Brien, B. J., "Direct Observations of Dumping of Electrons at 1000 Kilometer Altitude and High Latitudes," J. G. R., Vol. 67, No. 4, 1962
- *20. O'Brien, B. J., Laughlin, C. D., Van Allen, J. A., and Frank, L. A., "Measurements of the Intensity and Spectrum of Electrons at 1000 Kilometer Altitude and High Latitudes," J. G. R., Vol. 67, No. 4, 1962
- *21. O'Brien, B. J., Van Allen, J. A., Laughlin, C. D., and Frank, L. A., "Absolute Electron Intensities in the Heart of the Earth's Outer Radiation Zone," J. G. R., Vol. 67, No. 1, 1962
22. O'Brien, B. J., "Absolute Electron Intensities and Energy Spectra in the Outer Radiation Zone," American Geophysical Union, Forty-Third Annual Meeting, April 1962
- *23. Rosen, A and Farley, T. A., "Characteristics of the Van Allen Radiation Zones as Measured by the Scintillation Counter on Explorer VI," J. G. R., Vol. 66, No. 7, 1961
- *24. Rosen, A., Farley, T. A., and Sonett, C. P., "Soft Radiation Measurements on Explorer VI Earth Satellite," Proceedings of the First International Space Science Symposium, 1960

25. Rosen, A., "High-Energy Electron-Intensity Distributions Along Geomagnetic Lines of Force Before and After a Magnetic Storm," American Geophysical Union, Forty-Third Annual Meeting, April 1962
26. Rosser, W. G. V., O'Brien, B. J., Van Allen, J. A., and Frank, L. A., "Electrons in the Earth's Outer Radiation Zone," American Geophysical Union, Forty-Third Annual Meeting, April 1962
27. Rothwell, P. and McIlwain, C. E., "Magnetic Storms and the Van Allen Radiation Belts," J. G. R., Vol. 65, No. 1, 1960
28. Stolov, H. L., "Bifurcation of the Outer Van Allen Belt and Related Auroral Phenomena," J. G. R., Vol. 67, No. 1, 1962
29. "Symposium on Scientific Effects of Artificially Introduced Radiations at High Altitudes," J. G. R., Vol. 64, No. 8, 1959
30. Van Allen, J. A. and Whelpley, W. H., "Radiation Observations with Satellite Injun I, September 28 - October 4, 1961," American Geophysical Union, Los Angeles, California, December 27-29, 1961
31. Van Allen, J. A. and Lin, W. C., "Outer Radiation Belt and Solar Proton Observations with Explorer VII during March - April, 1960," J. G. R., Vol. 65, No. 9, 1960
32. Van Allen, J. A., McIlwain, C. E., and Ludwig, G. H., "Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field," J. G. R., Vol. 64, No. 8, 1959
33. Venkatesan, D., Pizzella, G., and Forbush, S. E., "Time Variations in the Outer Radiation Zone, October 1959 through December 1960," American Geophysical Union, Forty-Third Annual Meeting, April 1962
34. Vernov, S. N., Chudakov, A. E., Vakulov, P. V., Logachev, Y. I., and Nikolayev, A. G., "Radiation Measurements During the Flight of the Second Soviet Space Rocket," Proceedings of the First International Space Science Symposium, 1960
35. Vernov, S. N., Chudakov, A. E., Vakulov, P. V., and Logachev, Y. I., "Study of Terrestrial Corpuscular Radiation and Cosmic Rays during the Flight of a Cosmic Rocket," Soviet Physics Doklady, 4, 1959
- *36. Vernov, S. N., "Cosmic Rays and Outer Space," American Rocket Society Journal, 3, 1961
37. Vernov, S. N., Chudakov, A. E., Vakulov, P. V., Logachev, Y. I., and Nikolayev, A. G., "Radiation Measurements During the Flight of the Second Cosmic Rocket," American Rocket Society Journal, 7, 1961
- *38. Walt, M., Chase, Jr., L. F., Cladis, J. B., Imhof, W. L., and Knecht, D. J., "Energy Spectra and Altitude Dependence of Electrons Trapped in the Earth's Magnetic Field," Proceedings of the First International Space Science Symposium, 1960

IV. OUTER RADIATION BELT (THEORY)

1. Akasofu, S. I. and Chapman, S., "The Ring Current, Geomagnetic Disturbance, and the Van Allen Radiation Belts," J. G. R., Vol. 66, No. 5, 1961

2. Akasofu, S. I. and Chapman, S., "New Theory of the Aurora Polaris," American Rocket Society Journal, 6, 1961
3. Alfvén, H., "Cosmical Electrodynamics," Clarendon Press, Oxford, 1950
4. Coleman, P. J., "The Effects of Betatron Accelerations Upon the Intensity and Energy Spectrum of Magnetically Trapped Particles," J. G. R., Vol. 66, No. 5, 1961
5. Cowling, T. G., "Magnetohydrodynamics," Interscience, New York, 1957
- *6. Crawford, J. A., "Fermi Acceleration of Electrons in the Outer Van Allen Belt," Physical Review Letters, Vol. 3, No. 7, 1959
7. Davis, Jr., L. and Chang, D. B., "On the Effect of Geomagnetic Fluctuations on Trapped Particles," J. G. R., Vol. 67, No. 6, 1962
8. Dessler, A. J., "Discussion of Paper by R. L. Arnoldy, R. A. Hoffman, and J. R. Winckler, Observations of the Van Allen Radiation Regions during August and September, 1959, Part I," J. G. R., Vol. 65, No. 10, 1960
9. Dessler, A. J. and Vestine, E. H., "Maximum Total Energy of the Van Allen Radiation Belt," J. G. R., Vol. 65, No. 3, 1960
10. Dessler, A. J. and Karplus, R., "Some Properties of the Van Allen Radiation," Physical Review Letters, Vol. 4, No. 6, 1960
11. Dessler, A. J. and Karplus, R., "Some Effects of Diamagnetic Ring Currents on Van Allen Radiation," J. G. R., Vol. 66, No. 8, 1961
12. Farley, T. A. and Sanders, N. L., "Pitch Angle Distributions and Mirror Point Densities in the Outer Radiation Zone," J. G. R., Vol. 67, No. 6, 1962
13. Hamlin, D. A., Karplus, R., Vik, R. C., and Watson, K. M., "Mirror and Azimuthal Drift Frequencies for Geomagnetically Trapped Particles," J. G. R., Vol. 66, No. 1, 1961
14. Helliwell, R. A. and Bell, T. F., "A New Mechanism for Accelerating Electrons in the Outer Ionosphere," J. G. R., Vol. 65, No. 6, 1960
15. Herlofson, N., "Diffusion of Particles in the Earth's Radiation Belts," Physical Review Letters, Vol. 5, No. 9, 1960
- *16. Hess, W. N. and Poirier, J. A., "Energy Spectrum of Electrons in the Outer Radiation Belt," J. G. R., Vol. 67, No. 5, 1962
17. Hess, W. N. and Killeen, J., "Spatial Distribution of Electrons from Neutron Decay in the Outer Radiation Belt," J. G. R., Vol. 66, No. 11, 1961
- *18. Hess, W. N., Canfield, E., and Lingenfelter, R. E., "Cosmic Ray Neutron Demography," J. G. R., Vol. 66, No. 3, 1961
19. Inoue, Y., "Physical Properties in the Outer Van Allen Belt and Their Relations to the Phenomena in the Exosphere," Proceedings of the First International Space Science Symposium, 1960
20. Kaufman, R., "Experimental Tests for the Acceleration of Trapped Particles," American Geophysical Union, Los Angeles, California, December 27-29, 1961

21. Krasovskii, V. I., "Some Problems of Auroral Physics," American Rocket Society Journal, 11, 1960
- *22. Lenchek, A. M., Singer, S. F., and Wentworth, R. C., "Geomagnetically Trapped Electrons from Cosmic Ray Albedo Neutrons," J. G. R., Vol. 66, No. 12, 1961
23. Lew, J. S., "Drift Rate in a Dipole Field," J. G. R., Vol. 66, No. 9, 1961
24. Malville, J. M., "The Effect of the Initial Phase of a Magnetic Storm Upon the Outer Van Allen Belt," J. G. R., Vol. 65, No. 9, 1960
- *25. Montgomery, D. J. X., "Cosmic Ray Physics," Princeton University Press, 1949
- *26. Northrop, T. G. and Teller, E., "Stability of the Adiabatic Motion of Charged Particles in the Earth's Field," Physical Review, 117, 1960
27. Parker, E. N., "Geomagnetic Fluctuations and the Form of the Outer Zone of the Van Allen Radiation Belt," J. G. R., Vol. 65, No. 10, 1960
28. Parker, E. N., "The Distribution of Trapped Particles in a Changing Magnetic Field," J. G. R., Vol. 66, No. 9, 1961
29. Parker, E. N., "Transresonant Electron Acceleration," J. G. R., Vol. 66, No. 9, 1961
30. Parker, E. N., "Effect of Hydromagnetic Waves in a Dipole Field on the Longitudinal Invariant," J. G. R., Vol. 66, No. 3, 1961
31. Pennington, R. H., "Equation of a Charged Particle Shell in a Perturbed Dipole Field," J. G. R., Vol. 66, No. 3, 1961
32. Rosenbluth, M. N. and Longmire, C. I., "Stability of Plasmas Confined by Magnetic Fields," Ann Phys. 1, 1957
33. Seward, F. and Hess, W. N., "Electron Loss Rate from the Outer Radiation Belt," American Geophysical Union, Forty-Third Annual Meeting, April 1962
34. Vestine, E. H., "Note on the Direction of High Auroral Arcs," J. G. R., Vol. 65, No. 10, 1960
35. Vestine, E. H. and Sibley, W. L., "The Geomagnetic Field in Space, Ring Currents, and Auroral Isochasms," J. G. R., Vol. 65, No. 7, 1960
36. Walt, M. and MacDonald, W. M., "Energy Spectrum of Electrons Trapped in the Geomagnetic Field," J. G. R., Vol. 66, No. 7, 1961
- *37. Welch, J. A. and Whitaker, W. A., "Theory of Geomagnetically Trapped Electrons from an Artificial Source," J. G. R., Vol. 64, 1959
38. Wentzel, D. G., "Hydromagnetic Waves and the Trapped Radiation," J. G. R., Vol. 67, No. 2, 1962

V. GENERAL PAPERS ON VAN ALLEN BELTS

- *1. Allen, R. I., Dessler, A. J., Perkins, J. F., and Price, H. C., "Shielding Problems in Manned Space Vehicles," NR-104, 1960
- *2. Barnes, T. G., Finkelman, E. M., and Barazotti, A. L., "Radiation Shielding of Lunar Spacecraft," Astronautical Sciences Review, January - March, 1961

- *3. Chamberlain, J. W., "Physics of the Aurora and Airglow," Academic Press, 1961
- 4. Eiwen, C. J. and Winer, D. E., "Criteria for Environmental Analysis of Weapon Systems," 1960 WADD - Technical Report 60-627
- *5. Jacobs, G. J., "Proceedings of Conference on Radiation Problems in Manned Space Flight, June 21, 1960, Washington, D. C.," NASA TND-588
- *6. Jaffe, L. D. and Rittenhouse, J. B., "Behavior of Materials in Space Environments," ARS Journal, March 1962
- *7. Johnson, F. S., "Satellite Environment Handbook," LMSD-895006, 1960
- 8. Lunar and Planetary Exploration Colloquia, Santa Monica, California, May 1962
- 9. McCoy, T. M., "Hyperenvironment Simulation," WADD Technical Report 60-785, Part I, 1961
- *10. National Academy of Sciences, IGY Bulletin No. 58, April 1962
- 11. Redmond, R. G., "Space Radiation and Its Effects on Materials," REIC Memorandum 21, 1961
- 12. Schaefer, H. G., "The Fifth Navy Science Symposium (1961)," ONR-9, Vol. 2
- 13. Störmer, C., Z. Astrophys., 1, p 237, 1930
- 14. Wallner, L. E. and Kaufman, H. R., "Radiation Shielding for Manned Space Flight," NASA-TND-681
- 15. Winter Meeting, American Nuclear Society, Chicago, Illinois, November 1961, Special Session of Shielding Division: Panel Discussion on Space Radiation and Its Shielding

APPENDIX B

DEFINITIONS AND SYMBOLS

Symbol	Definition
μ	Magnetic moment. $\mu = IA =$ (current in loop x area of the loop encircled by the current)
m	Mass of the particle given in grams
$V_{\perp}$	Component of particle velocity perpendicular to the field line
$V_{\parallel}$	Component of particle velocity parallel to the field line
V	Total velocity of the particle = $V_{\perp} + V_{\parallel}$
B	Magnetic field intensity
θ	Pitch angle, angle between the magnetic field line and the particle velocity vector
J	Second adiabatic invariant
ϕ	Magnetic flux inside a surface = $B \times A$, where A is the surface
L	Magnetic shell parameter
P_1	Proton peak intensity geographic location ($\sim 10 \times 10^3$ km)
E_2	Nearest electron intensity geographic location ($\sim 17 \times 10^3$ km)
E_3	Furthest electron intensity geographic location ($\sim 22 \times 10^3$ km)
M	Dipole magnetic moment
λ	Magnetic latitude
R_o	Equatorial radial distance