The ManMade Radiation Belts

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Introduction

Shortly after the high altitude nuclear bomb explosion last summer called Starfish, it became obvious that a band of trapped radiation had been produced. This was no surprise. There had been three artificial belts made previous to this one. In 1958 the U.S. had exploded three high altitude bombs in the South Atlantic. For some time before this, Nicholas Christofilos, a physicist at the Radiation Laboratory at Livermore, had worked on Project Sherwood - the attempt to control the power of an H bomb to make an industrial power station. To contain the intensely hot material used in Sherwood experiments no walls can be used. They would melt. Magnetic fields are used - shaped into "magnetic bottles" to contain the particles. Such a bottle as that used in Fig. 1 has been used successfully to contain hot electrons and protons for short times. The particles eventually leak out of the magnetic bottle, mostly through the ends, but they are contained for a time. Christofilos took this idea for a laboratory-size magnetic bottle and expanded it to earth size. He suggested that the earth's magnetic field should be able to contain and trap energetic particles and showed that a nuclear explosion would be a reasonable source of particles to populate the terrestrial bottle. This suggestion led to the Argus experiments.

The planning for Argus was well underway before the discovery by Van Allen of the natural radiation belt. In the Argus planning sessions it had been suggested that a natural belt might exist around the earth, which was of course borne out by the Explorer I and Explorer III satellites.

The Argus explosions were conducted specifically to study the injection of particles into the earth's magnetic field. After each of the three explosions, trapped particles were observed by Van Allen on the Explorer IV satellite, so that artificial belts were no novelty in 1962. But the Starfish belt was much more intense and more extended in space than the Argus belts, so it represented more of a problem.

What is there about a nuclear explosion that produces a radiation belt? The radiation belts, both artificial and natural, are merely collections of high energy protons and electrons. A nuclear explosion releases a large number of energetic particles. When a uranium nucleus fissions into two lighter nuclei the fission fragments that are formed are unstable. They become stable by emitting fast electrons. This β-decay process produces about 6 electrons per fission fragment. The electrons formed have energies going up to 7 or 8 Mev with an average energy of about 1 Mev. The first electron is given off in about 1 second, and after   seconds   percent of the electrons have been produced. The debris from a high altitude explosion expands at around 500 km/sec, so the electrons emitted by the fission fragments can appear some distance away from the explosion. Measurements on the energies of the new electrons at 1000 km altitude after the Starfish explosion show that most of them have come from β-decay of fission fragments.

A second possible source of particles for the artificial radiation belt is neutrons. Large numbers of neutrons are also given off by a nuclear explosion.

A fission bomb works by a neutron splitting a uranium nucleus - the fission process liberates several neutrons, some of which in turn produce more fissions, making a chain reaction. In this process many of the neutrons produced leak out of the bomb. About 10^{24} neutrons are released by a one kiloton explosion. The neutron is radioactive. When bound up in an atomic nucleus it is stable, but by itself it decays with a half life of about 10 minutes into a proton, an electron, and a neutrino. Fission neutrons have energies of about 1 Mev and a velocity of about 10^9 cm/sec. It will take them about 5 seconds to travel 50,000 km to get out of the region of space where the radiation belts are. In this time about one percent of the neutrons released by the explosion will decay to form electrons and protons. The protons will have energies of about 1 Mev and fluxes of 10^4 particles per square cm per second. In general, these protons are not of interest, because they will not penetrate any appreciable thickness of matter, and therefore don't add to the radiation problems. The electrons made by neutron decay have energies up to .8 Mev, but they are considerably more penetrating then protons. These electrons do contribute to the artificial belt, but they do not appear to represent an important fraction of the source. Fission fragment decay appears to be the major electron source.

Particle Motion

In order to understand what happens to the electrons introduced into the field by the explosion we have to know how a particle moves in a magnetic field. Fig. 2 shows the motion. The motion can be broken down into three components, (1) gyration around a field line, (2) bouncing back and forth along a field line, and (3) drifting in longitude around the earth.

The electrons are made to move in a circle by the magnetic field, just as particles do in a cyclotron. The electrons gyrate around a field line in about one millionth of a second. They bounce back and forth along a field line about once a second. What causes the bouncing motion? The process is moderately similar to the operation of a corner reflector in radar. The radar waves enter the reflector, bounce several times, and return in the direction they came from. In the magnetic mirror, the particles moving into a region of increasing magnetic field, where the field lines are converging, feel a force that turns them around and make them move out of the converging field. This reflection process is caused by a magnetic force similar to the force that makes a particle move in a circle in a cyclotron (see Fig. 3). A particle moving with velocity V (into the paper) moves in the circle shown due to the magnetic field component $B_{\parallel}$. But in the converging field shown, the field component $B_{\perp}$ acts on the particle to produce a force perpendicular to both V and $B_{\perp}$

and directed so that it forces the particle out of the converging magnetic field. In a Sherwood machine (Fig. 1) the particles move toward a converging field at one end, are reflected, move to the other end of the machine and are reflected again. Because of this, it is called a magnetic mirror machine. The point of reflection is called the mirror point. The particle oscillates between its mirror points much as a pendulum oscillates back and forth, acted on by the force of gravity. The earth's magnetic field is a similar magnetic morror machine, bent in a crescent. Charged particles injected into the earth's field will bounce back and forth between two mirror points and stay trapped for a long time.

Besides gyrating and bouncing, the particles drift in longitude around the earth. The time it takes for one revolution depends upon the energy of the particle, but is about an hour for a typical electron. A reason for the drifting motion can be seen in Fig. 3. At the high altitude side of the particles' gyration the magnetic field is weaker and therefore the radius of curvature larger. This makes the particle drift sideways. Electrons drift east due to this effect and protons drift west. Particles with different velocities will drift at different rates.

The family of magnetic field lines on which a particle drifts around the earth is labeled by a value of L. For instance, the family of lines that has an average equatorial distance from the center of the earth of two earth radii has L=2. They intersect the earth's surface at 45° magnetic latitude.

From a knowledge of the motion of particles, we can tell what will happen to particles put into the field. A pulse of new particles, as from a bomb, will, in a few seconds, distribute themselves along a field line and in a few hours will drift around the earth several times and disperse in longitude because of their different drift rates. This will form a blanket of particles surrounding the earth. If the source of particles is rather limited in extent, then the blanket will be thin. This was the actual situation in the Argus experiment, where the blanket shown in Fig. 4 was only about 100 km thick at low altitudes and had L = 2. For Starfish the blanket was quite thick.

Early History of the Starfish Belt

Now that we have a feeling what ought to happen to the particles, let us see what the observations after Starfish indicated.

Within a matter of seconds after the explosion, aurorae were seen in Samoa. These aurorae were caused by electrons from the explosion that leaked out the holes in the earth's magnetic mirror and entered the atmosphere. The electrons collided with air atoms and excited them to emit light. Aurorae were also seen at the times of the Argus explosions. Rockets have been flown into natural aurorae and energetic electrons found, so this process of electrons making auroræ is well established.

Ground-based equipment in Alaska detected increased ionization in the ionosphere a few seconds after the explosion. This was very likely due to the electrons from the explosion leaking out the end of the magnetic mirror into the atmosphere the same way as those causing the aurorae did.

Ionospheric effects and the aurorae show that many electrons are lost promptly, but many remain trapped too. About 10 minutes after the explosion the National Bureau of Standards Radio Observatory in Peru, shown in Fig. 5, observed radio noise from the electron belt as it drifted eastward into view of their very elaborate antenna. This radio noise is called synchrotron radiation because it was first identified emitted by electrons in a synchrotron accelerator. Charged particles moving in a circle, as they do in a magnetic field, emit electromagnetic radiation. This process is an expected result of classical electromagnetic theory. A major worry about the Bohr atom when it was first introduced was that the electron moving in orbits around the nucleus should radiate energy away as electromagnetic radiation and therefore the electrons would spiral into the nucleus in a short time. The electrons in an atom do not continuously emit synchrotron radiation, but other places in nature, as for example, an electron in a synchrotron, do emit this electromagnetic radiation. In a synchrotron the radiation is of high enough frequency to appear as light. The light and radio noise from the Crab Nebula are both thought to be synchrotron radiation. The electromagnetic radiation from the electrons in the earth's field appears as radio noise of frequencies up to a hundred magacycles and higher. The radiation is strongly polarized, and is emitted in a very narrow cone along the instananeous direction of motion of the electron. This means that the radiation can be observed near the magnetic equator easily, but at mid-latitudes it will be difficult to observe, because the electrons do not move in the proper direction to transmit radiation in this direction. After Starfish, only radio observatories within 25° of the equator observed synchrotron radiation. The first signal in Peru was six minutes after the explosion, but at Wake Island it took 25 minutes for the signal to reach maximum. This showed that the electrons were indeed drifting eastward as predicted. After an hour or so, the electrons were sufficiently dispersed in longitude that a steady signal was received at the several stations. Near the equator this signal was about twice the pre-shot background noise. This signal died away with a time constant of about 20 days and became equal to the preshot background in about onemonth. Before the Starfish explosion, no synchrotron radiation was observed from the natural belt. The amount emitted was so small that it was hidden in the noise.

Satellite Data

On July 10 there were four satellites in orbit that had electron detectors on board and which gave useful information on the newly trapped particles.

	apogee	perigee	inclination	detectors
ARIEL	1209 km	393 km	54°	shielded GM counter $E_e > 4.7$ Mev
INJUN	1010 km	890 km	67°	shielded GM counter, counting several Mev electrons by Bremsstrahlung
TELSTAR	5630 km	955 km	44.7°	4 channel solid state detector $E_e > .2$ Mev
TRAAC	1110 km	951 km	32.4°	shielded GM counter $E_e > 1.6$ Mev

The Injun satellite had been in orbit a long time, and so it provided a very good before-after comparison of the radiation belt. The TRAAC detector also showed a good comparison this way, as did Ariel. Unfortunately, the Telstar satellite was launched the day <u>after</u> Starfish, so it could not give a before-after comparison. This is quite unfortunate, because the Telstar satellite goes to high altitudes and maps out regions of space that are unavailable to the other satellites.

The joint US-UK satellite Ariel showed that high energy electrons from the bomb appeared very shortly after the explosion at high latitudes - up to L = 5 or more. Ariel went out of operation a week after Starfish, but during this time the flux of energetic electrons stayed high up to L = 5.

The TRAAC detectors followed the decay of low altitude Starfish electrons until it also went out of operation. TRAAC also located a puddle of fission debris sitting on top of the atmosphere in the Pacific, continuously emitting electrons into the belt. These new electrons from the debris puddle will have short lives, because they are emitted at low altitudes, and therefore have low mirror points and encounter a fairly dense atmosphere.

The Injun counters mapped out the new belt up to 1000 km and produced the first flux contour picture of the Starfish electrons. Injun has also watched the decay of these electrons for several months.

The Telstar satellite produced all of the information above 1000 km for the first three months after Starfish. The rapid decay of the electrons above L = 1.7 was observed only by this satellite. The Telstar data was used to construct several flux maps at different times after Starfish.

By comparing the measurements of the several different detectors having different energy responses, the energy spectrum of the new particles was determined. At about 1000 km the spectrum closely resembled a fission energy spectrum, thus identifying the decay of fission fragments as the major particle source.

The Telstar detectors alone cannot clearly tell that the electrons have a fission spectrum - they measure too low energies to do this. Above 1000 km where only Telstar data was available the assumption was made at that time that the electrons had a fission energy spectrum also. (We now know this to be incorrect).

Understanding the Injun and Telstar Contours

The experimental data from Injun and Telstar for a short period after Starfish were organized and plotted, and are shown in Fig. 6. The region of highest flux for the red Injun data is about 10^9 electrons/cm^2/sec and for the blue Telstar data the highest value is also about 10^9 electrons/cm^2/sec. The outer edge of both sets of contours shown is at a flux of 10^7 electrons/cm^2/sec. These contours are only approximate and involve some extrapolations in both cases. Also they are not for the same time (Injun is plus 10 hours and Telstar is plus 5 days) but they still are fairly accurate and can be compared reasonably. It is obvious the Injun contours are much more compressed than the Telstar contours. The total number of particles found by integrating inside the Injun contours is about 10^{25} electrons and inside the Telstar contours is about 10^{26} electrons. These differences have caused some problems in the past, but they are now starting to be understood.

To understand the difference in the contours one must understand the nature of the data in Fig. 6 . The count rates of the detectors involved have been multiplied by efficiency factors to convert the count rates into fluxes of fission electrons. These efficiency factors have been calculated by assuming that the energy spectrum of the electrons present was an equilibrium fission energy spectrum, as in Fig. 6 . The experimental data from the different satellites indicated this was essentially correct at 1000 km, but at high altitudes it was only a guess. We are now quite certain that at high altitudes there were many more low energy electrons than are shown in Fig. 6 ; that is, the energy spectrum was "softer" there. Because the Injun detector would not count these low energy electrons efficiently, the Injun contours close at low altitudes, but the Telstar detector was a low energy electron detector so it counted these soft ~~electrons at high altitudes well, and therefore~~ the Telstar contours extend to higher altitudes. Most people are now quite sure that these low energy electrons at high altitudes resulted from the Starfish explosion, but whether they are fission electrons with the energy changed or electrons from some other source is not certain now, and may never be. There do exist processes that will tend to make the electrons far removed from the explosion site have lower energies. Electrons emitted by fission fragments some time after the fission event in general have lower energies than those emitted early. Also, the electrons may be slowed down by interactions with the magnetic field after they are emitted by fission fragments. No measurements were made that enable us to decide if these processes were important or not, so we cannot answer the question about the origin of the low energy electrons at high altitudes. There are still some people who are not sure whether the low energy electrons seen at high altitudes by Telstar are from the Starfish explosion, or if they are natural and were there beforehand.

The Natural Belt

In order to put theStarfish radiation belt in context, we should compare it with the natural radiation belt. The fluxes of natural protons of $E > 30$ Mev is shown in Fig. (a). These high energy protons are very penetrating, but there are not too many of them, so they are not too bothersome from the standpoint of radiation damage. In Fig. (b) is shown the flux of low energy protons of $.1 < E < 5$ Mev. There is a large flux of these particles, but they will not go through 10 mils of glass so they also are not much of a bother. Protons of $E \sim 10$ Mev are present in the natural belt in substantial numbers, and they are penetrating enough to produce damage to thinly shielded solar cells. In order to eliminate this problem, cover plates of about 1/32" of glass are commonly used on solar cells. Test cells with only a few mils of glass covers deteriorate rapidly in space.

The flux of natural electrons of $E > 40$ Kev is shown in Fig. (c). This particle population is not too well known, especially in the inner radiation zone at a few thousand kilometers altitude. It might be wrong by a factor of five or more in some places. Also, considerable time variations occur in this population. Fig. (d) shows the natural electron flux for $E > 1.5$ Mev. This group fluctuates up and down in time, sometimes by three orders of magnitude, but it rarely gets above 10^5 electrons/cm^2/sec. There are few if any electrons of $E > 5$ Mev in the natural belt.

This quick survey of the natural belt gives something to compare with the artificial belts. From Starfish the proton population is negligable compared to the natural proton population, but the Starfish electron population is considerably larger, and also of higher energy than the natural electrons.

There is another feature of the Starfish explosion that we should consider. What reaction did it have on the natural belt? Some European scientists predicted before the explosion that the natural radiation belt would be seriously damaged - that many particles would be shaken out of it. Most of the physicists in the U.S. who worked on this subject did not believe that any important changes would take place on the natural belt particles, and that the major change would be the introduction of new electrons in the earth's field. Several measurements were made on the protons before and after Starfish and the USSR explosions. The only measurable change so far reported was a modest-sized one at low altitude. Clearly no large changes have occurred on the natural high energy protons. We cannot tell about changes in the natural electrons, because they are masked by the artificial belt electrons. Considering the problem theoretically, it is very hard to see how Starfish could shake out more than a few percent at the most of the natural belt particles and as far as we know, it did not.

Radiation Damage

The energetic trapped particles can cause damage to various sensitive space systems (including man). It did not take long for damages to show up after Starfish. The Ariel satellite stopped transmitting data after about oneweek, and the TRAAC and Transit 4B satellites stopped in about one month. The solar cells on these satellites were progressively deteriorating due to the artificial electrons from Starfish. The output voltage of a solar cell goes down as the radiation exposure goes up, as shown in Fig. 1. A normally-designed satellite power supply will malfunction if the solar cell output drops to about 80 percent of its designed value. From Fig. 15 we see this will take about 10^{13} electrons/cm^2 for for the P-on-N type solar cells used on Ariel. Ariel stays in the high flux region of 10^9 electrons/cm^2/sec about 5 percent of the time so it encounters roughly 2×10^{12} electrons/cm^2/day on the front of its solar cells, so a week is about the right time for the power supply to last before going into undervoltage. The output from the solar cells on TRAAC and Transit 4B was monitored and the time history is shown in Fig. 9 . The initial slow decrease is due to the natural trapped particles, and the sudden change on July 9 is clearly due to the trapped electrons from Starfish. Telstar has a different and more radiation-resistant N-on-P type solar cells, and it lived a long time in the artificial radiation belt. Injun also lasted a long time after Starfish, because its power supply was designed so that it could stand a larger percentage degradation, and therefore more radiation. Satellites can clearly be designed to have long lives in the Starfish belt, or even more intense belts, but Ariel, TRAAC and Transit 4B were not expected to encounter these radiation levels, so they were not designed for it.

Shielding can be used to reduce the radiation dosage. For a fission energy spectrum, 1 gm/cm^2 of shielding material will reduce the dose about a factor of 10, 2 gms/cm^2 a factor of 100, and 3 gms/cm^2 a factor of 1000, But it is quite difficult to reduce the radiation by more than a factor of 5000 because of the X-rays produced by the electrons hitting the shielding. These X-rays are very hard to absorb out.

Attention was given to the problem of manned flight shortly after Starfish. The flux map for one week after

Starfish was used to calculate that about 1 R radiation dose would be received by an astronaut on a six-orbit mission at that time. By the time the MA 8 flight took place, decay of the trapped particles had reduced the expected dose considerably, and the dose Schirra received was well under 1 R. This is less than is received in some chest X-rays and is not a problem.

But consider the problem of attempting a manned flight at about 1000 miles altitude near the equator. In this region the electron flux is about 10^9 electrons/cm^2/sec. About 3×10^7 electrons/cm^2 gives 1 R dose. The dose inside a space capsule can be reduced by a factor of about 5,000 by using a shield thickness of 4 gms/cm^2. In one hour the dose inside the capsule for this orbit would be about

$$\frac{10^9 \times 3600 \text{ sec}}{3 \times 10^7 \times 5000} = 24 \text{ R}$$

Considering that a lethal dose is about 500 R, this means that manned flight in the heart of the Starfish belt must be quite limited in time. The Apollo flights to the moon will spend less than one hour in the high flux region of the belt, so they should be all right.

More Satellites and More Explosions

Even though we were relatively well prepared to make measurements on the Starfish radiation belt, and the information on it is reasonably complete, it was decided after Starfish to put up another satellite to improve the coverage and to make more definitive measurements on the energy spectrum of the electrons. The Explorer XV satellite was launched on October 27, 1962 with instruments on board to study protons and electrons of various energies. It was put in a low inclination orbit of $i = 19^o$, and had an apogee of 17,600 kilometers and a perigee of 315 kilometers. A DOD satellite called 1962βK was up in this period also, with several energetic particle detectors on it. This satellite had $i = 71^o$ and an apogee of 3000 nautical miles and perigee of 115 nautical miles. These two orbits are nicely complimentary and give good total coverage.

On October 22, 1962, the Soviets carried out the first of three high altitude nuclear explosions. The detectors in Telstar recorded this fact and watched the electrons decay quite rapidly, as had the high altitude Starfish electrons. Then, on October 28, only a few hours after Explorer XV had been launched, the Soviets conducted their second high altitude test. The results of this were very well documented. The Canadian satellite Alouette and Explorer XV and 1962βK studied this event. Fig. 10 shows the distribution in space of the electrons from the Soviet October 28 explosion in red, and also what was left of the Starfish electrons which had partly decayed away, at that time, in green. Various measurements showed that the electrons at the inner edge (presumably near the explosion site) of the new Soviet artificial belt had essentially a fission energy spectrum.

But at the outer edge the spectrum was softer - that is, there were more low energy electrons here. We have previously noted that a similar situation existed for the Starfish electrons. The October 28 electrons decayed with a mean life of about one week. Then on November 1, a third Soviet explosion produced another artificial radiation belt. This belt was of more limited extent, and fit in roughly in the gap on Fig. between the October 28 and Starfish electrons. There are no USSR measurements that have been reported on any of the artificial radiation belts. It is not known whether the Soviets had any satellites active and making measurements on their explosions. U.S. measurements on the artificial belt are continuing. It will be interesting to see what effects large magnetic storms will have on the artificial belt particles.

Decay of the Electrons

The high altitude nuclear explosions of this past year have provided a unique opportunity for understanding the lifetimes of electrons in the radiation belt. These explosions have produced large transient populations of trapped particles. By watching the behavior of these transients, we can get direct information about lifetimes of trapped particles.

Before the advent of these explosions the only methods of estimating electron lifetimes were indirect. In dealing with a steady state situation where the particle population is moderately constant with time, the only way to measure the lifetime, τ, of a trapped particle is by measuring either I, the inflow, or O, the outflow, of particles from the radiation belt and to use the "leaking bucket" equation

$$I = O = \frac{Q}{\tau}$$

or some similar procedure. Here Q is the total number of particles trapped in the volume of the belt association with the inflow, I, or outflow, O. In the past, the values obtained this way have involved estimates of the outflow, O, down into the atmosphere and have produced widely differing values of τ. We now have direct measurements of τ from the artificial belts which eliminate the necessity of using this indirect method, which is suspect anyway.

For low altitudes below L = 1.7, the decay of the electrons introduced by the Starfish explosion is quite slow and appears to be controlled by the atmosphere. Coulomb scattering of the electrons by the atmospheric atoms will change the direction of motion of the electrons, and therefore change the pitch angle, α (the angle between the magnetic field B and v, the electron's velocity). The change in pitch angle will result in changing the mirror point altitude. A series of coulomb scatters will move the mirror point of a particle up and down a field line, but out of this process a net loss of particles into the atmosphere will occur. This loss can be understood physically at low altitudes. If a scatter occurs very near a particle's mirror point, it can only lower the mirror point. At, and only at, the mirror point the particle's motion is perpendicular to the field line, so any scattering at this point, either up or down, which makes the motion not perpendicular to the field line can only lower the mirror point.

The effect of repeated coulomb collisions can be calculated by using a Fokker-Plank equation. This describes how a distribution of particles on a field line changes with time as the result of coulomb collisions.

As would be expected, the first particles to be lost are the ones mirroring at high B (or low altitude). Gradually the decay slows down and the spatial distribution eventually reaches an equilibrium shape. For the equilibrium situation, scattering down the line is nearly balanced by scattering up the line, so the decay proceeds slowly, being dominated by the scattering rate at theequator. The decay of the Starfish electrons has been measured over a period of 4000 hours by Injun and by Alouette. The observed mean life of the electrons at about L = 1.3 is about a year. The characteristics of the experimentally-observed decay agree with that which is expected from atmospheric decay.

During the process of atmospheric scattering, the electron energy spectrum changes. The lower energy electrons are more easily scattered and therefore lost first. Because of this, the fission energy spectrum hardens with time until an equilibrium spectrum is developed which has a peak at about 2 Mev.

The time history of the electrons for large L values after Starfish was quite different than for $L<1.7$. The solid state detector on Telstar counting electrons of $E\sim .5$ Mev showed very clearly the time decay of a transient particle population down to something resembling a steady state population in a period of about three months. So even though Telstar did not observe the particle populations before the Starfish event, one has good evidence from its record that a large transient population was produced out past $L = 2.5$ at about the time of Starfish.

At $L = 2.5$ the electron mean life is only a few days. This is very different from the particle lifetime of a year or more at $L = 1.4$. For $L>1.7$ the decay rates gets markedly shorter than values expected from atmospheric decay.

The instruments on the Explorer XV satellite launched on October 27 observed the October 28 and November 1 USSR explosions. The time histories of these events show a quite similar decay to the Telstar decay curves after Starfish. There is an initial redistribution of the flux along a field line followed by a decay with rather similar τ values to those seen by Telstar. It seems that this rapid decay for $L > 1.7$ is due to a usual condition in the magnetosphere and does not depend upon solar storms or other occasional events, although such events may also be important.

There is no good explanation of why the electron lifetimes are so short for $L>1.7$. The process responsible for this seems to have a quite sudden onset at $L = 1.7$, and by $L = 2.2$ the electron lifetime has been decreased roughly three orders of magnitude from that expected from atmospheric decay. The best candidate for this loss process is magnetic scattering. Waves in the magnetic field can scatter the electrons similar to coulomb scattering, but this is not a well understood subject. There is no quantitative explanation for the short lifetime yet.

Doing Physics with Nuclear Explosions

By studying the time decay of the Starfish electrons we have learned a considerable amount about the natural radiation belt. We know that electrons in the inner zone of the natural Van Allen belt have long lifetimes and those in the outer zone have short lifetimes. This information would have been very difficult, if not impossible to obtain, by observing only the steady state natural radiation belt. This is a very important contribution to our understanding of the radiation belts.

The idea of doing controlled experiments in space physics is not new - sodium clouds released by rockets study upper atmosphere winds, and water released from the Saturn rocket may help understand some ionospheric processes. But the idea of doing controlled energetic-particle experiments in space is rather new. Christofilos once suggested using a small particle accelerator in space to inject energetic particles, but this would be heavy and quite inefficient, and does not seem reasonable.

There are many areas of space physics that could benefit from controlled energetic-particle experiments. Artificial aurorae are made by nuclear explosions. We know natural aurorae result from energetic particle bombardment of the upper atmosphere, but we don't know much about the details of the process. Auroral simulation would be a valuable experiment. Ionospheric heating by particle bombardment and resultant changes in the composition of the ionosphere could be investigated this way.

We could help map the earth's magnetic field with charged particles. The Argus charged-particle blanket was studied by the Explorer IV satellite, and provided the best current experimental information on magnetic field shells. It would be very useful if we could determine rather exactly where the two ends of a few field lines are at the surface of the earth. There are many processes which should be observable at both of these conjugate points at the same time - ionospheric and magnetic disturbances, VLF emissions and aurorae, to name a few. It would be very interesting to study these simultaneously, but to do this we need to know where the conjugate points are, accurately. We could locate a pair of conjugate points quiteaccurately by a controlled emission of energetic particles at high altitude and subsequent ground observations.

It would be also interesting to see how a magnetic storm would disturb a thin blanket of particles at high altitudes.

This would help us understand the outer zone of the natural Van Allen belt.

The Future

There are many experiments we would like to do with controlled energetic-particle experiments, but we would like also not to lose any more satellites to radiation damage. There are also, of course, serious political problems with conducting high altitude nuclear explosions; but from a strictly scientific viewpoint, such a program would be quite worthwhile. If an explosion were designed with a major objective of getting geophysical data of importance to science, we should be able to make appropriate measurements without serious damage to anything. For most experiments, small explosions at high altitudes would suffice, so that the artificial belts could be limited in spatial extent and would decay rapidly. With international cooperation in the safety and measurements programs associated with these explosions, the political problems should be minimized.

But if more programs are carried out using large high altitude explosions, trouble could result. It is possible to make an artificial radiation belt much more intense than the Starfish belt. An increase of more than a factor of 1000 is possible over the Starfish fluxes. This could make large regions of space forbidden for manned flight for long times, and would severely limit unmanned satellites as well.

We must avoid such a circumstance, but we should not "throw the baby out with the wash." There are useful experiments that can only be carried out with small high altitude nuclear explosions. If such explosions are carried out properly, they would not produce any hazardous conditions, and could be very valuable scientifically.

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Figure Captions

1. A magnetic bottle for containing charged particles.

2. Motion of a charged particle in the earth's magnetic field showing (a) gyration around the field line, (b) bouncing back and forth along the field line, and (c) drifting longitude around the earth. Electrons drift east and protons drift west.

3. Particle drift in longitude. The variation of field drift with position causes a variation of radius of gyration with position, which results in a sideways drift.

4. The blanket of drift electrons made by the Argus explosion.

5. The radio observatory of the National Bureau of Standards at Jicamarca, Peru. This picture shows the antenna array.

6. A comparison of the flux contours shortly after the Starfish explosion as measured by Injun and Telstar. The maximum fluxes for both Injun and Telstar are about 10^9 and the minimum flux shown in the figure is 10^7.

7. Particle populations in the natural Van Allen radiation belt, (a) high energy protons, (b) low energy protons, (c) low energy electrons, (d) high energy electrons.

8. Solar cell degredation from electrons bombardment as measured at Bell Labs for various type solar cells.

9. Solar cell output for TRAAC and Transit IV B, measured by Applied Physics Laboratory before and after the Starfish explosion.

10. The artificial electron flux in space on October 28, 1962 showing the Starfish population of flux range 10^7 through 10^9 electrons/cm^2/sec and the electrons from the U.S.S.R. explosion of October 28 flux range 10^7 through 10^8 electrons/cm^2/sec.

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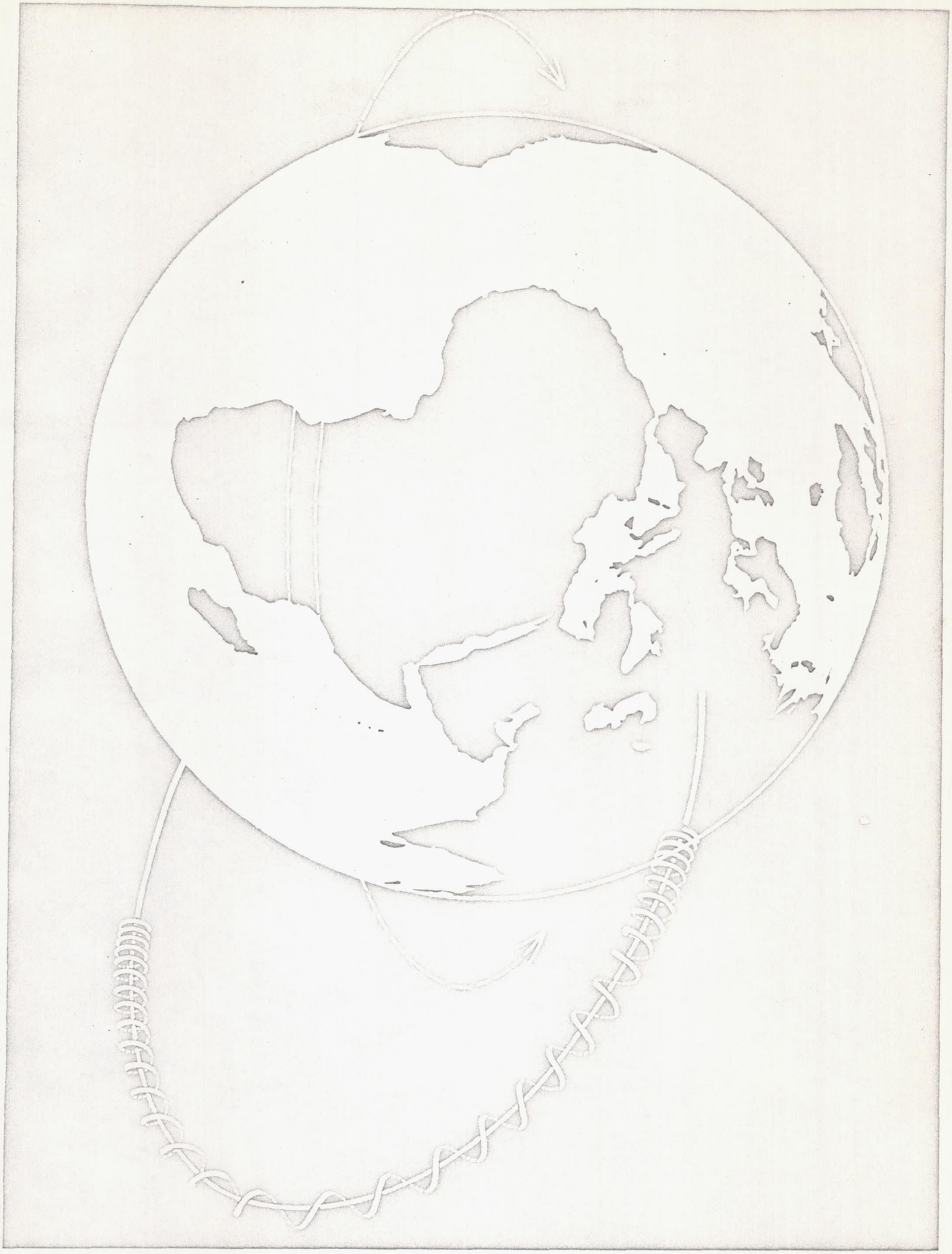
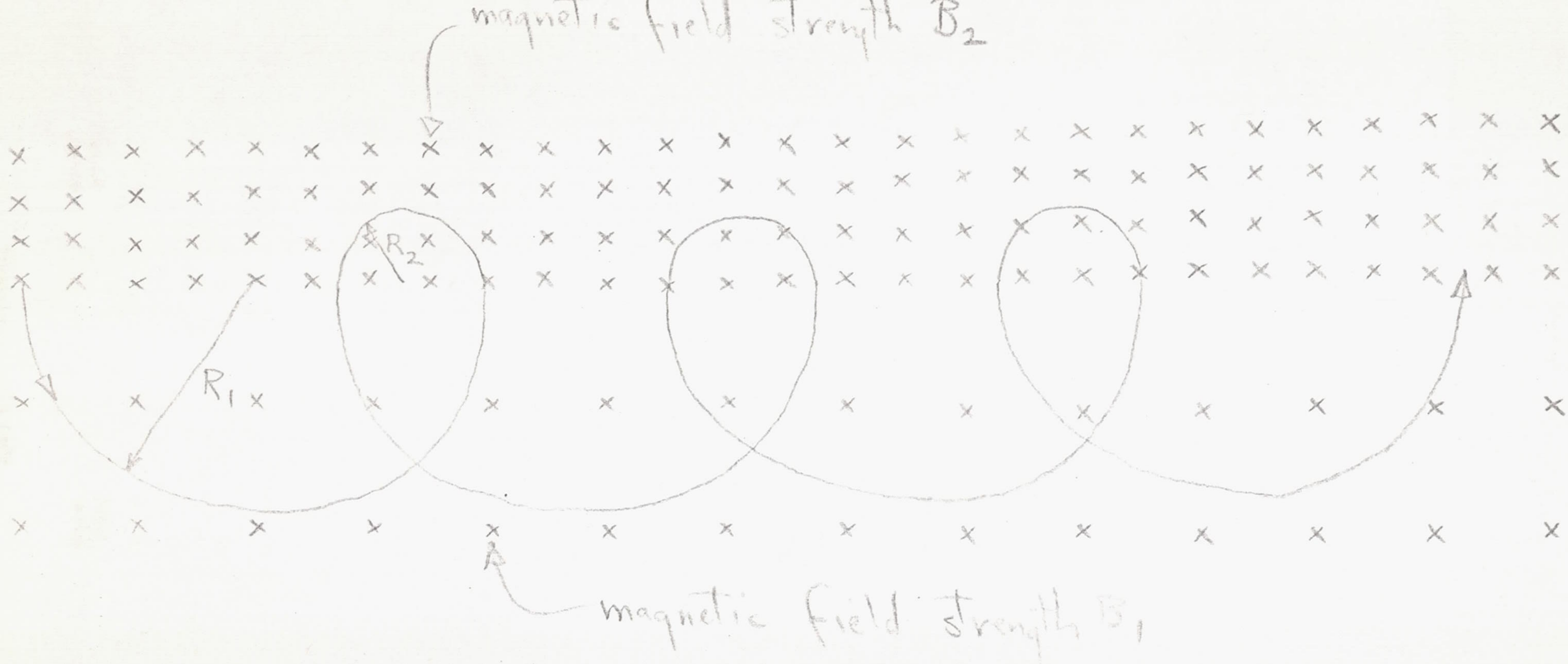
Fig 1



International Science + Tech Fig 3

WWH[illegible]



$B_2 > B_1 \quad \therefore \quad R_1 > R_2$

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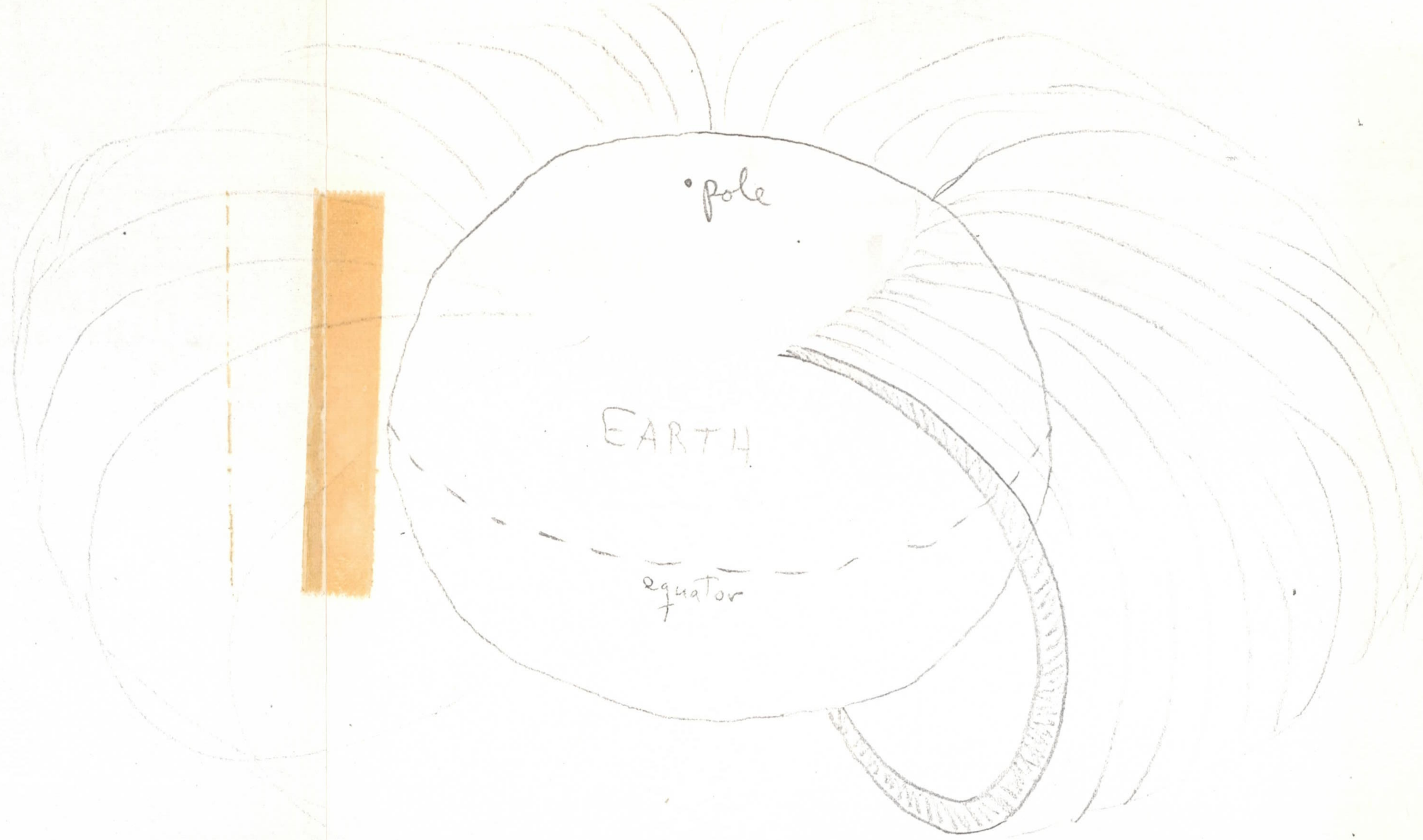
WNHess

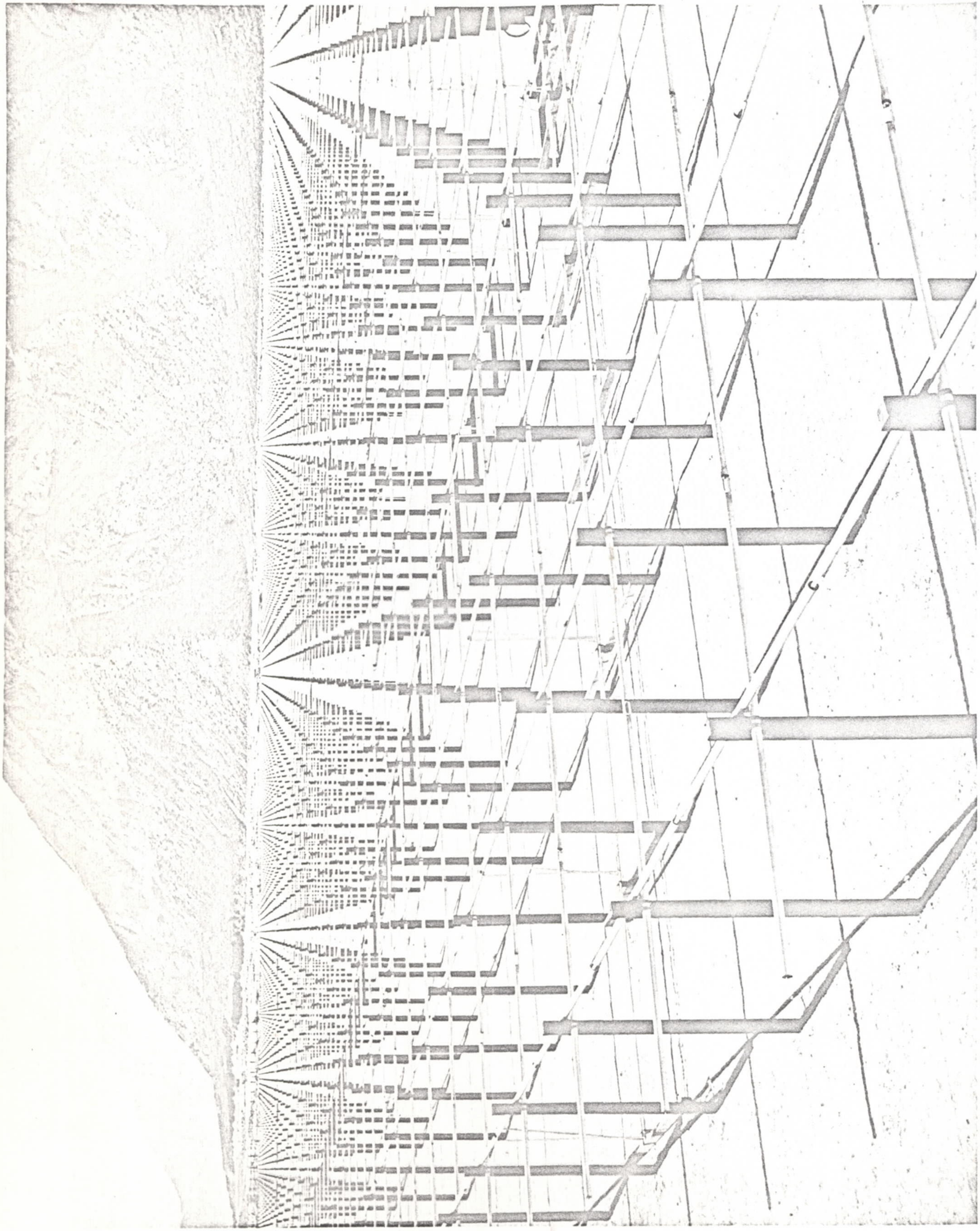
Fig 4

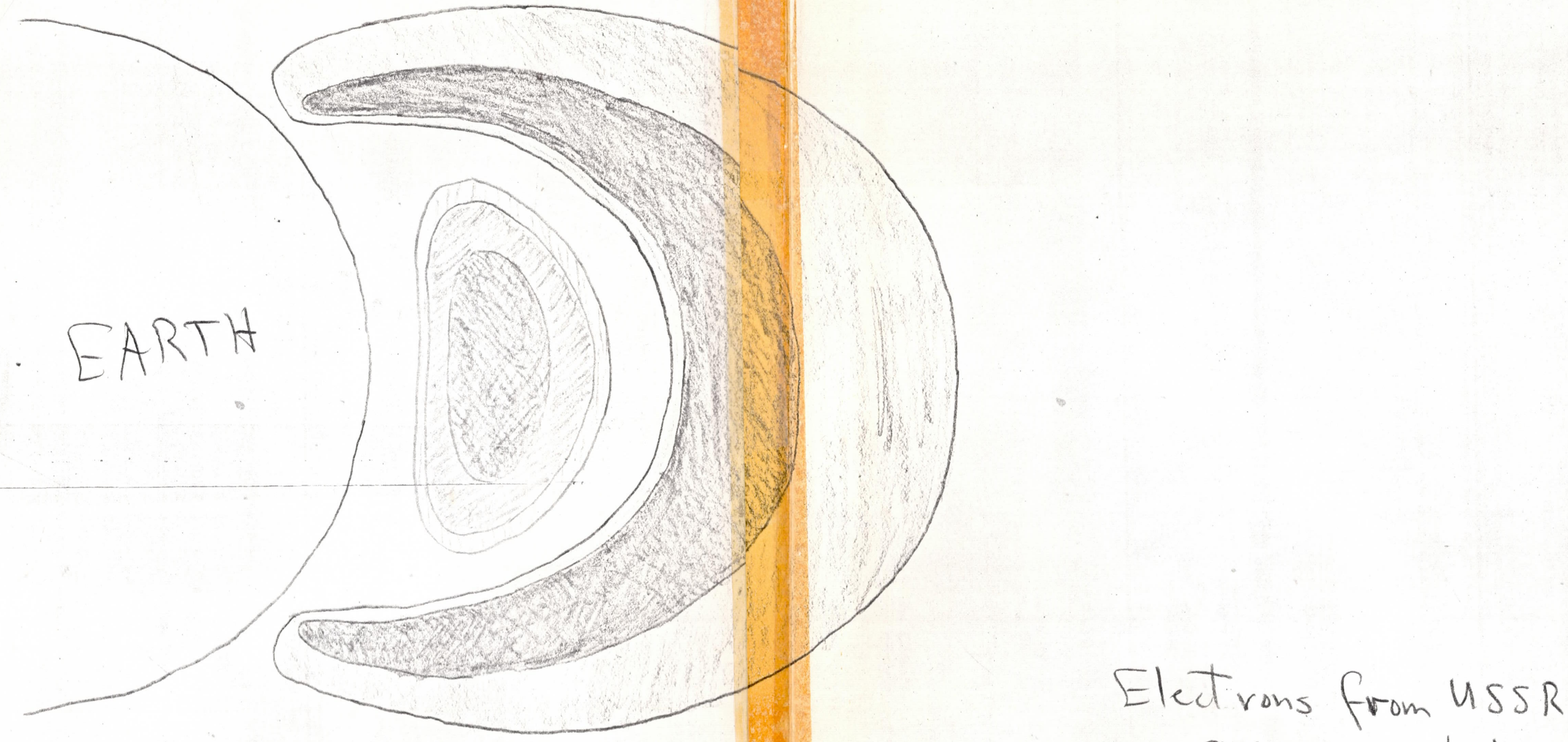


Sketch of the Argus Blanket of Electrons

A

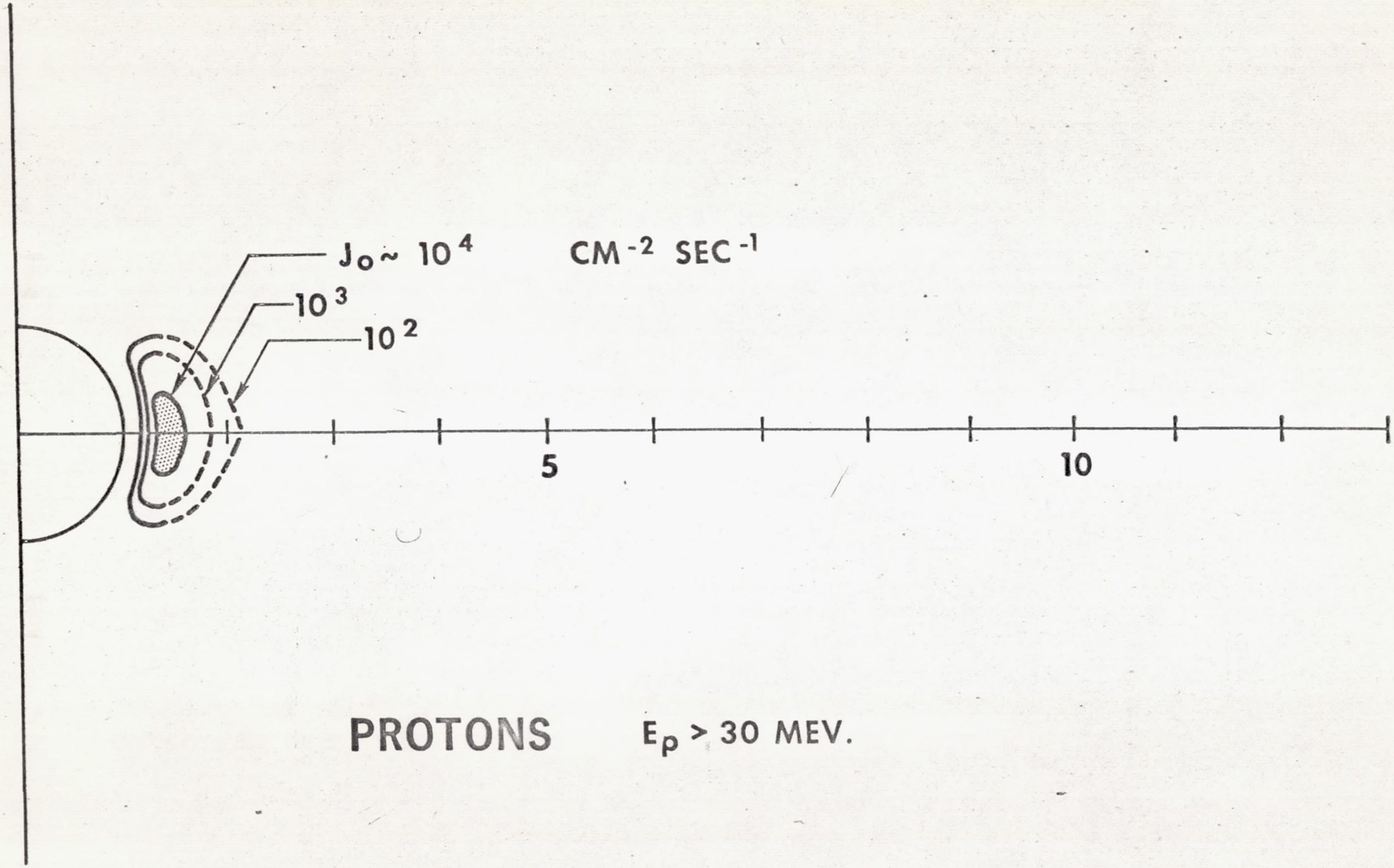
B



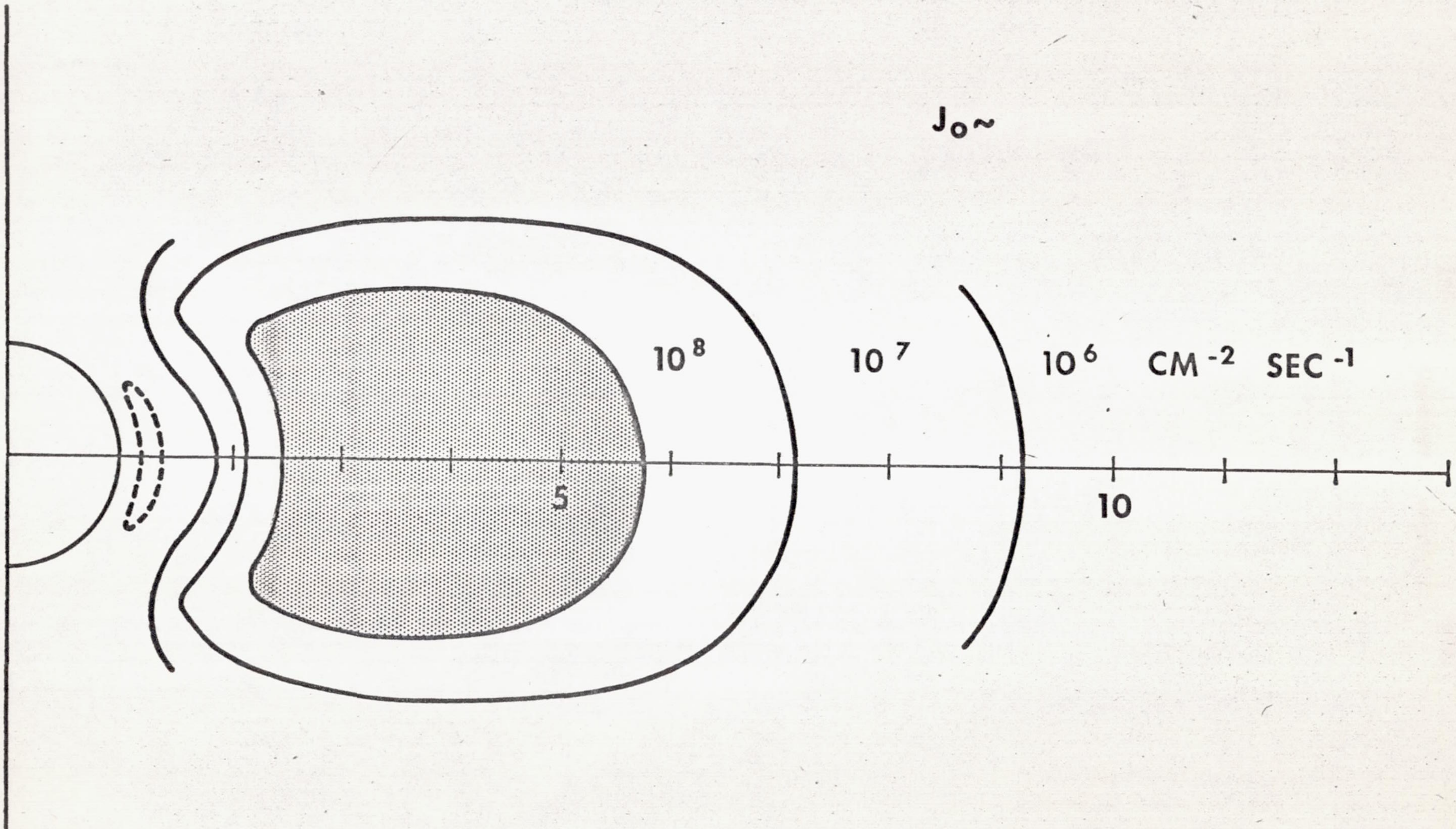


EARTH
Electrons from USSR Oct 28 Explosion
Electrons from Starfish as of Oct 28

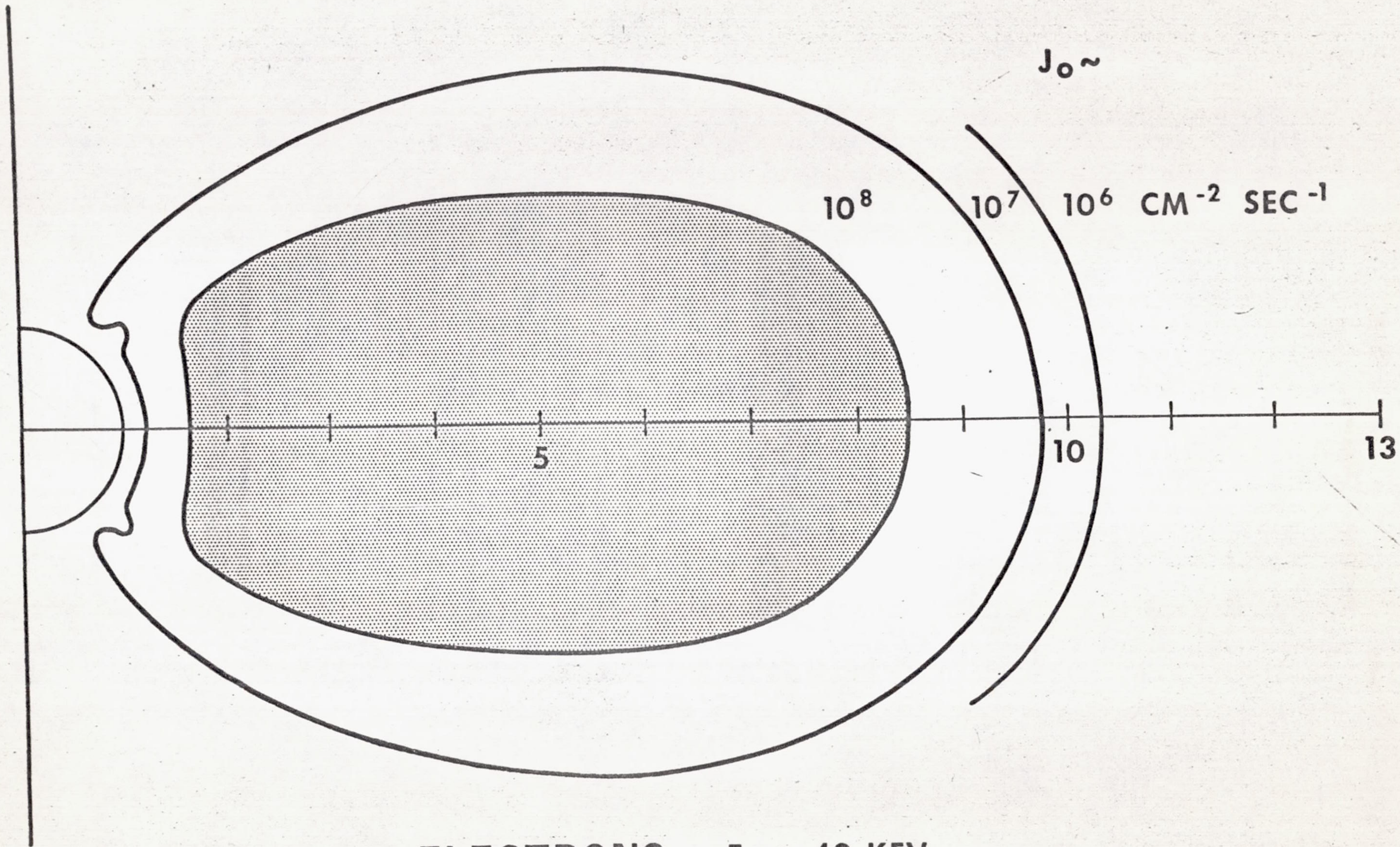
A Fig 10 B C



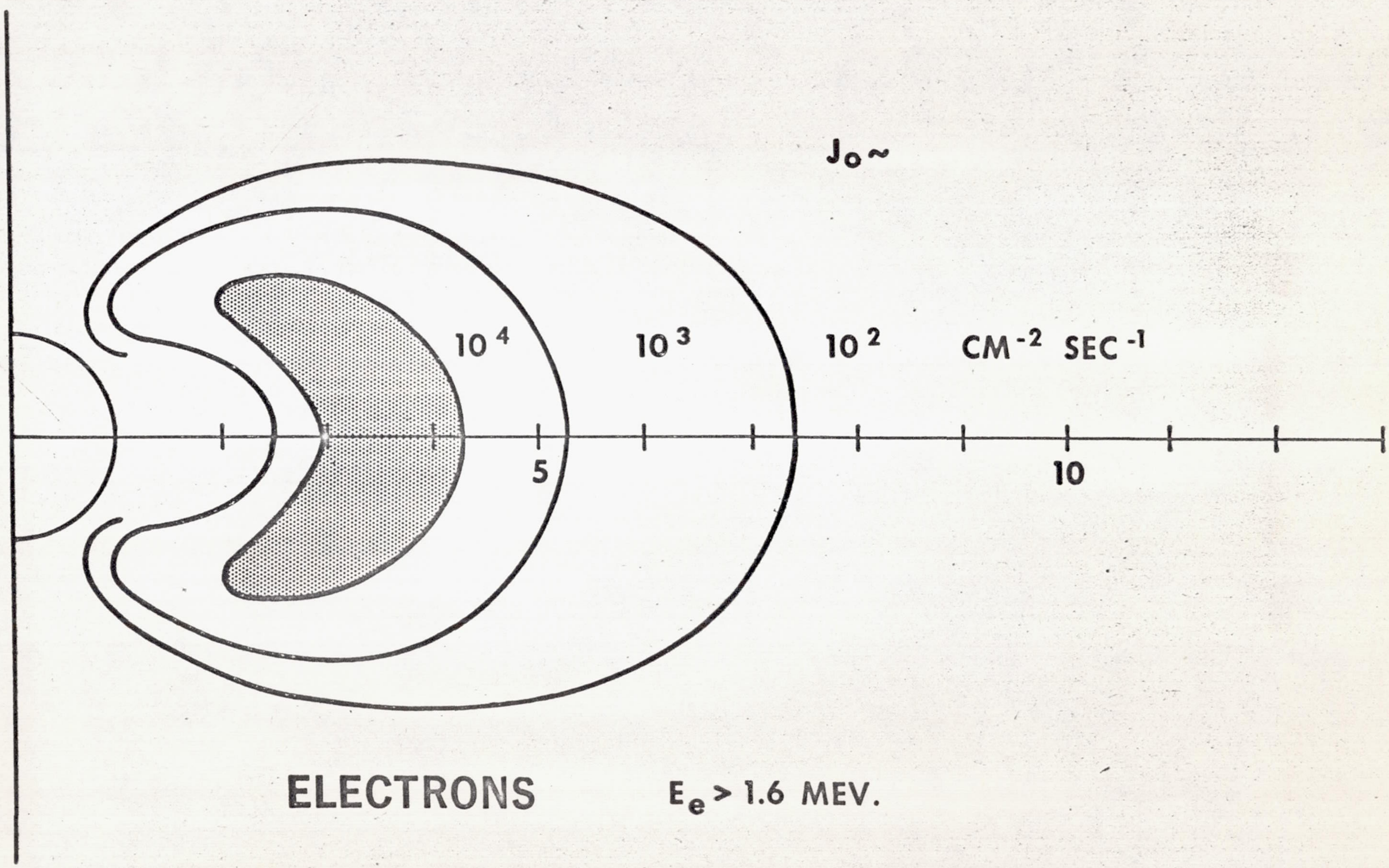
PROTONS $E_p > 30$ MEV.

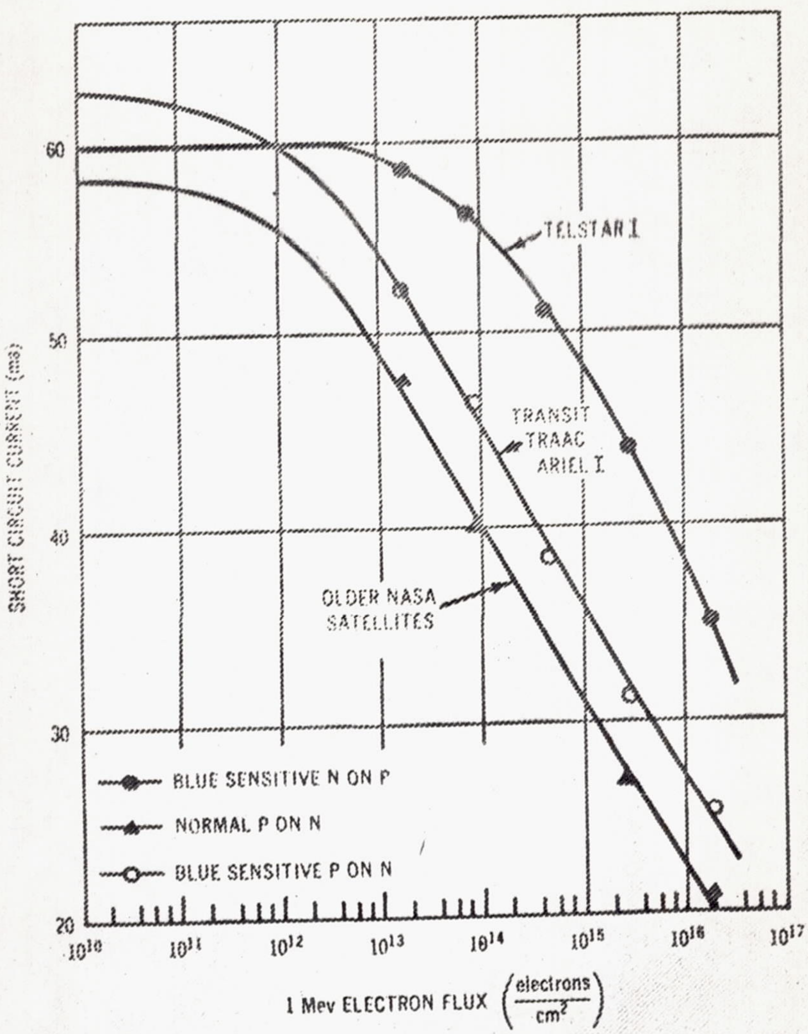


PROTONS $0.1 < E_p < 5$ MEV.



ELECTRONS $E_e > 40$ KEV.


J₀~
10 4
10 3
10 2
CM -2 SEC -1
5
10
ELECTRONS
E e > 1.6 MEV.



60
50
40
30
20
SHORT CIRCUIT CURRENT (ma)
TELSTAR I
TRANSIT
TRAAC
ARIEL I
OLDER NASA
SATELLITES
BLUE SENSITIVE N ON P
NORMAL P ON N
BLUE SENSITIVE P ON N
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
1 Mev ELECTRON FLUX $\left(\frac{\text{electrons}}{\text{cm}^2}\right)$

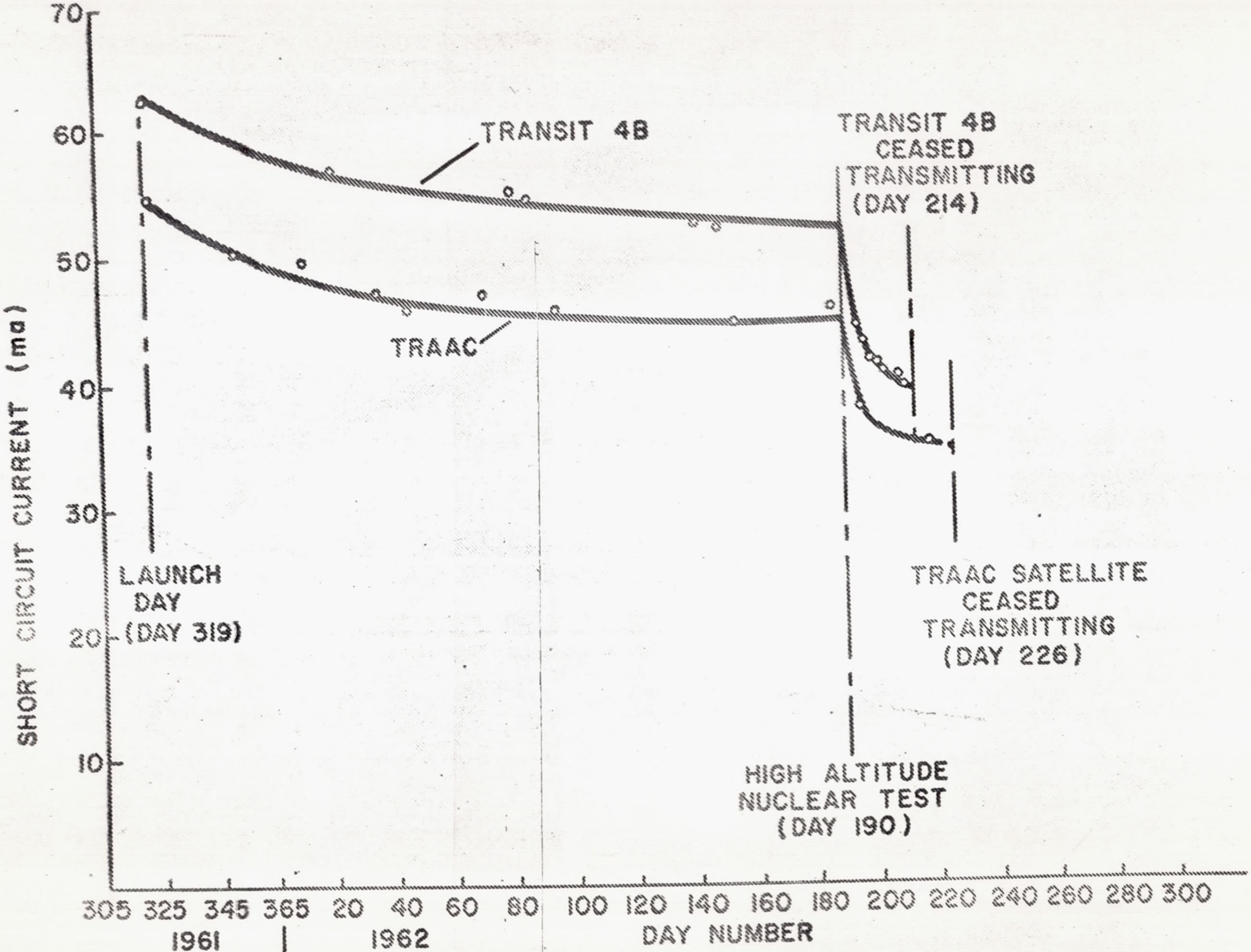


FIG. 3 SOLAR CELL OUTPUT AS A FUNCTION OF TIME FOR TRANSIT 4B AND TRAAC

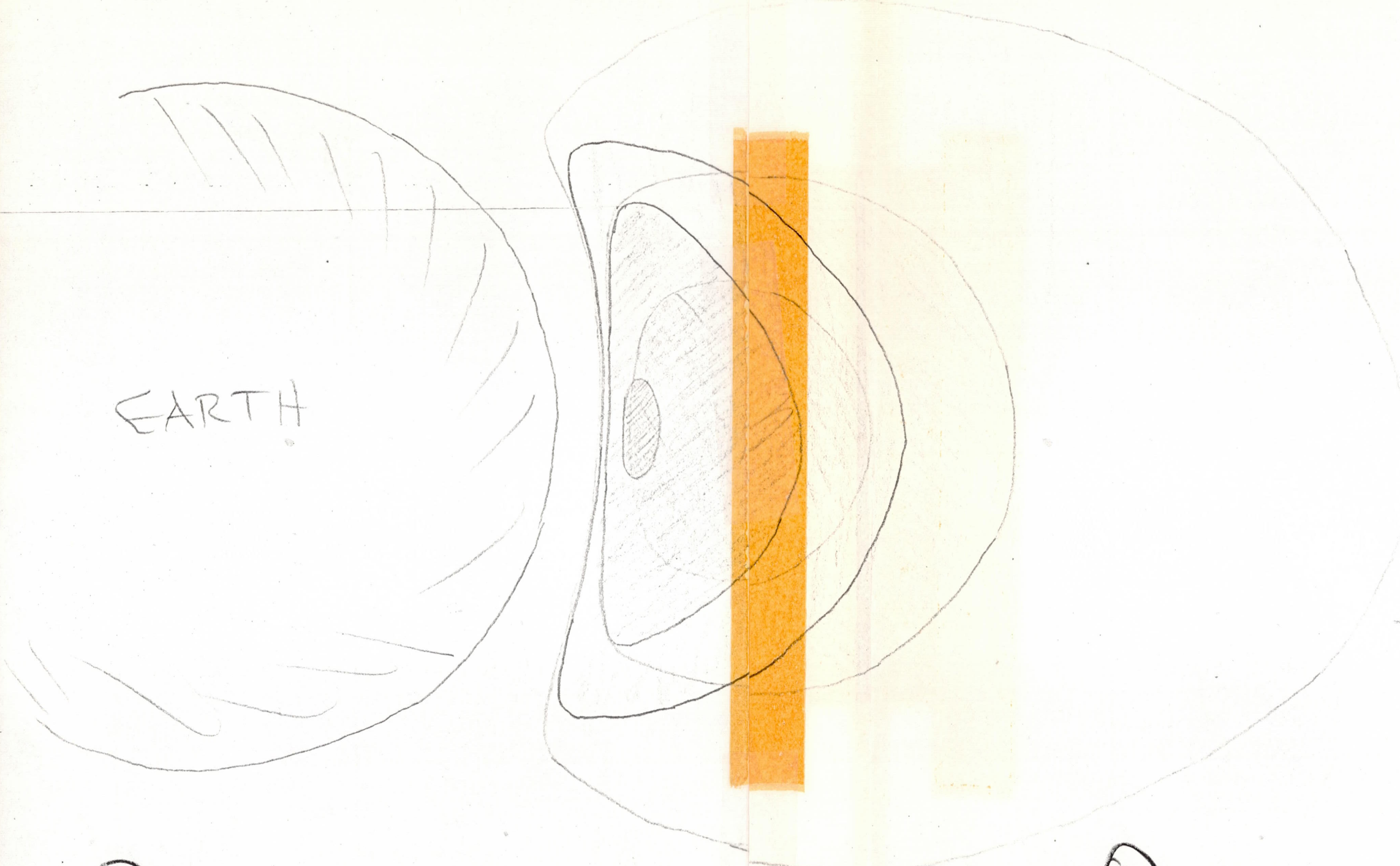


Fig 6

A Comparison of Injun and Telstar Contours