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LOG Id: LOG_0058
LOG Titel: The geocyclotron revisited: potentialities of modulated wave injection
LOG Typ: article

Übergeordnetes Werk

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J Geophys (1981) 49:245–246

Journal of Geophysics

Short Communication

The Geocyclotron Revisited: Potentialities of Modulated Wave Injection

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Key words: Modulated wave injection – Continuous cyclotron resonance – Whistler-electron interaction

Introduction

Controlled VLF-wave injection into the magnetosphere has been used in the Siple experiment (Antarctica, $L=4$) since 1973 (Helliwell 1977); similar capability also exists in the high-latitude ionospheric heating experiments ($L \sim 6$) run by the Murmansk Polar Geophysical Institute and the Max-Planck-Institut für Aeronomie, through modulation of the polar electrojet (Stubbe and Kopka 1977), and might possibly be implemented in an early space shuttle mission or on a satellite. We here draw attention to the potentialities offered by an adequate variation of the frequency and amplitude of the coherent, injected radio signal. They include selective modifications of the energetic electron distribution along a given magnetic field line, testing of nonlinear (wave-particle) interaction theories and enhancement, at lower power levels, of magnetospheric phenomena associated with wave injection. The modulation of the injected frequency extends the cyclotron resonance interval in the inhomogeneous magnetosphere, whereas the eventual need for amplitude modulation is suggested by a stability analysis of the trapped electron motion in the whistler field.

Modification of the energy of radiation-belt electrons through their gyro-resonance with artificial whistlers of modulated frequency was suggested twenty years ago as an alternative to high-altitude (e.g., Argus) nuclear detonations (Helliwell and Bell 1960). The idea was then to vary the frequency of the circularly polarized whistler in order to compensate for the change of mass experienced by relativistic cyclotron resonant electrons. This 'geocyclotron' was, however, not implemented; the feasibility study concluded that the information required to make a reliable prediction was not available at the time (Bell 1964).

Stability of Interaction

In contrast to the original geocyclotron mechanism whereby the electrons stayed in the vicinity of the equatorial plane and the change in the wave frequency compensated for the relativistic effects, we now propose to program the wave frequency so that energetic electrons moving towards the transmitter experience continuous cyclotron resonance with the wave in a way which maximizes the modification of the electrons energy and pitch angle.

The interaction between ducted CW parallel whistler mode waves and counter-streaming cyclotron resonant electrons ($v_\perp$, $v_\|$) might induce phase trapping (Dysthe 1971; Gendrin 1975). The evolution for the angle $\psi = \mathrm{ang}(-B_w, v_\perp)$, with $\operatorname{sgn}\psi = \operatorname{sgn}(E_w, v_\perp)$, is identical to the pendulum equation having a steady forcing term resulting from the inhomogeneity of the medium. This forcing term, which causes the equilibrium position ψ_0 of a trapped particle to be non-zero, increases as the particle moves away from the equator and detrapping eventually occurs. It should be stressed that a non-zero ψ_0 implies that even a deeply trapped (weakly oscillating) particle has a non-zero electrical force acting on it. Thus the energy, E, and the equatorial pitch angle, α_e, increase (decrease) when $\sin\psi_0$ is negative (positive). Although the inhomogeneity limits the effective interaction time, resonances involving CW whistlers are responsible for a wide variety of magnetospheric phenomena; extension of the interaction time would be expected to enhance these effects.

Variation of the whistler frequency ω originates a new forcing term in the pendulum equation proportional to $\dot{\omega}$. Adequate choice of the wave frequency can then lead to a constant equilibrium angle, ψ_0, and hence to a steady unidirectional transfer of energy between the particle and the wave. We have found, for a given ψ_0, the appropriate ω to be

$$\dot{\omega} = \left\{ \left[\frac{k v_\perp^2}{2\omega_c} + \left(1 + \frac{v_\|}{2V_G}\right) v_\| \right] \frac{d\omega_c}{dz} - \frac{k v_\|^2}{\omega_p} \frac{d\omega_p}{dz} - \omega_{NL}^2 \sin\psi_0 \right\} \Big/ \left(1 + \frac{v_\|}{2V_G} \frac{\omega_c}{\omega}\right), \qquad (1)$$

where V_G is the cyclotron resonant parallel velocity, $\omega_c/2\pi$ the gyrofrequency defined by the geomagnetic field aligned with the z-axis, $\omega_p/2\pi$ the plasma frequency, and $\omega_{NL}/2\pi$ the bounce frequency of deeply trapped electrons in the CW, homogeneous medium case.

Clearly, particle trapping has to be stable if the expected interaction enhancement is to occur. In this respect, we first note that direct analysis of the pendulum equation shows small deviations from ψ_0 to be unstable when $\cos\psi_0 < 0$; elsewhere, in the stable domain $|\psi_0| < \pi/2$, deeply trapped electrons have harmonic motion with angular frequency ω_{NL} $(\cos\psi_0)^{1/2}$. The long term stability of the trapped orbits can be assessed by following the evolution of a generalized trapping parameter. In the CW homogeneous case, the trapping parameter $\xi = \eta^2$ characterizes the resonant trajectories (Dysthe 1971): the separatrix ($\xi = 1$) divides the phase plane into trapped ($0 < \xi < 1$) and untrapped ($\xi > 1$) domains. For the general interaction, noting that our oscillating system is Hamiltonian with slowly (on the scale of $1/\omega_{NL}$) varying parameters, and adopting the generalized trapping parameter used by Dysthe and Gudmestad

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0340-062X/81/0049/0245/$01.00

(1977) in the study of trapping by Langmuir waves, we can establish that $\xi\omega_{NL}$ is an invariant of the interaction. Since ω_{NL}^2 is proportional to the whistler amplitude, trapping stability (non-increasing ξ) can prevail, even for particles initially not very deeply trapped, by appropriate amplitude modulation of the injected wave, thus preventing too large a decrease of ω_{NL} and a corresponding increase of ξ above unity.

Results and Discussion

Figures 1 and 2 show typical results obtained from the simultaneous solution of the average (deeply trapped, $\psi \sim \psi_0$) electron motion equations and Eq. (1). The electrons initiate the interaction at the equator, or at 10° N latitude, with $v_{\parallel *} = V_G$, as defined by the initial wave frequency ω_*, and $v_{\perp *} = v_{\parallel *} \tan \alpha_*$. Having computed the locally required whistler frequency $\omega(z, t)$, the desirable format of the ground transmitter spectrogram is determined by the propagation times of the various wavepackets from (z, t) to the emitter site. Occurrence of mirroring ($v_\parallel \sim 0$), entrance into the loss cone ($\alpha_e < 5.5°$), or un-ducting ($\omega/\omega_c > 0.5$) halted the computation. We adopted a diffuse equilibrium model for the thermal magnetospheric plasma, with the parameters used by Bernhardt (1979). Frequency modulated wavetrains of 10 mγ (duct) amplitude, propagating from south to north along $L=4$, with (transmitter) durations ranging from ~400 ms to ~800 ms are able, either to more than triple initial equatorial pitch angles of $\alpha_{e*} = 10°$ (interactions with $\psi_0 < 0$), or to push into the loss cone resonant electrons with $\alpha_{e*} = 20°$ (interactions with $\psi_0 > 0$); except for the deeply trapped particles, interactions with $\psi_0 > 0$ would require a stabilizing wave amplitude modulation. Although the occurrence of $\Delta\alpha_e \neq 0$ implies $\Delta E \neq 0$, the change of the electron energy ($E \sim 2$ keV) in these examples is well below 20%; the slope of the variation of the average α_e with position,

$$\frac{d\alpha_e}{dz} = -a\frac{v_\parallel}{v^3}\left(v^2 + \frac{\omega}{k}v_\parallel\right)\sin\psi_0\left(\frac{\omega_c}{\omega_{c_e}} - \frac{v_\perp^2}{v^2}\right)^{-1/2}, \qquad v^2 = v_\perp^2 + v_\parallel^2$$

is almost constant here, and the interaction might induce a sizable alteration in the pitch angle distribution (and hence, in the whistler stability through the 'temperature' anisotropy). The sharpness of the cyclotron resonance (roughly $\pm 2\omega_{NL}/k$ in $v_\parallel$) imposes stringent limits on the accuracy of the magnetospheric parameters used in the calculation of the appropriate frequency variation, curtailing the generalized implementation of the proposed mechanism. However, analysis of resonances occurring under favorable conditions (small interaction regions near the equatorial plane with large $|d\alpha_e/dz|$) suggests that use of data from whistler ground stations and in situ satellite measurements might overcome this difficulty in the plasmasphere.

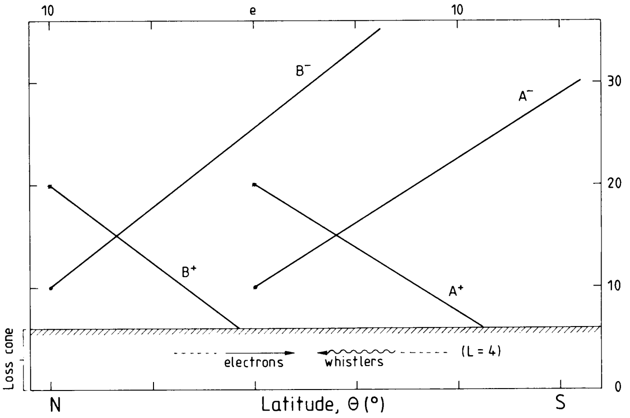

Fig. 1. Evolution of the average equatorial pitch angle of resonant electrons along a field line $L=4$ when appropriate (Fig. 2) whistler frequency modulation is used ($*$ identifiers the conditions at the start, $t=0$, of the interaction). $\omega_*/\omega_{c_e} = 0.366$ (A), 0.5 (B); $\alpha_{e*} = 20°$ (+), 10° (−); $\psi_0 = 30°$ (+), −30° (−)

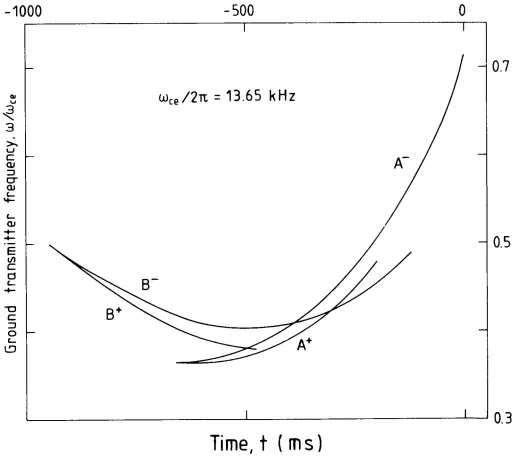

Fig. 2. Formats of the ground transmitter spectrogram required to achieve continuous cyclotron resonance for the cases contemplated in Fig. 1

An appropriate choice of the transmitter spectrogram format (possibly utilizing sequences of variable frequency pulses) permits selection within generous bounds of the location of the interaction region, and the type of selective modifications to be introduced in a given domain of the energetic electron distribution. This flexibility is welcome in the research of waves and wave-particle interactions in the magnetosphere (Gendrin 1975), and is a recommendation for the use of the technique in the near future since, in contrast to the situation faced twenty years ago, the expensive components of the required experimental setups are now (or will soon become) installed.

Acknowledgments. I thank Professor J.A. Fejer for helpful comments. This research was carried out as a Research Fellow of the Alexander von Humboldt Foundation.

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Received April 9, 1980; Revised Version February 25, 1981
Accepted March 5, 1981