Electron Acceleration in the Ionosphere by Obliquely Propagating Electromagnetic Waves

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The relativistic equations of motion have been analyzed for electrons in magnetized plasmas and externally imposed electromagnetic fields that propagate at arbitrary angles to the background magnetic field. The electron energy is obtained from a set of non-linear differential equations as functions of time, initial conditions and cyclotron harmonic numbers. For a given cyclotron resonance the energy oscillates in time within the limits of a potential well. Stochastic acceleration occurs if the widths of hamiltonian potentials overlap. Numerical analyses suggest that, at wave energy fluxes in excess of 10^8 mW/m², initially cold electrons can be accelerated to energies of several MeV in less than a millisecond. Practical attempts to validate the theory with a series of planned rocket flights over the HIPAS facility in Alaska are discussed. The HIPAS antennas will be used to irradiate the magnetic mirror points of 10–40 keV electrons emitted from the ECHO 7 rocket in the early winter of 1988. Follow-on rocket experiments to exploit the wave amplification properties of the ionospheric “radio window” are described.

1. Introduction

Attempts to actively perturb space plasmas using HF emissions from ground based antennas have generally used O-mode radiation (STUBBE *et al.*, 1985; ROSE *et al.*, 1985; LEE *et al.*, 1988). The X-mode can only propagate to the altitude of cutoff. This is because the circularly polarized X-mode rotates in the same sense as electrons about the magnetic field, and thus interacts strongly with them. Recently scientists at the Air Force Geophysics Laboratory (AFGL) have become interested in using this characteristic for controlled, gyroresonant acceleration of electrons in space plasmas. Indeed, gyroresonant X-mode radiation has been used successfully to accelerate electrons to relativistic energies in the ELMO Bumpy Torus (BATCHELOR and GOLDFINGER, 1980). Although the driving mechanisms have not been established, JAMES (1983) has reported the presence of electrons accelerated up to several kilovolts in energy after sounder emissions from the ISIS satellites. BABAEV *et al.* (1983) have also reported the detection of electrons accelerated to kilovolt energies through interactions with a low power telemetry system.

The motion of an electron moving in the presence of a right circularly polarized wave propagating along the magnetic field has been treated by ROBERTS and

BUSCHBAUM (1964). They show that if the Doppler shifted frequency of the driver wave is at the electron gyrofrequency, and the phase speed of the wave is that of light in free space, test electrons stay in resonance and can be accelerated to arbitrarily high energy. For other wave phase speeds, electrons eventually lose resonance due either to the relativistic lowering of the gyrofrequency or to unbalanced Doppler shifts. In either case the electrons appear to move in pseudo-potential wells in which they alternately gain and lose kinetic energy. Recently the analysis of Roberts and Buschbaum has been extended to include the case of obliquely propagating waves using two different perturbation formalisms. MENYUK *et al.* (1987) utilized the canonical Hamiltonian while VILLALON and BURKE (1987) solved the Lorentz equation. While the first concentrated only on the stochastic regime, the second considered both stochastic and sub-stochastic acceleration.

This paper is divided into three sections in which we discuss: first, the relativistic Lorentz equation for a test electron moving under the influence of an electromagnetic wave in a cold magnetized plasma, second, wave propagation through the ionospheric "radio window," and third, a series of planned space flights to test the validity of our model.

2. Analytical and Numerical Solutions of the Lorentz Equation

We consider the motion of an electron gyrating in a constant magnetic field $B_0\hat{z}$ in the presence of an obliquely propagating electromagnetic wave with wave vector $\mathbf{k}=k_x\hat{x}+k_z\hat{z}$ and frequency ω . The wave's electric field is given by

$$\mathbf{E} = E_1\hat{x}\cos\phi - E_2\hat{y}\sin\phi - E_3\hat{z}\cos\phi,$$

where the phase angle $\phi=k_x x+k_z z-\omega t$. The Lorentz equation is

$$\mathbf{p} = q[\mathbf{E} + \mathbf{V} \times (\mathbf{B}_0 + \mathbf{B}_w)],$$

where $\mathbf{p}$, $\mathbf{V}$ and q represent the momentum, velocity and charge of the electron; $\mathbf{B}_w$ is the wave magnetic field. This equation admits three constants of the motion derived from

$$d/dt[\mathbf{p} - q\mathbf{r} \times \mathbf{B}_0 - \mathbf{k}H/\omega + q\mathbf{A}] = 0,$$

where $\mathbf{A}$ is the vector potential of the wave and $H=mc^2\gamma$, is the relativistic energy. γ is the standard relativistic factor $1/\sqrt{1-v^2/c^2}$. The relativistic momentum and velocity are related by $\mathbf{p}=m\mathbf{V}\gamma$. The time rate of change of the electron's Hamiltonian is

$$dH/dt = qc^2(\mathbf{E} \cdot \mathbf{p})/H.$$

Substitution into the Lorentz equation gives

$$\begin{aligned}
\dot{p}_x + p_y[\Omega + (qE_2k_x)/(m\gamma\omega)\sin\phi] &= (qE_1/\omega)(\omega - K_zz)\cos\phi, \\
\dot{p}_y - p_x[\Omega + (qE_2k_x)/(m\gamma\omega)\sin\phi] &= -(qE_2/\omega)(\omega - k_zz)\sin\phi, \\
\dot{p}_z - (K_z\dot{H}/\omega) + (E_3/E_1)(\dot{p}_x + \Omega p_y) &= 0,
\end{aligned}$$

where $K_z = k_z[1 + E_3k_x/E_1k_z]$ and $\Omega = qB_0/m\gamma$ the relativistic electron cyclotron frequency. Dots over quantities indicate time derivatives. To this point the equations are exact.

Our first assumption is that terms containing the quantity $(E_2k_x/\omega) = B_z \ll B_0$ can be ignored in any reasonable geophysical situation. The second assumption is that to zero-order the x and y components of the momentum vector of any test electron follow Larmor trajectories.

$$\begin{aligned}
p_x &= -p\sin(\sigma + \alpha_0), \\
p_y &= p\cos(\sigma + \alpha_0),
\end{aligned}$$

where

$$\begin{aligned}
\sigma(t) &= \int_0^t \Omega(t') dt', \\
\alpha_0 &= \tan^{-1}(p_{x0}/p_{y0}),
\end{aligned}$$

with the subscript 0 referring to initial momentum conditions.

After substituting into the Lorentz equation, expanding in a series of Bessel functions, averaging over fast time variation and filling many pages of algebra, whose main steps are indicated by VILLALON and BURKE (1987) we arrive at an equation in the form

$$[1 + U]^2 [dU/dt]^2 + \omega^2 V_n(U) = 0.$$

This is very similar to the equation of a particle moving in a pseudo-potential field. The term $U = (H - H_0)/H_0$ represents the hamiltonian of the electron normalized to its initial value. The subscript n on the potential functions $V_n(U)$ represents the contribution of the n -th harmonic of the electron gyrofrequency. The actual form of the potential is given in Appendix 1. Here we note several features of the potential that provide immediate insight into this electron acceleration model. First, an electron can only access the regions of parameter space in which V_n is negative. The regions of access can be determined for each harmonic by solving for the zeros of the potential. Second, at large value of U the potential increases as U^4 . Thus, in the asymptotic limit V_n is positive and the amount of energy that can be absorbed from the wave is finite. Third, the contributions of the right, left and parallel polarizations are distinct and depend on Bessel functions of order $n-1$, $n+1$ and n , respectively. Thus, right circularly polarized waves should interact most strongly. Since the arguments of the Bessel functions are products of k_x and the gyroradius, accelera-

tion efficiency should be enhanced for test electrons with a substantial, initial kinetic energy.

To test the range of validity of the assumptions presented above, we have performed a series of numerical solutions of the Lorentz equation and compared the results with the predictions of our pseudo-potential model. In all cases we used electromagnetic waves propagating in the X-mode at a frequency twice that of the electron gyrofrequency. The ratio of the plasma frequency to the drive frequency is 0.58. These correspond the conditions of $B_0=0.55$ G and $n=10^4$ /cc, typical of the bottomside of the ionosphere at auroral latitudes during periods of magnetic quiet. Note that under these conditions the waves are propagating below the right hand cutoff where VILLALON and BURKE (1987) predict the strongest electron/wave interactions. All cases presented here represent averages of 33 cases with random initial phases.

In Fig. 1 we present a summary of the numerical results. In log-log format we have plotted the maximum kinetic energy gained by initially cold test electrons normalized to their rest energy as a function of the wave Poynting flux in milli-Watts per square meter. Note that existing mega-Watt ionospheric heaters typically

Fig. 1. Numerical solutions of Lorentz equation. The kinetic energy gain is plotted as a function of input wave energy flux. The straight line and triangles represent average energy gained by thirty three test electrons with random initial phase from gyroresonant waves propagating along and at 30° to magnetic field lines, respectively.

deliver $1\text{--}10\text{ mW/m}^2$ to ionospheric altitudes of 200–300 km. The straight line and diamond symbols represent effects of radiation propagating along and at 30° to the magnetic field, respectively. Results for higher angles are similar to those at 30° . The characteristics of the acceleration divide into three categories which we call quasi-periodic resonance, chaotic and direct wave acceleration. The range of chaotic acceleration extends roughly from 10^7 to 10^{11} mW/m^2 .

Figure 2 provides examples of each type of acceleration with the solutions followed for 0.7 ms. Wave intensities of 10^6 mW/m^2 accelerate initially cold electrons to 60 keV in $400\text{ }\mu\text{s}$ and then fall back to low energy. If the wave intensity is increased to 10^8 mW/m^2 electron are accelerated irregularly to 9 MeV. In the direct

Fig. 2. Numerical solutions of the Lorentz equation for three wave energy flux levels followed for 0.7 ms.

acceleration regime wave magnetic fields are greater than B_0 and electrons undergo periodic accelerations up to 50 MeV.

Comparisons of the predictions of the pseudo-potential model of VILLALON and BURKE (1987) with the numerical solutions of the Lorentz equation are given in Fig. 3, represented by dashed lines and triangles, respectively. The first impression gained from this comparison is that predictions of these independent approaches to the problem are in remarkable agreement. At a propagation angle of 0° the V - B and numerical solutions agree exactly. At other angles V - B predicts less acceleration than was numerically calculated.

Fig. 3. Comparison of predictions of pseudo-potential models with exact numerical solutions of the Lorentz equation for different wave propagation angles.

Figure 4 plots the values of $V_n(U)$ for selected values of n . Again the wave frequency is at the second gyroharmonic, with a Poynting flux of 10^7 mW/m². The region of negative potentials extends down to $U=0$ for the first and second harmonics. We note however, that the slope of the potential for the first harmonic is steeper than the second at low energies. Thus, initial acceleration is by the first, rather than the second harmonic. Potentials of higher harmonics are initially positive and do not accelerate low energy electrons.

Fig. 4.

3. Radio Window Mode Conversion

It is obvious from the discussion presented above that serious acceleration of ionospheric electrons by ground antennas requires power enhancements that greatly exceed any capabilities that can be achieved within a reasonable time span. This is one time however, when nature appears to be working on our side. MJOLHUS and FLA (1984) have studied O-mode radiation propagating in the ionosphere where the vertical plasma density gradient is at an arbitrary angle to the earth's magnetic field. Consequent to obeying Snell's law the cold plasma dispersion relation reduces to the Booker quartic (BOOKER, 1938). Normally, O-mode radiation propagates to the altitude where the driver frequency is equal to the local plasma frequency and is reflected. It is possible however, for radiation transmitted from ground in the O-mode close to a critical angle θ_c to convert linearly to the Z-mode, where

$$\sin \theta_c = \sqrt{Y/(Y+1)} \sin \psi.$$

Here $Y = \Omega/\omega$. For the case we have been considering here $Y=2$. In Alaska where the magnetic dip angle is about 13° , $\theta_c = 7.5^\circ$ towards the south of vertical.

O-mode rays in this "radio window" propagate in the slow extraordinary (Z) mode to the altitude of cutoff where they are reflected. As they approach the altitude where

$$X = (1 - Y^2)/(1 - Y^2 \cos^2 \psi),$$

with $X = (\omega_p/\omega)^2$, the Z-mode undergoes resonance. Here the group speed slows to zero. In this region the Z-mode turns into an electrostatic wave that propagates perpendicular to the $\mathbf{B}_0$. Cold plasma theory does not allow the possibility of electrostatic waves. VILLALON (1988) had included warm plasma effects as second order corrections to the Booker quartic. In the resonant region the group velocity (V_g) of the electrostatic waves is much less than the speed of light with which the radiation enters the ionosphere. The conservation of energy requires that the amplitude of the wave electric field steepens as $(c/V_g)^{1/2}$. Calculations by VILLALON (1988) show that in the resonant region electrons can be accelerated by several keV with modest input powers of 1 mW/m^2 . The possibility of the wave energy being dissipated by other non-linear processes must next be given careful analysis.

4. Planned Space Experiments

Experiments to test in space the validity of the theoretical models outlined in the last two sections are planned for the next several years. To perform such experiments two major elements are necessary: (1) an HF ground source, and (2) properly instrumented space vehicles. We first consider the impact of these constraints for mission planning.

Suitable ground antennas exist at Tromso in Norway, Arecibo in Puerto Rico and HIPAS in Alaska. Although the Tromso and HIPAS antennas have access to nearby rocket ranges, Arecibo does not. From the closeness of the "radio window" to both the vertical and magnetic field directions at high latitudes, rocket trajectories must pass both overhead and close to the magnetic meridian. Rockets fired from the Andoya range are constrained to over-water trajectories at some distance from Tromso. It is possible to launch rockets toward magnetic north from mobile launchers located south of HIPAS.

To measure the characteristics of the waves transmitted from the ground as well as their effects on both the ionospheric plasma and the acceleration of electrons to kilovolt energies, *in situ* diagnostics are necessary. These instruments should measure: (1) the density and temperature of the ionospheric constituents to specify the cold plasma dielectric coefficient, (2) the spectral characteristics of waves in the ionosphere to provide information on alternate decay modes of the primary wave associated with parametric instabilities, and (3) energetic electron detectors that look both up and down magnetic field lines. The latter are useful for distinguishing wave-acceleration from natural auroral effects.

Some or all elements of this complement of passive detectors are available on present or planned American and Japanese polar orbiting satellites. Because of the repeatability of coordinated ground-satellite experiments these resources should be utilized to the fullest. There are however, significant drawbacks to satellite based experiments that cannot be ignored. First, satellites generally fly at altitudes far above the interactions discussed in the previous sections. At these heights it is very difficult to meet exacting magnetic conjunction conditions. Thus, only debris from wave-electron interactions can be detected. Second, because of the high speed of satellites and the relatively low sampling rates allowed to particle detectors, spatial resolution is probably insufficient. Limitations of the second kind are directly addressed by the joint US/Canadian satellite FOCUS 1, scheduled for a Scout launch in the early 1990's. FOCUS will only operate in real time when in view of ground receiving stations. High spatial resolution will be achieved by using a broad band telemetry system normally associated with rocket experiments. Coordinated studies of wave-plasma interactions using ionospheric heaters is a prime scientific goal of this mission.

To understand the basic physics of wave particle interactions suborbital rocket flights have much to offer. First, they can be designed to pass close to or through critical volumes of space at relatively low speeds. Second, available telemetry rates allow important parameters to be measured with high resolution. Third, spatial-temporal ambiguities are easily resolved by simultaneous measurements with multiple payloads. Fourth, the environment can be actively varied to meet specific experimental goals. In the case at hand, an artificial auroral environment can be turned on and off by emitting charged particle beams from one of the rocket payloads. Fifth, rocket launches can be coordinated with satellite passes over heaters to gain maximum insight into the large-scale effects of localized plasma perturbation experiments.

An initial attempt to validate the electron acceleration concepts will be carried out during the flight of the ECHO 7 rocket. ECHO 7 represents a cooperative effort between NASA, the University of Minnesota and AFGL. Launch from Poker Flat toward magnetic east is scheduled for a moonless evening during a period of low magnetic activity in the early winter of 1988. There are four payloads, one to emit electrons with controlled injection energy between 10 and 40 keV and pitch angles between 15° and 180° ; the other three measure plasma, energetic particle and electromagnetic field effects of the beam emissions. The primary mission of ECHO 7 is to study the long distance transmission properties of electron beams in space. It is also ideally instrumented to measure the effects of HF waves interacting with controlled plasma environments.

The ground track of the ECHO 7 trajectory along with the positions of the Poker Flat Range, the HIPAS facility and Eilson AFB are sketched in Fig. 5. The heavy part of the trajectory line represents the post-deployment segment of the flight. The hatched portion near the HIPAS magnetic meridian represents the "radio window." The dashed line to the north of the trajectory represents the

Fig. 5. Schematic representation of ECHO 7 trajectory relative to the position of the HIPAS facility. The heavy line represents the post deployments phase of the flight. The dashed line represents the mirror points of beam electrons emitted downward from ECHO. This region will be illuminated by X-mode radiation at the second harmonic of the electron gyro-frequency.

location of magnetic mirror points at 100 km for beam electrons injected down the field lines. We note that full deployment of the ECHO payloads occurs about thirty kilometers to the east of the HIPAS magnetic meridian. Experiments designed to verify the effects of transmission through the "radio window" are thus doomed to failure. For this reason we have decided that during the ECHO flight it is better to illuminate the region of the magnetic mirrors with radiation near the second harmonic of the electron gyrofrequency in the X-mode. This is the right hand polarization mode that does not propagate to very high altitudes in the ionosphere. However, the V - B model predicts efficient acceleration near the right-hand cutoff.

A series of follow-on rocket flights along the magnetic meridian over HIPAS is planned for the early 1990's as a joint effort with NASA and UCLA. The diagnostic packages to be flown during these experiments will be similar to those flown on ECHO 7. Photometers will be added to the complement to measure radiation from cavitons expected to form in the vicinity of the Z-mode resonance. Periodically during the mission, energetic electron beams will be injected into the resonance region. Thus, the relative efficiencies for cold/warm electron acceleration by Z-mode radiation can be determined.

Figure 6 is a sketch of the planned experimental geometry. The rocket trajectories will be in the HIPAS magnetic meridian. HIPAS will transmit at the

Fig. 6. Schematic representation of a ray propagating in the ionospheric "radio window." Near the Z-mode resonance it is expected that plasma density cavitons will form.

second gyroharmonic, in the O-mode. Rays outside the “radio window” are reflected to the ground with little effect on the ambient plasma. Inside the “radio window” radiation that converts to the Z-mode continue to propagate to the altitude of the left hand cutoff where they are reflected. As the Z-mode radiation approaches resonance the intensity of the wave vector turns normal to the magnetic field and the electric fields steepen. Ponderomotive forces generate plasma density cavitons (WONG and SANTORU, 1981; WONG *et al.*, 1987). Electrons within the cavitons see intense electric field variations at the second gyroharmonic. When the rockets are near magnetic conjunction with HIPAS created cavitons, particle detectors should measure intense fluxes of accelerated electrons.

Appendix 1. Mathematical Form of Pseudo-Potentials

In the main text we argued that the equations of motion for a test electron in an obliquely propagating electromagnetic wave can be reduced to the form of motion in a potential well.

$$(dU/dt)^2 + \omega^2 V_n(U)/(U+1)^2,$$

where $U=(H-H_0)/H_0$ is the energy gained normalized to the initial relativistic Hamiltonian. The potential well associated with the n -th harmonic of the electron gyro-frequency is

$$\begin{aligned} V_n(U) = & (d_1 U/2)^2 (U + 2r_n/d_1)^2 - \psi(0) \sin \phi_n d_1 U (U + 2r_n/d_1) \\ & + (\Sigma_1 - \Sigma_2)/2 \{ (\Sigma_2 d_1 - \Sigma_1 h_1) (G_{n+1}(U) + F_{n+1}(U)) \\ & \quad + (\Sigma_2 d_2 - \Sigma_1 h_1) F_{n+1}(U) \} \\ & - (\Sigma_1 - \Sigma_2)/2 \{ (\Sigma_1 h_1 + \Sigma_2 d_1) (G_{n-1}(U) + F_{n-1}(U)) \\ & \quad + (\Sigma_1 h_2 + \Sigma_2 d_1) F_{n-1}(U) \} \\ & - \Sigma_3^2 \{ h_1 (G_n(U) + F_n(U)) + h_2 F_n(U) \} - (\psi(0) \cos \phi_n)^2. \end{aligned}$$

Terms with $\Sigma_1 + \Sigma_2$ and $\Sigma_1 - \Sigma_2$ refer to the right and left hand polarization modes, respectively.

Here also

$$\begin{aligned} \Sigma_i &= -(qE_i/\omega)c/H_0 \quad i = 1, 2, 3, \\ d_1 &= 1 - K_z k_z c^2/\omega^2, \\ d_2 &= (K_z k_z c^2/\omega^2) - k_z \dot{z}_0/\omega, \\ h_1 &= 1 + (K_z/k_z)(d_1 - 1), \\ h_2 &= (K_z/k_z)d_2, \end{aligned}$$

$$\begin{aligned}
r_n &= 1 - k_z \dot{z}_0 / \omega - n \Omega_0 / \omega, \\
\phi_n &= k_z z_0 + n(\alpha_0 + \pi/2), \\
\psi(0) &= V_0/2c[-(\Sigma_1 + \Sigma_2)J_{n-1}(k_x \rho_0) + (\Sigma_2 - \Sigma_1)J_{n+1}(k_x \rho_0)] \\
&\quad + V_{z0}/c \Sigma_3 J_n(k_x \rho_0),
\end{aligned}$$

where J_n represents a standard Bessel function of order n . The functions $G_n(U)$ and $F_n(U)$ are defined by

$$\begin{aligned}
G_n(U) &= \int_0^U J_n^2[k_x \rho(U')] U' dU', \\
F_n(U) &= \int_0^U J_n^2[k_x \rho(U')] dU'.
\end{aligned}$$

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