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SOME PROPERTIES OF THE VAN ALLEN RADIATION

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The Van Allen radiation belt (energetic particle radiation trapped in the geomagnetic field) has been shown[1-4] to consist of a hard proton component centered at about 10×10^3 km from the earth's magnetic axis (the proton belt) and an electron component centered at about 22×10^3 km from the earth's magnetic axis (the electron belt). The electron belt extends through the region occupied by the proton belt. It is generally accepted that the proton belt is produced by the decay of cosmic-ray albedo neutrons,[5-8] although some doubt has been expressed on this point.[9] The electron belt is usually held to be of solar origin.[10] The purposes of this Letter are twofold: first, to point out that the results of the observations of the outer zone of the Van Allen radiation belt made with the Explorer IV and Explorer VI satellite systems are inconsistent with the solar injection hypothesis; and second, to show that the electrons released in the decay of cosmic-ray neutron albedo may represent a satisfactory source for the outer zone. Source strength and trapping lifetime are not discussed.[11]

An illustrative sketch of particle flux vs radial distance in the equatorial plane is shown in Fig.1. This sketch is based principally on the measurements made by Simpson and his co-workers.[12] Hydromagnetic scattering probably limits the radial extent of the proton belt.[13] The measurements show that the electron belt consists of two regions separated by a relative minimum near 19×10^3 km from the geomagnetic axis. We know of no satisfactory explanation for this gap in the electron belt other than the one offered by the Capetown anomaly (a region several thousand kilometers in extent, centered southwest of Capetown, South Africa, and having an abnormally weak magnetic field strength).

It has been pointed out that the Capetown anomaly lowers the mirror altitude of the trapped radiation reflected near the anomaly by about 1000 km.[14] Since the atmospheric density is almost constant above about 1300 km where hydrogen predominates and increases very rapidly below this altitude where heavier atmospheric constituents predominate,[15] we should expect radiation mirroring

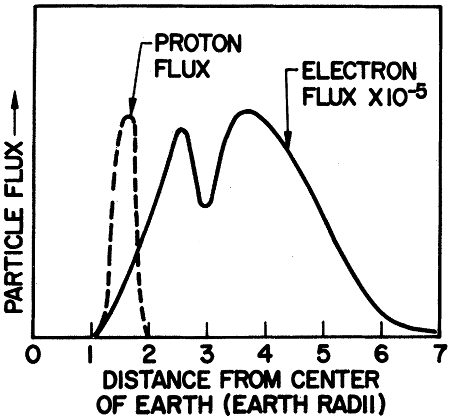

FIG. 1. Illustrative sketch of the Van Allen radiation belt particle flux vs radial distance in the equatorial plane. This sketch is based principally on data presented by Simpson et al.[12] The electron belt undergoes changes during magnetic storms which produce large variations in the counting rate of instruments flown through the belt.

below about 1300 km to be rapidly removed from the radiation belt. As the trapped radiation drifts around the earth's magnetic axis, a zone of relatively low radiation intensity will be developed at the magnetic latitude of the Capetown anomaly because that part of the Van Allen radiation which normally mirrors at altitudes up to 2300 km will be removed by atmospheric scattering at the lower mirror altitude over the Capetown anomaly. The part of the radiation belt affected by the anomaly has been determined from the surfaces given by the two adiabatic invariants (magnetic moment and integral invariant) of a charged particle in the earth's field as calculated by Vestine and Sibley[16] using the 48-term harmonic analysis of the geomagnetic field. With these data plus data on the altitudes of surfaces of constant field strength,[16] the effect of the Capetown anomaly is illustrated in Fig. 2. In this figure, mirror altitude is plotted against longitude for 3 different shells (the surface generated by a particle as it drifts arount the magnetic axis) as defined by the adiabatic invariants. It is apparent from this figure that the greatest decrease from a "normal" mirror altitude occurs over the Capetown anomaly for the field line or shell which crosses the equatorial plane at 17×10^3 km from the earth's center. Adjacent shells on either side of this one show a less pronounced effect. Further, it is expected that the sharpness of the anomaly is underestimated because the spherical harmonic analysis contains too few terms to describe its features adequately.[16] This view is supported by recent magnetic field measurements made by Heppner et al., with the Vanguard III satellite.[17] These measurements show that at altitudes of 2000 - 3000 km, the Capetown anomaly is much sharper and slightly deeper than predicted. Thus, we may conclude that the effect of the Capetown anomaly is much more localized than shown in Fig. 2. It therefore appears that the observed gap in the electron belt is in satisfactory agreement with the location of the Capetown anomaly.

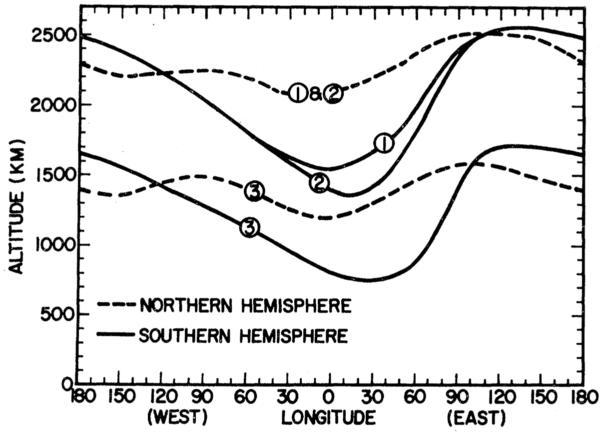

FIG. 2. The altitude of a given mirroring field, B_m, along 3 different traces determined from integral invariant calculations for magnetic field lines which extend a distance b from the earth's center in the equatorial plane.

Trace (1): $B_m = 0.18$ gauss, $b = 13\times10^3$ km.
Trace (2): $B_m = 0.20$ gauss, $b = 17\times10^3$ km.
Trace (3): $B_m = 0.30$ gauss, $b = 28\times10^3$ km.

Note that the average mirror point altitude for trace (2) in the northern hemisphere is lowered by about 1000 km over the Capetown anomaly. Traces (1) and (3) are not so severely affected.

As we have said, the Capetown anomaly can lead to the rapid removal only of electrons with mirror points below 2300 km altitude which will be reflected below 1300 km over the anomaly. Electrons with high mirror points will not be affected and will be responsible for a counting rate in the region where the gap is observed. The electron source, therefore, if reasonably isotropic, must inject electrons predominantly at low altitudes so as to assure low mirror points. This is quite a severe requirement. It seems obvious that particles of solar origin would not satisfy it. Electrons from neutron decay, on the other hand, do have the desired property of mirroring principally at low altitudes. Hess[8] finds that the neutron decay density near the earth varies approximately as $r^{-4}(1+3\sin^2\lambda)$, where λ is the latitude. This injection distribution leads to a flux decrease of about 10% near the equator if we use an altitude of 1300 km as the lower cutoff for injection but retain only particles mirroring above 2300 km. On the basis of this model we predict that the depth of the gap in the electron belt will show an altitude dependence: the gap will be more pronounced at low altitudes than near the equator on the magnetic field shell that passes through the Capetown anomaly.

The spectrum of the electrons resulting from neutron decay is peaked near 300 kev. The electrons which form the radiation belt are "cooled" by electron-electron collisions[11] to the observed E^{-5} spectrum.[2] These interactions will also affect the depth of the gap as measured by detectors of different thresholds.

We turn finally to a discussion of the magnetic-storm-induced fluctuations in the radiation belt.[12,18] These fluctuations (during which the counting rate in the electron belt may change by 10^4) are the principal evidence cited in support of the solar origin hypothesis of the trapped electrons. There are four difficulties with the solar injection hypothesis: (1) Solar particles could most probably be injected during the active phase of a magnetic storm, when the dipole character of the earth's field is disturbed. Yet, at this time, a decrease in counting rate is observed. That is, when additional electrons could be injected, they are not. (2) After the active part of a storm is over (recovery phase—low K index) the observed counting rate increases by several orders of magnitude. However, this is the time when the geomagnetic field is restored so that the entry of any but cosmic-ray particles into the field is most unreasonable. Thus, we argue that the counting rate increase occurs too late for solar injection to have been effective. (3) The particles have a lifetime of a year or more in the very rare atmosphere at high altitude. This lifetime is in accord with the fact that the intensity of the belt is stable during magnetically quiet periods. Nevertheless, with the solar injection hypothesis it is proposed that additional electrons are injected during a magnetic storm and that most of them disappear with a lifetime of a few days. This short lifetime seems inadmissible. (4) As discussed earlier, the existence of the gap in the electron component, and especially its persistence during and after magnetic storms, seem impossible to reconcile with the solar injection hypothesis.

The 10-kev solar wind protons, whose injection into the earth's field gives rise to the stresses that produce the magnetic field decrease during the main phase of a magnetic storm, have a trapping lifetime that is comparable to the time required for the enhanced counting rate to return to prestorm values. These protons are removed by charge exchange with the neutral hydrogen telluric corona.[19] We propose, therefore, that it is the magnetic field changes rather than changes in the number of trapped particles that give rise to the varying counting rates. There are two mechanisms by which this may happen. First, since the field changes are slow compared to the electron cyclotron frequency, the displacement of field lines will cause an accompanying displacement of particles. Many particles may therefore appear where only few had been before. Second, changes in the field intensity will result in an energy change of the particles; because the radiation counters have a threshold, the measured flux will be strongly affected. Both mechanisms can cause large changes in the counting rate, the first because the particle density varies rapidly with position, the second because the energy spectrum is very steep (e.g., an integral spectrum[2] as steep as E^{-5}). It seems clear that an appreciable fraction of the magnetic storm energy can be temporarily given to the radiation belt by the mutual inductance between the ring currents: (1) the solar wind protons and (2) the Van Allen belt electrons.

There are some incompletely treated problems that must be resolved before we can claim a complete understanding of the radiation belt. The source strength, the trapping lifetime, and the details of the magnetic storm effects[20] are the most important. Still, we feel that the present analysis leads to a fairly satisfactory picture in which the entire Van Allen radiation belt is due to neutron decay: The decay of fast neutrons produces the proton belt while the electron belt is attributed to the large number of slow neutrons which decay relatively near the earth.

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VARIATION WITH TEMPERATURE OF THE ENERGY OF RECOIL-FREE GAMMA RAYS FROM SOLIDS*

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The 14.4-kev γ ray emitted without recoil by 0.1-μsec Fe^{57} in metallic iron[1-4] excited great interest as the most precisely defined electromagnetic frequency yet discovered. It may be adequately well defined to allow measurement of the influence of a gravitational potential on frequency[5] and of other small effects hitherto beyond the sensitivity available in the laboratory. As a preliminary step in the operation of an experimental system designed to measure the gravitational effect, we have been making tests to find out whether other influences than the one intended might lead to systematic errors by introducing important frequency shifts not taken into account.

So far the largest such effect found is that of temperature. That temperature should influence the frequency exactly as we observe is very simply explained. Thermally excited vibrations cause little broadening through first order Doppler effect under the conditions obtaining in the solid because the value of any component of the nuclear velocity averages very nearly to zero over the nuclear lifetime. The precision of the γ ray of Fe^{57} requires the second order Doppler effect also to be considered. A shift to lower frequency with increased temperature results from this because the also well-defined average of the square of the velocity of the particle increases in direct proportion to the average kinetic energy. As a consequence one would expect a temperature coefficient of frequency in a homogeneous solid,

$$(\partial\nu/\partial T) = -\nu C_L/2Mc^2,$$

where C_L is the specific heat of the lattice and M is the gram atomic weight of iron. In the high-temperature classical limit where $C_L = 3R$,

$$(\partial\nu/\partial T)_{T\to\infty} = -2.44\times10^{-15}\nu \text{ per °K}.$$

At lower temperatures one would expect a coefficient reduced by the value of the appropriate normalized Debye specific heat function. For iron, at 300°K one should find about 0.9 times, and at 80°K about 0.3 times, the above classical value.

The temperature dependence has been measured by counting the γ rays from our 0.4-curie Co^{57} source transmitted through enriched Fe^{57} absorbing films (0.6 mg Fe^{57}/cm^2). The Co^{57} of the source is distributed in about 3×10^{-5} cm thickness below the surface of a 2-in. diameter iron disk, made in the manner described earlier.[1] Small frequency shifts that result when the source and absorber are held at different temperatures were measured by using a transducer to move the source sinusoidally at ten cps toward and away from the absorber at a peak speed of about 0.01 cm/sec. A gate pulse and mercury relays were used to make one counter record during 25 milliseconds of the modulation period symmetrically disposed about the time of maximum velocity toward the absorber. Another