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II-2-9. Source of Electrons in the Van Allen Belts

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At the present time, three years after the discovery of the Van Allen belts, the source of the trapped electrons is still not understood. It has been shown that these electrons cannot be due to the beta decay of albedo neutrons as this source is too weak. Comparison of measurements made by the U.S. space probe Pioneer V and the satellite Explorer VII shows that the electrons do not come from the sun, at least with the energy that they have after trapping. It appears therefore that the electrons of the Van Allen belts are accelerated in the trapping region, with the acceleration energy somehow supplied by the sun.

Recently it has been shown that during the main phase of a magnetic storm, a ring current develops in the region around 10 earth radii. Since the earth's equatorial field is reduced, this ring must represent the arrival of new energy in the trapping region. Comparison of cosmic ray cutoff observations and geomagnetic measurements shows that after its formation, the ring moves inward, without much loss of total energy. This inward motion can be understood if the particle energy in the ring is shuffled among particles in a way that preserves $W_{\perp}/B$; *i. e.* by a process whose time constant is longer than the cyclotron period. Those particles which gain energy then move inward, and therefore so does the effective position of the ring. This picture also agrees with observations of the outer Van Allen zone during and after magnetic storms.

Conjectures can be made about the mechanism which causes the shuffling of the particle energy. It seems possible that a known plasma instability associated with a "pancake" velocity distribution is responsible and this throws light on the original mechanism for ring current formation.

Although the proton component of the earth's trapped radiation now seems fairly well understood as being due to energetic neutrons produced in the atmosphere by cosmic rays, the electrons, which are a more important component in every way, are not understood at all. It is clear that albedo neutrons are too weak a source by a factor of 1000 or so to account for the large observed fluxes. I wish to show how the work which I presented yesterday (paper II-4-9) can be used to throw some light on the electron problem.

First, I had better review the work presented yesterday on behalf of J.R. Winckler and myself. It has been observed that, at times, solar protons reach the top of the atmosphere at Minneapolis with energies far below the normal geomagnetic cutoff energy. Such protons are observed to arrive only during the main phase of a magnetic storm. We have shown that the same ring current which has been postulated to account for the main phase of a storm, can account for the lowering of the cutoff energy, and that new information is obtained on the parameters of the ring current; namely, that its radius is about 7–10 earth radii, and its magnetic moment is 1–3 times that of the earth. It is further observed that the cutoff returns toward normal at Minneapolis before the magnetic storm is over, and to account for this it was necessary that the ring current move inward after its formation.

The ring current must be due to charged particles trapped in the earth's magnetic field. Now, the field produced at the center of the ring by a charged particle trapped in a dipole field is roughly independent of the line of force on which the particle is trapped, and is proportional to the particle's energy. This is easily seen, for the contribution of a charged particle to the magnetic moment of the ring is generally equal to W/B multiplied by a small numerical factor which depends weakly on the particle's pitch angle. W is the energy of the particle, and B is the value of the magnetic field at the position of the particle. The field at the center of a ring is proportional to its magnetic moment divided by the cube of its radius. But for a dipole field, the product Br^3 is constant, and equal to $B_0 R_E{}^3$ where B_0 is the earth's surface field and R_E is its radius. Hence the field at the center of the ring, and therefore the field at the surface of the earth for a distant ring, measures the total energy of trapped particles. It may also be shown that the perturbation field is always in a direction to decrease the horizontal component of the earth's field at the equator.

It is clear then, that abrupt additions of energy to the Van Allen radiation must be reflected in decreases of the earth's surface field at the equator and must be detectable by surface magnetometer measurements. Slow, steady additions of energy balanced by loss of particles from the trapping region will, of course, not be detected by these means.

Our conclusion is then that major additions to the energy of the Van Allen belts occurs at the time of the beginning of the main phase of a magnetic storm, and only at that time. But this conclusion should be modified somewhat. The transition from initial phase to main phase is rather abrupt in most cases, and it seems offensive to our intuition to think that all the energy is added in a short time. We have left out of consideration the compression of the earth's field due to a cloud of plasma from the sun, which is the now generally Chapman-Ferraro picture of the initial phase of the storm. This compression causes an increase of the earth's surface field, which may mask the decrease due to addition of energy to the trapped radiation. It is consistent with the observations to think that energy is added all during the initial phase of the storm, and that the main phase begins when the exterior pressure of the plasma cloud is released in some way, leaving only the effect of the added energy to show itself.

A number of mechanisms have been put forward by various writers for the supply of energy to the trapped radiation, and the present work does not allow us to distinguish between them. Parker has shown, for a model which does not fit the expected situation very well, that the surface between the plasma cloud from the sun, and the earth's magnetosphere is unstable. Waves are generated in it, like the surface waves on water when a wind blows on it. These waves may propagate inward as hydromagnetic waves of some sort, to be absorbed and deposit their energy in the ring current region. Alternately, the waves may grow to the point where they break, and blobs of plasma may travel into the trapping region. The earth's field may be expected to penetrate slowly into the blobs, accelerating the particles by the betatron effect and trapping them at the same time. Other authors have not required the plasma-magnetosphere surface to be unstable, but have depended on irregularities of the moving plasma cloud to generate waves on the surface, with the same two possible effects. Any of these mechanisms seems to be capable of supplying energy to the ring current region, and some of them supply particles as well. All of them have the desirable property that they supply energy most strongly while the plasma cloud is blowing most strongly on the earth, a period which we have tentatively identified with the initial phase of a storm.

As has been already stated, the geomagnetic cutoff at Minneapolis returns toward normal faster than the magnetic field at the equator does, and in order to account for this on our theory, Winkler and I had to require that the radius of the ring decrease. It is possible to give a quite general mechanism for this, which includes a number of the special cases which have been invented by other authors. It is known that at magnetically disturbed times the magnetosphere is full of electromagnetic waves of various frequencies, which are observed at the earth's surface as micropulsations, in VLF observations as auroral hiss, dawn chorus etc. When a trapped particle interacts with a short electromagetic wave train it will gain or lose energy, depending on the phase of its gyrations around the lines of the earth's field. We may suppose that all of the electromagnetic waves act to shuffle the energy of the particles, so that some gain energy, and some lose it. These waves are probably also generated by the interactions of the particles themselves. Therefore they cannot change the total energy of the trapped particles, but can only redistribute it. Now the largest part of the electromagnetic waves probably has frequencies low compared to the electron cyclotron frequency. Then the first adiabatic invariant of the particle motion, $W_\perp/B$, will be conserved. A particle which gains energy therefore must move inward to a place where B is larger, and one losing energy moves out. The net motion of the center of gravity of the energy is inward, and it is the center of gravity of the energy which gives the effective position of the ring. (Actually, a detailed argument shows that the net motion of the energy is inward only if the field falls off faster than r^{-1}.)

This general mechanism accounts very well for the movement inward of the ring, without much change in total energy and therefore of magnetic field at the surface of the earth. Total energy of the ring will be lost only if one of the particles is lost to infinity or to the earth's atmosphere after an interchange of energy, otherwise the ring can move in without any change in total energy at all.

The observations of geomagnetic cutoff do not allow following the inward motion of the ring very far. Nevertheless it is logical to think that the more energetic electrons continue to move inward by energy shuffling and eventually become the energetic electrons of the outer Van Allen belt.

If this picture is correct, then the detailed structure of the outer zone depends on the average power in electromagnetic waves. Where there are large fluctuations of the field, diffusion of particles will be rapid, and therefore the gradient of particle density will be small. Our understanding of the structure of the Van Allen zones then would depend on our knowledge of the average power in waves as a function of position in the earth's magnetosphere, and it therefore seems very important to me to try to survey the power spectrum from satellites.

Discussion

Hess, W.N.: I would ask Dr. Kellogg whether he believes that the electrons of energy above 100 Kev and intensity about 10^8 electrons/cm^2. sec. in the outer belt can be due to neutron decay? The source strength and calculated lifetimes seems reasonable for this.

Kellogg, P.J.: I don't know if neutrons contribute appreciably to the high energy electrons. They can do so if the lifetime is the long lifetime of tens of years given by scattering and energy loss. But the lifetime is probably much shorter and determined by magnetic fluctuations. Even if the lifetime is long, it seems that there are still electrons having energy above the 780 Kev end point for neutron β-decay, and so there must be another source even at high energies.

Hess: Electrons in the outer belt of about 50 Kev will have a quite short lifetime about 10^7 sec. or less. This will mean that we need quite a large constant energy source to maintain a steady population of 10^{10} to 10^{11} electrons/cm^2. sec. in the outer belt. Would you comment on the nature of this energy source?

Kellogg: The energy supplied during a magnetic storm produces a field of the order of $100\,\gamma$ at the earth's surface. The whole energy of the Van Allen zones must produce a field less than $300\,\gamma$. Therefore at least one third of the whole energy is supplied by one storm and the energy source seems to be strong enough.