tude 8° west, latitude 50° south. A similar succession of phenomena followed.

The third and final detonation, of the same size, was at about 22 hr 10 min UT on September 6 at the same nominal altitude in the neighborhood of longitude 10° west, latitude 50° south. Again a series of remarkable geophysical phenomena was produced. And for the third time, Explorer IV faithfully observed the power of artificially-produced trapped radiation.

Throughout the testing period a series of firings of high altitude sounding rockets was carried out successfully, yielding valuable results in the lower fringes of the trapping region.

Explorer IV continued to observe the artificially-injected electrons from the Argus tests, making some 250 transits of the shell, until exhaustion of its batteries in the latter part of September. By that time the intensity had become barely observable above the background of natural radiation at the altitudes covered by the orbit of this satellite. It also appears likely that the deep space probe Pioneer III detected a small residuum of the Argus effect at very high altitudes on December 6, 1958, but the effect appears to have become unobservable before the flight of Pioneer IV on March 3, 1959.

An immense body of directly related observations has now been under study and interpretation by a large number of persons for about seven months and, as you will shortly hear, useful scientific results are being derived. It is also possible that other important contributions will arise as the many diverse geophysical observations being conducted by other countries participating in the International Geophysical Year are accumulated and analyzed.

THE ARGUS EXPERIMENT*

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With the advent of the satellite era the thoughts of the scientists have extended to outer space, since means have become available for measurements and experimentation in the region of the upper atmosphere. Two classes of experiments are possible with satellite-carried instruments:

(1) To measure natural phenomena.
(2) To create artificial effects under controlled conditions.

This class of experiments is most interesting as the initial conditions are known. Hence physical quantities can be measured under completely different conditions than those which the natural phenomena allow.

Just after the first Sputnik was launched I was attracted by outer space problems. The second class of experiments appeared very intriguing to me and I started thinking about possible experiments in outer space. The first experiment which occurred to me stemmed out of my main field of endeavor in the last five years, namely, the Astron thermonuclear device. In this device it is contemplated to establish a cylindrical layer of relativistic electrons between two mirror coils.

This electron layer then will establish in turn a magnetic bottle for plasma confinement, while the relativistic electrons will subsequently heat this plasma by Coulomb collisions up to fusion temperature. Then it occurred to me to extrapolate this idea of the electron layer to global dimensions, inasmuch as the earth's magnetic field provides a natural mirror effect. The trapping phenomenon was known theoretically for many years from the work of Stoermer, Alfven, and others, namely, that charged particles released at one point will spiral about a magnetic line being reflected at two points along this line. These points came to be known as mirror points. In addition to this motion the electrons would drift eastward due to the fact that the earth's field is decreasing as one moves away from the earth. Consequently, it was obvious that if sufficient electrons would be released at one point, these electrons would spread all around the earth creating a layer of rather small thickness but of global dimensions. Thus the first conclusion was that the electrons could be released from one point source; provided, however, that this source would be sufficiently large.

The question then arose whether or not these electrons will survive long enough to complete several circuits around the earth. The time for one circuit around the earth is approximately inversely proportional to the electron energy. The lifetime has been calculated. The conclusions from these calculations was that most of the losses are due to Coulomb scattering with air atoms. Since the density of the atmosphere decreases exponentially with altitude it turned out that most of the losses occur near the mirror points. The result of the scattering is that the mirror points move down toward denser atmosphere. The electrons are practically lost after the mirror points have moved downward by about one scale height. The lifetime is proportional to the air density at the mirror points and approximately to the square of the electron energy, and is proportional to the length of the magnetic line. The conclusion was that electrons of one to two mev energy injected at an altitude of a few hundred miles will survive several hours or more, depending on the air density at the mirror points. In more detail the results of these calculations were (see also Appendix 1):

The energy loss ($\dot{E}$) of the electrons by Coulomb scattering is equal to the energy loss ($\dot{E}_0$) corresponding to the air density at the mirror points divided by the length (ψ) of the magnetic line from the mirror point to the equatorial plane, measured in units of earth radii, times the square root of the ratio of the earth's radius (r_0) to the scale height (h). Namely

$$\dot{E} = \dot{E}_0/(\psi\sqrt{r_0/h}) \tag{1}$$

or

$$\dot{\gamma} = 3\cdot 10^{-8}\, N_0 Z/(\psi\sqrt{r_0/h}) \qquad \text{rest mass units/day} \tag{2}$$

From the energy loss we can compute the square of the scattering angle and thus the downward velocity of the mirror points.

$$\dot{r}/r_0 = -\frac{Z(Z+1)}{\gamma^2}\,\frac{10^{-8}\,N_0}{\psi}\sqrt{\frac{h}{r_0}} \qquad \text{days}^{-1} \tag{3}$$

where Z is the atomic number, N_0 the numerical density, r_0 the earth radius, and γ the electron energy in rest mass units.

Electrons in the few mev range are lost by scattering without appreciable energy loss. In this case the lifetime is

$$T = 1.7 \cdot 10^6 \frac{\psi\gamma^2}{N_0} \sqrt{\frac{h}{r_0}} \quad \text{days} \tag{4}$$

For the following parameters

$$(r_0/h)^{1/2} = 8 \qquad N_0 = 10^4$$
$$\psi = 1.5 \text{ (latitude } 45°) \qquad \gamma = 3$$
$$T = 2.86 \text{ days}$$

These results pointed toward a convenient source of a large quantity of electrons, namely, to an A-bomb. This source is so plentiful that even one megaton of fission would create an electron layer so dense as to constitute a radiation hazard in outer space. To illustrate this I cite the following example: one megaton of fission yields 10^{26} fissions, approximately. If we assume that 4 electrons per fission are above 1 mev energy and half will be trapped in the earth's field we derive the number of trapped electrons, namely, $2 \cdot 10^{26}$. Then let us assume that these will be spread in a volume in outer space equal to the earth's volume, or 10^{27} cm.^{3} The resulting electron density is 0.2 electron/cm.^{3} The flux against any surface exposed to the electrons is

$$N_e = n_e c/4 \tag{5}$$

or

$$N_e = 1.5 \cdot 10^9 \quad \text{electrons/cm}^2\text{, sec.}$$

A small part of the energy of the electrons is converted to bremsstrahlung. The efficiency of this conversion is proportional to the atomic number of the target material.

The radiation level inside a space vehicle is

$$R = 8Z\gamma(\gamma - 1)\, n_e \quad \text{roentgens/hour} \tag{6}$$

where Z and γ were defined previously. Assuming an atomic number $Z = 10$ and $\gamma = 3$, we observe that the radiation level is more than 100 roentgens/hour, which is a good fraction of the lethal dose. Consequently, it is obvious that any explosion of such magnitude can create a radiation hazard in outer space and any space experiments involving A-bomb explosions must be carefully designed to avoid creation of hazardous radiation.

Fortunately a much smaller yield, namely in the kiloton range, is sufficient to yield detectable quantities without creating any radiation hazard at all.

It is obvious that the scientific aspect of such experiments is extremely important. Consequently, as soon as I suggested this experiment about the end of October, 1957, the matter was discussed with interest within the Radiation Laboratory for several weeks. In January, 1958, I had completed preliminary calculations and a paper was prepared. The matter was further discussed with scientists from other laboratories. Finally, a group of scientists was appointed to evaluate the proposal, and it was recommended to proceed with a test employing a small yield A-bomb in the kiloton range. Further an altitude was selected such so that the effect would not last more than a few days. In the meantime the natural radiation belt was discovered by Dr. James Van Allen.

This discovery was partial proof that the trapping effect actually exists as postulated, so that about the end of April, 1958 it was decided to proceed with the Argus test. Argus was the code name given to the experiment. The most pertinent question then was the selection of the location of the tests. Since the magnetic axis of the earth is tilted and the center of the dipole is displaced toward the Pacific Ocean, it is obvious that the trace of the mirror points will have their closest distance from the surface of the earth over the South Atlantic Ocean. Hence a location in the South Atlantic was finally selected for the test.

The over-all responsibility for the preparation and conduct of the experiment was vested in the Advanced Research Projects Agency (A.R.P.A.), then just established. It required only four months from the time it was decided to proceed with the tests until the first bomb was exploded. This is a remarkable achievement in organization, and if we were to single out the one man as most responsible for this accomplishment it would be Dr. Herbert York, who was at that time Chief Scientist of the A.R.P.A. During this short time a task force including the rocket launching ship, Norton Sound, was organized, and special instrumentation on satellites was prepared by Dr. James Van Allen. Many other activities were coordinated with the help of dozens of scientists.

In addition to the trapping effect the creation of an artificial aurora was predicted. The nontrapped electrons would be guided along the magnetic lines of force (which pass through the burst point) toward the upper atmosphere, producing strong ionization along these magnetic lines. Hence in both points where these lines re-enter the atmosphere auroral luminescence was expected.

The persons responsible for organizing the observations of auroral phenomena and magnetic disturbances as well as some of the minitrack stations were Dr. Philip Newman (A.F.C.R.C.) and Dr. Allen Peterson (S.R.I.). Besides the satellite observations, some rocket launchings were scheduled for observations at the very beginning of the formation of the Argus shell. This responsibility was assumed by a group of scientists in the A.F.S.W.C.

The experiment was successful in all respects except that Explorer V was not placed in orbit. However, the one satellite available, Explorer IV, yielded most of the important information although valuable information resulted from other observations.

The bursts occurred on the 27th and 30th of August in the early morning hours and on the 6th of September shortly before midnight, Greenwich time. The locations were, respectively, 38°S, 12°W; 50°S, 8°W; and 50°S, 10°W, approximately.

A very interesting sequence of observations was obtained. The initial flash of the burst was followed by an auroral luminescence extending upward and downward along the magnetic line where the burst occurred. Simultaneously at the point where the same magnetic line returns to the earth's atmosphere (the so-called conjugate point) in the North Atlantic another auroral luminescence appeared in the night sky near the Azores Islands.

The instruments of Explorer IV recorded and reported to ground stations, around the earth, the electron density in the shell, as well as the position and its thickness. The satellite continued to penetrate the shell several times a day at various altitudes, so that the density as a function of altitude and time was measured. The apogee of the electrons was about an earth's radius out in space or 4000 miles approximately. Thus, for the first time the earth's magnetic field was being plotted experimentally. The conjugate points were a few hundred miles farther away than the theoretical calculations indicated. However, this is rather a small error considering that ring currents at high altitudes are not yet well known and that all the measurements of the earth's field were thus far taken at the earth's surface.

When the location in the South Atlantic was selected, the data on the natural radiation belt were rather meager. However, it turned out that the Argus shell was located at a region where the intensity of the natural radiation passes through a minimum. If the location were further south or north of the one selected, the Argus shell effects would have disappeared in the background much earlier. For the first time an experiment was conducted in outer space on a global scale where all the measured quantities were related to a known cause, namely, to the trapping in the earth's field of a known number of electrons of a known energy, injected at a known location at a known time.

The satellite measurements are described in detail by Dr. James Van Allen.[1] The general conclusion on electron lifetime is that the electrons died of natural death, namely, by scattering with the air molecules near the mirror points. No effect was observed which appeared to expedite or enhance the loss of the electrons.

Another important observation was that (within the limit of observational error) neither did the electron shell move at all across the magnetic lines nor did the electrons diffuse across these lines. This verifies the theory that there are two adiabatic invariants, namely, the magnetic moment and the action or the integral of the momentum along the magnetic lines. The first adiabatic invariant has been known for a long time. The second was postulated in 1953 by Marshall Rosenbluth. According to a theory by T. Northrup and E. Teller,[2] the particles follow a closed magnetic surface even if the field is not axially symmetric. A rigorous proof that these quantities are invariants in all orders has been provided by Dr. Martin Kruskal (Princeton University), the first about two years ago, the other recently. Also it was believed that invariance in time exists. This means that any change of the magnetic field in time in a period which is long in comparison with the period of one oscillation between mirror points will not affect permanently the position of the shell.

Since the changes in the earth's field occur in a matter of hours, very rarely in minutes, whereas the oscillation period is less than a second, one should expect no effect in the position of the shell. Actually these postulations have been verified. In connection with the position stability of the shell another conclusion can be drawn concerning hydromagnetic instabilities. According to hydromagnetic theory the relevant quantity in generating unstable motions is the ratio of the particles' energy density to the magnetic field energy density. In the case of the Argus shell this ratio was negligible; hence the trapped electrons could not create any instability. However, an ionized plasma either permanently existing there or temporarily trapped as a result of the sun's activity would create such motions characterized by unstable magnetic line interchange. In such a case the Argus shell would have followed the motion of the magnetic lines and be deformed and change location. Since no such motion has been observed this is a good indication that such instabilities are not occurring in the earth's field at least at the latitudes of the Argus shell or lower (toward the equator). This is a useful observation and I will elaborate later on some possible conclusions.

The first Argus experiment provided us with very important information. However, this is only a fraction of what is possible with experiments of this nature. A variety of experiments is possible as well as a variety of methods of injecting electrons into the geomagnetic field. We can classify the means of injection into three categories:

(*a*) Injection through atomic explosions as in the Argus experiment.
(*b*) Injection from a satellite carrying a payload of radioactive β-decay material.
(*c*) Injection from a satellite-borne electron accelerator.

Comparing the three categories, we observe that the first is the easiest, but the last affords much more controlled experiments since monoenergetic electrons can be injected in any desirable direction. However, experiments of the first category are already being conducted whereas a satellite-borne accelerator might require two years to be developed and launched. Consequently, one can plan a sequence of experiments over a number of years in such a way that the satellite-borne accelerator experiments will be scheduled two to three years hence. In such a sequence of experiments several important results of geophysical interest may be obtained. Some of these are:

(1) Complete mapping of the earth's magnetic field and defining the extent of the region of closed lines of the earth's field. According to existing theories this region ends at a distance from the earth, at the equatorial plane, where the magnetic pressure equals the gas pressure. Since this distance is many earth radii, the residual gas there is the solar corona consisting of hydrogen atoms in an ionized state. The equivalent gas pressure is half the mass density times the square of the orbital velocity of the earth. Due to this effect, according to these theories, the earth's magnetic field is swept away beyond this distance. A magnetic line passing through the equatorial plane at a distance of 10 radii returns to the earth at 70° north or south latitude. This is the latitude of the auroral zones. Hence, it is quite possible that lines originating in the polar regions beyond this latitude do not return to the earth but vanish in outer space intermixing with the sun's field or the interplanetary field. It is of extreme interest to determine the earth's field in this fringe region. It is quite probable that this region is very turbulent and that the region of the closed magnetic lines is variable during magnetic storms or other disturbances created by the interaction of plasma streams originating in the sun and the earth's magnetic field. By conducting well designed Argus experiments it is possible not only to monitor these changes but also to measure approximately the density of the solar corona near the earth. Further, it will be possible to clarify auroral phenomena and advance the theory of such phenomena.

(2) To shed light on the origin and lifetime of the natural radiation belts. The first indications are that the region of the outer belt is very turbulent. Hence we cannot exclude the possibility that particles which originated in the sun are responsible for the outer belt. A continuous monitoring of the density of artificially injected electrons in that region might shed light not only on the origin of the outer

radiation belt but on the origin and behavior of the auroral phenomena as well.

The lifetime of the radiation belts cannot be directly determined since the density is more or less constant under steady-state conditions. However, by injecting labeled electrons and measuring the lifetime we can determine the lifetime of the particles in the belt. Consequently, the required source strength will be derived. Thus it will be easier to explain the origin of the natural radiation belts. As a matter of fact, already one observation from the Argus experiment appears to be very useful and offers tentative conclusions on the origin of the inner belt. The Argus shell was located beyond the maximum of the inner belt. As I mentioned above, this shell exhibited remarkable stability and did not move at all during the few weeks when observations were possible. This indicates that no convection currents existed. Consequently, plasma cannot be transferred from the outside to the inner belt. However, since during the Argus experiment there did not occur any extremely violent solar disturbances, this conclusion must be considered as being only tentatively true at this time. Then, according to this tentative conclusion, the inner belt particles are born within this region. The only explanation therefore is that the inner belt particles are neutron decay products where the neutrons originate from cosmic ray interactions with the upper atmosphere. It seems that this radiation consists of protons and electrons, both products of neutron decay. During the initial discussion on Argus, I suggested the possibility of neutron decay and I postulated that electrons must already be trapped up there. However, I did not proceed with the quantitative calculations, which have been done later by Dr. Kellog.

In suggesting this effect I have in mind thermal neutrons. Professor Singer, however, proposed that high energy neutrons are responsible, yielding upon decay high energy protons. These theories of neutron decay origin seem to be verified by the stability of the Argus shell. However, final conclusions will be possible only after further experiments, especially, an Argus experiment during a period of intense solar activity.

The above result was not expected when the Argus experiment was first proposed since the natural radiation belt was not yet discovered. Continuation of the Argus experiments in any of the three categories may yield new information in addition to that anticipated. This has happened many times in physical experiments, particularly when a new class of experiments was conducted in a relatively new field.

In conclusion, I would like to say that there is now available a new tool for exploring the part of outer space encompassed by the geomagnetic field, and for clarifying the phenomena of interaction of the earth's magnetic field with various charged particles of natural or artificial origin.

APPENDIX

Calculation of the Lifetime of the Electrons.—The electron loss is due mainly to Coulomb scattering near the mirror points. A given increase ($\Delta\theta^2$) of the square of the scattering angle will cause an increase of the square of the parallel velocity by $\Delta W_{||}{}^2$, namely

$$\Delta W_{||}{}^2 = c^2 \Delta\theta^2 \tag{1}$$

From the invariance of the magnetic movement we have the relation

$$W_{||}^2 = c^2\left(1 - \frac{B}{B_m}\right) \tag{2}$$

where

$$\frac{B}{B_m} = \left(\frac{r_0}{r}\right)^3 \tag{3}$$

r_0, B_m are the radius and field at the mirror point, respectively. Equation (3) is valid at high latitudes where the lines are almost normal to the earth's surface.

Equations (2) and (3) yield

$$W = \dot{R} = c\left[1 - \left(\frac{r_0}{r}\right)^3\right]^{1/2} \tag{4}$$

From the above equations we derive

$$\Delta R = \frac{r_0}{3}\,\Delta\theta^2 \tag{5}$$

where ΔR the downward shift of the mirror points caused by an increase of the square of the scattering angle by $\Delta\theta^2$.

By differentiating equation (5) we obtain

$$\dot{R} = \frac{r_0}{3}\,\dot{\theta}^2 \tag{6}$$

The value of $\dot{\theta}^2$ is given by the known equation

$$\dot{\theta}^2 = -\frac{(Z+1)\dot{\gamma}}{\gamma^2} \tag{7}$$

where $\dot{\gamma}$ is the energy loss by scattering measured in rest mass units, (γ is the electron energy in rest mass units). The energy loss by scattering is given by the known Bethe formula. In the present case, after substituting the numerical values we obtain

$$\dot{\gamma} = -3.10^{-8}\,NZ \qquad \text{rmu/day} \tag{8}$$

The value of the air density is a function of position which in turn is a function of time. We shall express the air density as a function of time and integrate along a trajectory from the point of reflection to the equational plane.

By integrating equation (4) we obtain

$$\frac{ct}{r_0} = \int \frac{d(r/r_0)}{\left[1 - \left(\frac{r_0}{r}\right)^3\right]^{1/2}} \tag{9}$$

Since most of the losses occur at a distance $(r - r_0)$ from the mirror points much less than r_0 we can substitute, $x = r - r_0$, in equation (9), which upon integration yields

$$x = \frac{3}{4}\frac{c^2}{r_0}\,t^2 \tag{10}$$

The air density varies with the distance (x) from the mirror points as $N_0e^{-x/h}$ where N_0 is the air density and h the scale height at the mirror points, respecitvely. From the above equations we obtain

$$\dot{\gamma} = -3.10^{-8} N_0Z \exp\left(-\frac{3c^2}{4r_0h} t^2\right) \tag{11}$$

Integration of this equation from zero to infinity shall yield the energy loss along one trajectory from the reflection point to the equator. Then considering the oscillation time we derive the average energy loss, namely

$$< \dot{\gamma} > = \frac{3.10^{-8} N_0Z}{\psi} \sqrt{\frac{h}{r_0}} \quad \text{rmu/day} \tag{12}$$

where ($r_0\psi$) is the length of the magnetic line from the mirror point to the equator. The rate of change of the scattering angle ($\dot{\theta}^2$) is a function of $\dot{\gamma}$, just evaluated, and a function of γ^2. The value of γ is reduced from Coulomb scattering and Schwinger radiation loss. However, the contribution from Schwinger radiation is small for N_0 more than 10^5 atoms per cm^3. Equations (6), (7), and (12) yield

$$\dot{x} \equiv \dot{R} = -\frac{10^{-8} Z(Z+1)N_0}{\psi\gamma^2} r_0 \sqrt{\frac{h}{r_0}} \tag{13}$$

As the mirror points move downward the air density increases. Consequently at a distance x (downward) from the initial mirror point the downward velocity is

$$\dot{x} = -\frac{10^{-8} Z(Z+1)}{\psi\gamma^2} N_0e^{-x/h} r_0 \sqrt{\frac{h}{r_0}} \tag{14}$$

In the case of electrons of a few Mev energy, the loss of the electrons is due more to scattering than to energy loss, namely, the mirror points move downward one scale height without appreciable energy loss. In this case equation (14) yields upon integration

$$T = 1.7 \cdot 10^6 \frac{\psi\gamma^2}{N_0} \sqrt{\frac{h}{r_0}} \text{ days.} \tag{15}$$

* Work was performed under auspices of the U. S. Atomic Energy Commission.

[1] Van Allen, James A., Carl E. McIlwain, and George H. Ludwig, these PROCEEDINGS, **45**, 1152–1171 (1959).

[2] Northrop, T., and E. Teller, Univ. of Calif. Rad. Lab. Report, UCRL-5615 (to be published).

SATELLITE OBSERVATIONS OF ELECTRONS ARTIFICIALLY INJECTED INTO THE GEOMAGNETIC FIELD

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Following our discovery with Explorer I (Satellite 1958 Alpha) and with Explorer III (Satellite 1958 Gamma) that there were very great intensities of charged particles trapped in the geomagnetic field,[1] we undertook to make arrangements for a further satellite flight of equipment of greater discrimination and much greater