THE RADIATION ENVIRONMENT NEAR THE EARTH

by Wilmot N. Hess

Introduction

Only a few years ago it was commonly thought that the atmosphere of the earth extended up a hundred miles or so and from there to the sun was essentially empty. This picture of the earth's environment has been drastically revised in the satellite era. We know the earth's atmosphere and magnetic field extends out about 10 earth radii towards the sun (and further in the direction away from the sun). Also we know that outside this sphere of influence the sun rules. The sun's atmosphere, the corona, extends all the way to this boundary at 10 earth radii and may even penetrate inside the boundary. The sun controls the location of this boundary which varies some with time. Energetic particles from the sun fairly frequently reach the earth. In fact, as might be expected, the sun controls in a significant fashion essentially all the components of the earth's radiation environment.

In considering the radiation environment of the earth we want to study not only particles found close to the earth but also the environment that satellites and space probes have encountered or may encounter in the future. This environment includes at least:

1. cosmic rays
2. solar wind
3. solar energetic protons
4. the Van Allen radiation belt

TABLE II

Approximate Threshold Doses for Radiation Damage

photographic film	.1 - 200 R
man	~ 500 R
solar cells	200 - 40000 R (of 30 Mev protons)
optical glass	1000 - 10^8 R
teflon	3×10^4 - 10^7 R
transistors	2×10^4 - 2×10^8 R (of 30 Mev protons)
organic seals and adhesives	10^6 - 10^9 R

5. auroral particles
6. shock wave particles
7. artificial radiation belts
8. planetary radiation belts.

We will consider briefly some of the engineering problems associated with the particle radiations.

Galactic Cosmic Rays

Going upwards from the earth the first component of the radiation environment we encounter is cosmic rays. We find some cosmic rays at sea level but they are quite different in nature from cosmic rays in space. The incident cosmic rays, mostly protons, strike the earth's atmosphere and in nuclear collisions with oxygen or nitrogen produce other particles including π mesons. At sea level most of the particles we see are μ mesons made by the decay of the π mesons. In space there are about 2 protons/cm^2-sec plus a small percentage of He and heavier nuclei. These protons are typically of several Bev energy..

It was recognized in 1911 that cosmic rays come from outside the earth because the intensity increased going up in altitude. We know now they come from outside the solar system but we don't know what the source of the particles is. They may be accelerated by repeated bouncing off turbulent magnetic field clouds in space or they may be borne in gigantic explosions of stars called supernovae which only occur about once per century in our galaxy.

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These particles are not produced by the sun but they are controlled somewhat by the sun. The solar wind affects the ability of cosmic ray protons to enter the solar system.

The Solar Wind

In 1950 as a result of studying comet tails, Biermann suggested that there must be an outflow of protons from the sun to interact with the comet to produce some of the long straight tails found in comets. Then in 1957 Parker showed that the corona of the sun must be unstable. To assume the corona was stable led to the ridiculous conclusion that it must have a finite pressure at infinity. Therefore the corona must be continuously expanding and blowing outwards. So before the advent of satellites there was considerable support for the idea that the sun blows a supersonic wind outwards at the earth. This solar wind has now been observed directly on several satellites, Explorer X, XIV, Mariner, and IMP. Its average characteristics are quite well known. There usually is a flux of about 10^8 protons/cm^2-sec of energies about 1 kev. This corresponds to a density of roughly one proton/cm^3. There must be, of course, an equal number of electrons in the solar wind so that it is electrically neutral, but the electrons are of low enough energy so that have not been observed yet.

This solar wind is composed of low enough energy particles so that it is not of special interest, as a radiation problem in itself (a 1 kev proton will be stopped by a sheet of paper).

but it controls several other elements of the environment. For example, the solar wind pushes the sun's magnetic field around. The solar wind is a good electrical conductor which does not let the magnetic field mingle with it. Therefore as the wind flows outwards it carries the magnetic field with it. Because the sun rotates, the magnetic field lines trace out a spiral pattern as in Fig. . The magnetic field measured well outside the magnetosphere of the earth is about .00005 gauss--which is about what one should expect for the sun's field at the earth. Also, the direction of the magnetic field is about what is expected. At the earth the field lines appear to come from about 45° to the right of the sun.

The solar wind plus solar magnetic field affects the galactic cosmic rays arriving at the earth from outside the solar system. The sun shows an 11-year variation in activity. The number of sun spots goes up and down in 11 years as do several other measures of solar activity. The galactic cosmic rays show a similar cyclic effect. At the time of maximum solar activity the cosmic ray flux is lowest. The proton flux varies from about 4 cm^{2}-sec at solar minimum to 1.5 at solar maximum. It appears that the cosmic rays entering the solar system from outside have to swim upstream against the solar wind. Disturbances in the solar magnetic field moving outward with the solar wind velocity scatter the incoming cosmic rays and hinder their entry into the solar system. Therefore the increased solar activity at solar maximum makes a lower cosmic ray flux. By this process the 11-year cycle in solar activity shows up as an 11-year cycle in the cosmic ray flux of opposite phase.

Solar Proton Events

It has been known since 1942 that the sun can occasionally produce high energy particles which arrive at the surface of the earth. These solar proton events always occur in connection with large solar flares which are large disturbances on the sun which can be observed optically. There are relatively few solar proton events which produce particles energetic enough to reach the surface of the earth. This requires protons of roughly 1 Bev or more. Only about one-half dozen solar events have been seen at the surface of the earth in the last 20 years. But, since the coming of satellites, we know that solar proton events are much more frequent than this. Usually the particles produced at the sun do not have enough energy to penetrate the earth's atmosphere to the surface of the earth.

In the period 1956-61 about 50 solar proton events were recorded and studied. The particles have been detected directly by equipment carried on balloons, at high latitudes by detectors on satellites, and by the effect of the proton beams on the polar atmosphere. It is now well established that when these proton beams impinge on the upper atmosphere they ionize the oxygen and nitrogen present and produce a more dense ionosphere. This effect increases the absorption of the radio noise arriving at the earth from outside. Instruments called riometers which measure radio noise coming to the earth from space show considerable decreases in the noise observed at the time of solar proton events. This process is well enough studied now so that it can be used as an indirect method of measuring fluxes of particles in the earth from the sun. Frequently at early stages in a solar proton event the protons appear to arrive from a preferred direction not from the sun but from about 45° west of the sun. This indicates that they have been guided to the earth from the sun along the spiralling magnetic field of the sun. After this initial stage the particles arrive uniformly from all directions.

In the last seven years about 30 large solar events were observed in which a flux of more than 10^6 protons/cm^2 of energy greater than 30 Mev arrived at the earth. From looking at the characteristics of these events we have a fairly good idea of the average properties of solar proton outbursts. The protons get to the earth more easily and more rapidly if the flare which produced them occurred on the right side of the sun. This is quite clearly due to the fact that they can move along the solar magnetic field lines from near the point of origin and arrive directly at the earth. For a flare on the left side of the sun the particles must diffuse across the solar magnetic field in order to eventually reach the earth. This is harder. We have no basic understanding of the processes going on at the sun which make these high energy particles. There is no question but what the protons are accelerated in the region of solar flares. It has been suggested that at magnetic neutral points, places where the sun's magnetic field becomes zero between oppositely directed magnetic field regions, there may occur certain types of electrical discharges where energy from the magnetic field can be pumped into the particles. Flares frequently take place near magnetic null points and changes in magnetic field strength before and after flares have been observed in agreement with this idea.

In a typical solar proton event the proton energies can go up to a few hundred Mev. These energies are low enough so that the particles cannot penetrate the earth's magnetic field to arrive at the equator. They are restrained to enter the earth only at high latitudes. The Riometer records show this effect during what are called polar cap events during which the absorption of cosmic radio noise increases significantly but only in the region of the polar caps. This is the region where the protons can penetrate the atmosphere and increase the ionospheric opacity. A flare proton event typically starts at the earth an hour or so after a large flare and may last for several days.

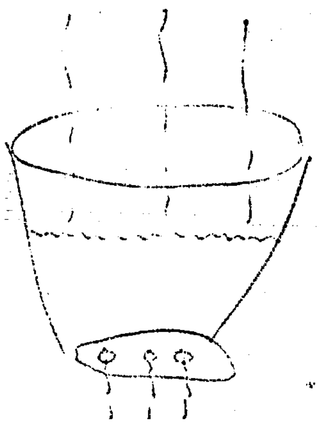
What are the radiation hazards in space from solar proton events? Webber has studied and summarized what is known about the largest events of the last colar cycle and finds that there have been several occasions where in the absence of any significant shielding integrated particle doses of more than 100 rad would have been encountered. The table below gives a summary of radiation doses from Webber's work. Five or ten grams/cm^2 of shielding is adequate to reduce the doses from even the large events to levels that are not dangerous and these large events are quite rare. In the last solar cycle there were maybe six or eight events large enough to worry about in connection with manned flight. For short manned missions of a few days or weeks such as lunar landings there is some chance that we may be able to predict the occurrence of solar flares accurately enough to aid materially in avoiding solar proton events. Solar proton events normally occur in connection with flares that take place in large and magnetic complicated sunspot groups. If the groups have persisted for one solar rotation of 27 days or more, they are more likely to produce large flares. Sunspot groups that have made large flares are liable to repeat. Webber feels that using a prediction process, based on these ideas, lunar missions should be possible 50 percent of the time at sunspot maximum with only about 1 percent probability of encountering a large solar flare during a two week period. One would avoid flying when large sunspots with several regions of different magnetic polarity were on the sun, especially if they had been seen the month before going across the face, and especially if they had already made large flares. This shows that solar proton events should not consitute a limiting factor in short manned missions in space. The problem is, of course, considerably more severe for long duration flights that might occur in the future. For example, during a one year mission to Mars one would expect to encounter one or more significant solar proton events near solar maximum and would have to shield for that appropriately. Near solar minimum few proton events occur.

Radiation Belts

When Van Allen discovered the trapped particle radiation belt on the first U.S. satellite Explorer I, it was a surprise but it did not take long to get a general understanding of the phenomena. The fact that a magnetic field could trap charged particles was at that time being exploited in the U.S. laboratories and abroad in an attempt to make controlled thermonuclear reactions to generate power by burning hydrogen. This process is like a controlled H bomb. Christofolis had suggested that the earth's magnetic field could act as a magnetic bottle also and that a nuclear explosion could inject particles into the field. This idea lead to the Argus explosions in 1958. The planning for Argus was well underway before Van Allen's discovery of the natural belt so a general comprehension of the natural radiation belt was immediately obtained.

But progressing from a general understanding of trapped radiation to actually understanding in detail how the earth's radiation belt works where the particles come from and where they go to has taken five years and is by no means finished. First, what do we know about the population of trapped electrons and protons? Fig.   shows the distribution in space of four types of particles--high and low energy electrons and high and low energy protons. These particular populations are shown because they have been measured well experimentally.

The protons of $E > 30$ Mev in Fig.   were the first particles well studied experimentally and the first particles whose origin we understood. By studying nuclear emulsions recovered from Atlas rockets the particles were identified. Galactic cosmic rays are the grandparents of these inner belt protons. The galactic cosmic rays entering the atmosphere (as in Fig.   ) produce neutrons by colliding with nucleii of oxygen or nitrogen. Some of the neutrons diffuse out of the top of the atmosphere and move away from the earth. The neutron is radioactive and decays with a lifetime of about 1000 seconds, giving birth to the protons which are trapped. When we test this theory that neutrons are the parents of the proton in a quantitative way by putting in numbers for the neutron flux and rate of loss of protons by interactions with the atmosphere at several thousand kilometers we find very good agreement with the experiments on how many protons of what energies are present. This model of the trapped protons has been called the "leaky bucket" by Van Allen. We put particles in the bucket (the radiation belt) from neutron decay and particles are lost out the holes in the bottom of the bucket by interacting with the atmosphere. The water level in the busket will adjust itself until the inflow and outflow are equal. In this way an equilibrium flux of



trapped particles is built up. Using the leaky bucket model we find some of the protons at a few thousand kilometers altitude live 100 years or more.

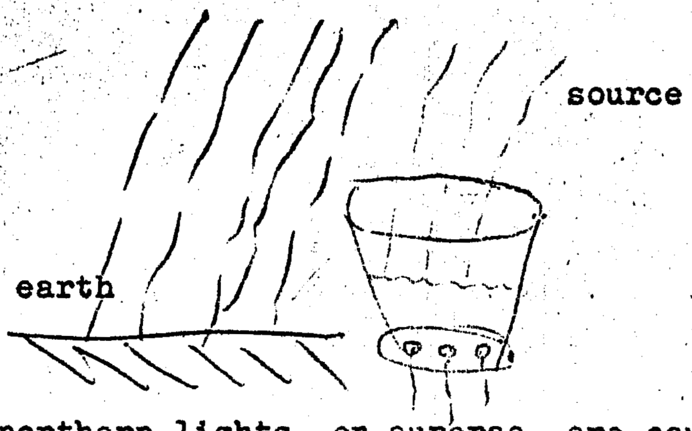
The sun also exercises some control over this population of particles. Ultraviolet rays from the sun heat the upper atmosphere much more at solar maximum than at solar minimum. We know the atmospheric density is nearly x 100 larger at about 500 km at solar maximum than at solar minimum by studying the drag on satellites. The increased density causes the trapped protons to be lost faster. So the proton population at low altitudes oscillates up and down with the solar cycle having a maximum flux near solar minimum. This effect is of interest in considering the radiation problem for low altitude manned flight like Gemini.

There seems little doubt but that we understand this one population of trapped particles well. We are not in as good shape when it comes to the other populations of Fig. . Recently some progress has been made towards understanding the low energy outer belt protons in Fig. . When we inspect the energies of these protons we find their energies are systematically higher closer to the earth. This is very suggestive that the particles have been moved radially into the magnetic field from the outside and have gained energy as they moved into the increasing magnetic field much as particles do in a betatron accelerator. What process can move the particles inwards? Usually the trapped particles bounce back and forth along field lines and slowly drift around the earth but return to the same starting point after one revolution around the earth. In this normal motion there is no tendency to move in or out. At least one process can disturb this orderly motion. When the intensity of the solar wind increases, the magnetic field of the earth is pushed inwards and the effect can be measured by magnetometers at the surface of the earth. If this compression of the field occurs fast enough it disturbs the particles and causes some of them to move to new orbits. A repeated "pumping" of the field by a changing wind will diffuse the protons both in and out. Some will escape out the edge of the earth's magnetic field but some will move inwards and be energized as they go. To get the protons of the energies observed in Fig. we need to start outside the earth's magnetic field with protons of 1-10 Kev. If this idea is right, and it hasn't been fully tested yet, the sun is the origin of the protons which have come to the earth in the solar wind. The sun also provides the motive force to pump the particles inward.

We know considerably less about the electrons in the radiation belt than the protons. When magnetic storms occur on earth caused by disturbances on the sun the electrons in the outer radiation belt are disturbed considerably. The protons are not strongly affected. At the time of a large magnetic storm caused by an increased strength solar wind the low energy electrons, Fig. , might increase in population by a factor of 10, and the high energy electrons, Fig. might almost completely disappear. After a few days the storm would be over and the fluxes would return towards pre-storm values. We have no good ideas about this variation of the electron flux. Are lots of new low energy electrons injected into the field at the time of the storm? Are the high energy electrons lost and then new ones injected afterwards or are they only temporarily slowed down, and then after the storm return to their original energy? Whatever happens to the electrons, the sun is certainly responsible for it.

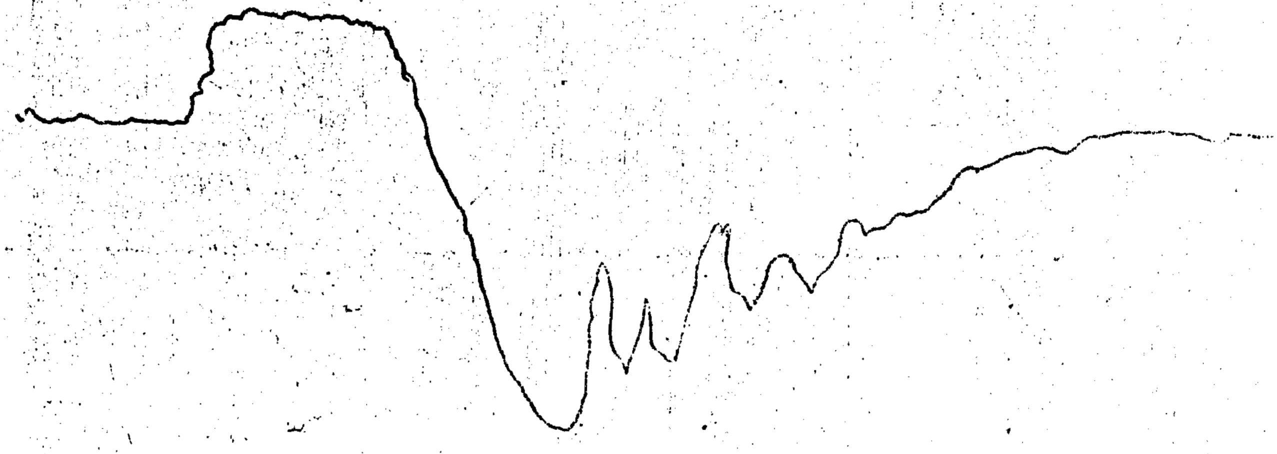
We do know something about the lifetimes of the electrons in the natural radiation belt as a result of studying the artificial radiation belts. In the inner zone the electrons have lifetimes of a year or more; and because of this long lifetime, neutron decay may supply most of the observed electrons. But in the outer belt at about 10,000 miles altitude, the electron lifetime is only about one week. The only available source that has enough energy to make the electrons here seems to be the solar wind. We don't know whether electrons are diffused into the belts as we suspect the protons are, or if some electrons already in the region of the belt are accelerated perhaps by some kind of waves in the magnetic field.

There is another interesting feature of the outer belt electrons. Frequently large fluxes of electrons are lost directly into the atmosphere. But we are quite sure these precipitated electrons aren't produced from the already trapped electrons because the trapped fluxes increase at these times. Apparently some particle source is causing electrons to flow through the radiation belt with most of the electrons being lost into the atmopshere, but some electrons get trapped in the belt. This idea of the outer belt has been called the "splash catcher" by O'Brien to contrast it with the "leaky bucket." The thought is that the bucket (the radiation belt) catches only a small fraction of the electrons from the source most of which hits the earth.



The northern lights, or aurorae, are caused by energetic particles, mostly electrons, being precipitated into the atmosphere from above. Rockets have been shot through auroral displays to study these particles. It seems likely that these auroral electrons are related to the electrons observed to be precipitated in the region of the outer radiation belt. In fact, the Injun III satellite found electron precipitation occurred all the time in the auroral zone. It probably just takes a more intense than usual precipitation to make a visual aurora.

We are relatively sure we have not found all the particles which make up the radiation belt yet. One unmeasured group are the magnetic storm particles. When a magnetic storm occurs on earth, first the magnetic field increases due to the compression by the stronger solar wind (see Fig.), then some hours later the field decreases to less than pre-storm values. This decrease is commonly thought to be due to lots of new trapped particles in the field which stretch the field out and decrease the field at the surface of the earth. If these are protons of E ~1 Kev as we suspect, they would not have been found yet. None of the instruments flown on satellites so far have been designed to study these particles. They would have as a group more



energy than all the rest of the trapped radiation, but individually they must have relatively low energy.

Artificial Radiation Belts

Christofilos' idea that a nuclear explosion at high altitude should produce an artificial radiation belt was tested in 1958 in the three Argus explosions, and worked. Rather small radiation belts were produced that decayed in a few weeks. Since then, four more artificial belts have been made all in 1962--one by the U.S. and three by the USSR. The US explosion Starfish of 1.4 megatons at 400 km in the Pacific made a large artificial radiation belt extending out to 5 earth radii or more. The belt was populated mainly from the decay of the fission fragments made by the explosion. These nuclei left after fissioning uranium are radioactive and each emits about six electrons before becoming stable. These electrons with average energies of about 1 Mev and extending in energy up to 6 Mev or more were made with fluxes of up to 10^9 elec/cm^2-sec. These fluxes were large enough so that they overwhelmed the natural belt electron flux. Because of this the lifetimes of trapped particles could be determined directly by watching the decay of the Starfish electrons. Up to several thousand kilometers altitude the decay was slow and was clearly caused by coulomb scattering of the electrons by the thin atmosphere. But above a few thousand kilometers the picture is very different. The decay becomes muc more rapid and must be cuased by something other than the atmosphere.

It has been suggested that certain types of electromagnetic waves, called whistlers, cause the particles to scatter. The electrons lifetime due to scattering by these waves should be short--measured in days--in agreement with the observations. At about 10,000 km altitude the Starfish electrons decayed away completely to the natural belt background in just two or three months. For similar high altitudes, the artificial belts from the three Soviet explosions decayed in like times. This shows the rapid high altitude decay is a normal state of affairs.

The measurements on artificial belts show there are two regions of the natural electron belt--an inner zone up to a few thousand kilometers where the electrons have long lifetimes and an outer zone of short lifetimes.

Other Belts Other Places

It is intriquing that we already know that at least one more radiation belt exists in our solar system besides ours and we can be suspicious about other possibilities. Jupiter quite definitely has a considerable radiation belt. We know this because of strong radio signals received from Jupiter. Some of these signals are interpreted as being synchrotron radiation from the natural radiation belt of the earth. In the decimeter wave length range the signals from Jupiter are plane polarized and the source area is considerably larger than the disc of the planet. The radiation comes from about three times the width of the planet along the equator. This extended source is strongly suggestive of a radiation belt. There is no other reasonable explanation of the Jupiter decimeter radiation than from synchrotron radiation from trapped electrons. This can explain reasonably the polarization, spatial extent, and steadiness in time of the decimeter radiation. Jupiter also emits in the decameter range an intermittent and not at all understood circularly polarized signal but this is not connected with synchrotron radiation. If the Jupiter surface magnetic field is about 10 gauss, as some ideas based on the decameter radiation say, then there must be about 10^8 electrons/cm^2-sec of about $E \sim 10$ Mev in order to generate the observed synchrotron radiation. This is a considerably more intense electron belt than the earth has.

One other space measurement has given a negative result. The satellite Mariner went close to Venus and did not observe a planetary magnetic field or trapped particles. This does not preclude there being a radiation belt there. It only puts a limit on the size of the belt. The satellite passed about 40,000 km from the sunny side of the planet. The fact that it stayed outside the Venus magnetopause puts a limit on the Venus surface magnetic field about 1/10 of the earth's surface field. Some theories about the generation of planetary magnetic fields require rotation of the planet to make the field. Jupiter rotates in 10 hours and apparently has a large field. Venus rotates very slowly and has a weak field. Based on the necessity of rapid rotation and reasonable size to generate a planetary field (and therefore to have a radiation belt) we might expect radiation belts on Saturn, Mars, and Jupiter--none on Mercury and the Moon. There is some slight evidence of radio noise from Saturn that might indicate a radiation belt, but nothing like Jupiter's. All other evidence about belts is negative. No other planets show interesting radio emission. Lunik II showed the moon's magnetic field must be very weak, which indicates no trapped particles.

Even though these bodies have small magnetic fields they may have shock waves like the earth has upstream of the magnetosphere. The planetary surface would take the place of the magnetopause and the shock wave would stand off in front of this. If so, then we would expect transition zones with energetic particles in them as the earth has between the bow shock and the magnetopause. This means that even with no radiation belt the planetary surface might have a significant radiation environment. If there is an electron flux of 10^{10} cm^{-2} sec of E = 10 Kev at the surface of the moon the astronaut would want to be careful about film in his camera.

The Magnetopause and Bow Shock

In the beginning we mentioned that the sun controlled the environment ouside of about 10 earth radii from the earth. The solar wind pushes the earth's magnetic field in until the pressure of the deformed magnetic field balances the pressure due to the wind. This stand-off occurs at about 10 earth radii towards the sun and about 15 earth radii at right angles to the sun. In this way the earth's magnetic field is limited to be inside a cavity, called the magnetosphere, as shown in Fig. . We don't know much about the back end of the magnetosphere either experimentally or theoretically so the picture has been chopped off appropriately. The sharp boundary, the magnetopause, between the solar medium and the terrestrial field of 100 km thickness or less has been directly observed by satellite measurements of magnetic fields and trapped particles on Explorer X, XII, XIV, and IMP. The magnetic field inside the boundary decreases going towards the boundary steadily much as expected for the earth's field, but then suddenly at the boundary the field changes direction and strength and becomes disordered. At this same point on the side towards the sun the radiation belt abruptly ends. Particles cannot be trapped for long by the turbulent magnetic field outside the boundary. On the dark side of the earth the tail of the magnetosphere will not contain trapped particles. Beyond about 8 earth radii the particles, due to their normal drift in longitude, will drift out the side of the magnetosphere and return to the solar environment. Particles inside 8 earth radii can drift to the front side of the earth and complete the circuit and be trapped a long time inside the magnetosphere.

A recently discovered and very interesting feature of the earth's environment is the shock wave towards the sun from the magnetopause (see Fig.). The magnetometer on the IMP satellite showed that at this point the turbulent magnetic field in the transition region outside the magnetopause changed and became quite steady at about .00005 gauss usually at about the direction predicted by the spiral pattern of the solar field in Fig. 1. This indicates a shock wave. It is quite reasonable that a shock wave should exist at about this point. A supersonic bullet produces a shock wave in the air ahead of it. Similarly the supersonic solar wind, blowing at the earth, then might be expected to make a similar shock wave and at just about the stand-off distance found. This shock wave is of a peculiar type - a collisionless magneto-hydrodynamic shock produced not by direct collisions of particles but through the action of the magnetic field. Outside the shock wave the solar wind is directed radially away from the sun. In the transition zone the wind is random in direction.

In the transition region inside the shock wave are found more energetic particles than in the solar wind. Fluxes of about 10^{10} electrons/cm^2-sec of $1 < E < 10$ Kev and 10^7 protons of $E > 2$ Kev exist here. Also at about the shock location a narrow region of about 30 Kev electrons is found. It appears that in the shock and also probably in the turbulent region behind the shock particles are accelerated. It seems likely that a Fermi-type acceleration can take place here. The particles will be pushed to-and-fro by the turbulent magnetic fields and in this process some particles will be speeded up. This transition region probably is the breeding ground of many of the outer Van Allen belt trapped particles. There are reasons for believing that the magnetopause is unstable - that various kinds of waves can grow in the surface and that particles can leak in through the surface as a result of the instabilities. This would mean that we could take some particles from the transition region and bring them into the region of trapping. In fact, electrons are observed in the tail of the magnetosphere past 8 earth radii where we feel sure they cannot be permanently trapped. These electrons are of similar energies to those in the transition zone. It is quite likely that they have been brought in through the sides of the magnetopause probably by an instability and after a short time in residence in the tail of the magnetosphere drift out to the edge again into the transition zone. This transition zone contains just the right kind of protons to be the source of the outer zone protons that we have suggested may be magnetically pumped into the field from outside the magnetopause.

Effects

What can we say about the earth's environment as it affects space flight and people who work on problems related to space flight? The most obvious problem area is in radiation damage to solar cells, transistors, optical surfaces, and man. A particle flux of 3×10^7 particles/cm^2 of high enough energy particles to be minimum ionizing will give one Rad dose. The table below shows radiation levels to damage several sensitive systems.

To give some examples of radiation belt particle doses we have shown in Fig. the particle fluxes that a circular orbit satellite would encounter in a day at different altitudes from high energy protons and from the artificial radiation belt, as it existed in Nov. 1962. The artificial belt has probably decayed by about x 10 to the present. These data are for an unshielded satellite. As we add shielding we cut the particle flux down as shown in Fig. . This shows there are trade-offs between acceptable dose, flight duration and altitude and shielding that must be considered in designing a flight.

For the astronaut going to the moon the radiation belt dose is probably quite small because the transit time through the belt is small. The artificial belt is decaying and should be almost gone by the time Apollo flights occur. Solar protons are the big problem. If by getting some fairly reasonable prediction scheme for solar flares we can cut the probability of encountering a large one to a small percentage this is quite good. Also with several gm/cm^2 shielding the dose even from a large flare is unlikely to be larger than 50 Rad (see Table I).

If the moon has a bow shock as the earth does, then there may be energetic electrons and protons in the lunar transition region to consider also. These are of low enough energy so that they can be shielded out rather easily. For photography on or near the lunar surface care must be taken that the electron flux doesn't darken the emulsions.

If in the future attempts are made to send satellites to Jupiter considerable care should be taken about radiation. The design engineer has my sympathies. From what we know of the Jovian radiation belt it is a rather fierce one. If there are lots of 10 Mev electrons as we suspect, shielding will be difficult because the electrons will use a large fraction of their energy to make very penetrating X-rays. It takes about 20 gms/cm^2 to cut this X-ray flux in half. If the electron flux is 10^8 elec/cm^2-sec one may have to put up with doses of about 1 Rad per second over a distance of several Jovian radii. This will pose some interesting design problems.

The radiation environment of the earth also affects long distance communications. The ionosphere which is responsible for reflecting radio signals varies substantially as a result of the influx of charged particles. Radio blackout may occur in the polar regions during a solar proton event. During magnetic storms the ionosphere is unusually disturbed. We do not understand the process that maintains the nighttime ionosphere but it may be due to particle precipitation into the atmosphere. We could improve our understanding of long-distance communications by understanding our knowledge of the radiation environment of the earth.

Summary

In the next few years NASA will be carrying out research programs aimed at answering some of the questions we have left unanswered here. Clearly efforts will be made to study the low energy trapped particles we do not know well now and to watch time changes in the already measured higher energy radiation belt particles. We will get more detailed data on the energetic particles in the transition outside the magnetopause and will continue to study all solar proton events that occur. Also studies of the radiation environments of the moon, Venus, and Mars will move forward. With the OSO satellites and the Advanced OSO, studies will be made of the sun, especially to get more detailed information about solar flares.

It is clear that our understanding of the radiation environment of the earth is quite incomplete. Having been surprised before, as by the discovery of the radiation belts, we should be prepared for more surprises and treat this present survey of the problem as a progress report and not the final word on the subject.

Radiation doses in Rads from large solar proton events

	1 $\frac{gm}{cm^2}$	2 $\frac{gm}{cm^2}$	5 $\frac{gm}{cm^2}$	10 $\frac{gm}{cm^2}$ of H_2O
23 Feb 1956	55	35	20	14
10 May 1959	315	116	27	5
July 1959 (3 events)	885	405	100	31
Nov 1960 (2 events)	396	211	72	37
July 1961 (2 events)	90	42	11	4

No allowance is made here for -particles or for late arriving low energy magnetic-storm protons.