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Letters

Time Reversal of the Geocyclotron Mechanism

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The purpose of this report is to outline a possible method of removing high-energy particles from natural or artificially produced radiation belts. This method is based on the idea of the geocyclotron [*Helliwell and Bell*, 1960] and in essence is the time reversal of the geocyclotron mechanism.

In this inverse geocyclotron interaction the object is to de-energize high-energy electrons by means of gyroresonance, a phenomenon in which electrons in the earth's outer ionosphere are decelerated by frequency-modulated, circularly polarized electromagnetic waves generated on the ground. These waves would be guided approximately along the earth's magnetic field lines in the whistler mode until they reach a region suitable for interaction. In the interaction region, electrons in the proper relativistic energy band will see a wave whose frequency is equal to the electron's natural relativistic frequency of rotation about the field lines (i.e., the electron's relativistic gyrofrequency). If the wave frequency increases slowly with time, it is possible to trap a number of these relativistic particles for a time in the potential well of the wave; during this period the particles can be continuously decelerated.

If it is assumed that the medium parameters vary quasi-statically in the region of interaction, it can be shown [*Bell et al.*, 1963] that the following relations hold for ϕ, the phase of the particle motion; E, the total particle energy (measured in units of rest mass energy); and τ, the transformed time:

$$\frac{d^2\phi}{d\tau^2} + \sin\phi\left[1 + 3\beta\frac{d\phi}{d\tau}\right] + \alpha\beta\frac{d\phi}{d\tau} + \alpha = 0 \tag{1}$$

$$d/dt\,[\sqrt{E^2 - 1}] = \gamma\sin\phi \tag{2}$$

in which $d\tau = \omega\beta\, dt$; α, β, and γ are quasi-statically varying parameters, and t is the real time.

The simultaneous solution of the above equations yields the rate of particle deceleration in the interaction region.

In theory the 'interaction region' can consist of any portion of the outer ionosphere that can be properly illuminated by the circularly polarized waves and that contains relativistic particles of a given energy range. Since it is assumed that the electromagnetic waves will follow the earth's magnetic field lines, the longitude of the transmitter will define the approximate mean longitude of the interaction region and the latitude of the transmitter will define the particular field line group along which the electromagnetic waves are assumed to propagate. It is known that a combination of effects causes particles trapped in the earth's magnetic field to drift in longitude about the earth [*Welch and Whitaker*, 1959]. Because of this longitudinal drift about the earth, particles entering the interaction region will spend but a limited time in this region. It can be shown [*Bell et al.*, 1963] that a group of particles trapped by a sufficiently strong wave (of the order of 10^{-4} volt/meter) can lose up to a few Mev in energy during one pass through the interaction region. On subsequent passes through the interaction region the same particles can be further decelerated by properly adjusting the transmitter frequency-time function. In this manner it may be possible to remove some of the higher-energy components of radiation-belt particles.

A simple numerical example will serve to demonstrate some of the features of the inverse geocyclotron mechanism. We will assume that there is in operation at 38° geomagnetic latitude a transmitter of 100-kw output capable of transmitting the desired frequency-time function, and we will assume that this transmitted wave reaches the interaction region. We will specify the interaction region to be the portion of the outer ionosphere that is within a few degrees of the geomagnetic equatorial plane and is illuminated by the electromagnetic waves from the transmitter. The illuminated region at the equatorial plane is estimated to be approximately 2500 km in diameter, and the length of the interaction region along the field lines approximately 700 km.

Let us consider all high-energy electrons whose natural motions carry them through this interaction region and whose mirror points lie within a few degrees of the geomagnetic equatorial plane. Let us assume that of this particular group of electrons we wish to interact with those that initially lie in the kinetic energy band 2.2 ± 0.01 Mev. Let us further suppose that we wish to decelerate approximately one-half of all the electrons in this band. For the assumed transmitter power a single frequency sweep of the proper shape will be sufficient to decrease from 2.2 ± 0.01 Mev to 0.5 Mev the kinetic energy of most of the electrons in the given energy band that are located in the interaction region at the initial time of wave transit.

It can be shown that under these conditions the transmitter frequency sweep function will have the general form

$$f(t) = f_H[E_0 - \epsilon t]^{-1} \tag{3}$$

in which $f(t)$ is the transmitter frequency sweep function, f_H is the mean gyrofrequency in the interaction region, E_0 is the mean total relativistic energy of the electrons (in our case 2.7 Mev), t is the real time, and ϵ is a parameter dependent upon the transmitter strength and location. Approximately 100 frequency sweeps would be necessary to deplete the total number of electrons in the given energy band by the factor 0.5. Each sweep would take of the order of 40 seconds, and the total operation would require approximately 1 hour. Longer times are required to deplete the particle density in an energy band of greater width. For instance, if it is desired to deplete the particle density by a factor of 1/2 in the energy band extending from 2.2 to 1.7 Mev, approximately 20 hours of transmitter operation would be required. The majority of the particles removed from this band would be reduced in energy to approximately 0.5 Mev.

The above results are predicated upon the assumption that the waves from the ground-based transmitter actually reach the selected interaction region. On the basis of the present state of knowledge of VLF ionospheric propagation there is no known way to ensure that this condition can be satisfied. Indeed, it appears reasonable to suppose that as the transmitter frequency changes so will the propagation path of the waves through the ionosphere. On the other hand there is strong evidence from whistler studies that discrete paths of propagation, sometimes called 'ducts,' exist and are capable of guiding multifrequency wave packets over an approximately 'fixed' path. These ducts have lifetimes of the order of hours, which is sufficient to enable the geocyclotron mechanism to operate successfully in a given interaction region.

There is a second and perhaps more critical restriction in regard to the wave propagation. It can be shown for the transmitter location considered that, for the inverse geocyclotron interaction to take place, it is necessary that the wave normals in the interaction region be confined to within approximately 15° of the magnetic field lines. Although the behavior of the wave normals has not yet been measured, it seems likely that this restriction can be satisfied for ducted but probably not for nonducted modes of propagation. This question clearly requires more study.

It should be noted that recently *Dungey* [1963] has proposed a method of artificial removal of high-energy electrons from the radiation belts by means of a transresonant interaction [*Parker*, 1961] between the electrons and man-made waves traveling in the whistler mode. This method involves random scattering of the particles by the wave as the particles pass through a gyroresonance, and the net result of the individual encounters is a random walk in altitude of the particle mirror points. It would appear that this proposed mechanism of high-energy particle removal is in principle inefficient in comparison with the geocyclotron mechanism; however, during the operation of the geocyclotron transmitter this scattering mechanism can be expected to occur in addition to the inverse geocyclotron effect. Consequently, slightly higher rates of particle removal than shown above can perhaps be expected.

Despite the inadequacy of existing knowledge about VLF ionospheric propagation, it may be concluded that the reversal of the geocyclotron mechanism offers a possible method of removing high-energy particles from natural or artificially produced radiation belts.

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