ON THE STIMULATED PRECIPITATION OF ELECTRONS AND THE MECHANISM OF WAVE GENERATION IN THE WHISTLER RANGE IN THE "ARAKS" EXPERIMENT

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ABSTRACT

During the flight of a rocket on 15 February 1975, which was launched as part of the ARAKS program, bursts of precipitated electrons in the pauses between injected electron pulses and simultaneous bursts of emission in whistler range were observed. The physical mechanisms of these phenomena are considered.

Keywords: Whistler, ARAKS

1. INTRODUCTION

In 1975 two rockets with electron accelerators on board were launched from Kerguelen Island (L∿4) in the ARAKS program. Experimental objectives for each rocket launch and descriptions of the scientific payload are presented elsewhere (Cambou *et al.*, 1980, Ref. 1).

Some effects observed during the rocket flight 15 February 1975 are described in the paper by Gringauz *et al.* (1980, Ref. 2). These effects consisted of bursts of the stimulated precipitation of electrons with energies E > 8 keV recorded on board the rocket in the pauses between electron pulses injection downward and correlated wave emission bursts in the whistler frequency range measured on the rocket nose cone, separated from the rocket. These effects were observed from the moment of switching on the devices (at about 160 km) up to the apogee of the rocket trajectory (∿185 km) and descending to the altitude of ∿170 km until the plasma generator on the board was switched on (Cambou *et al.*, 1980, Ref. 1). Hence these effects were observed during comparatively short periods of time and altitude intervals (160 to 185 km) when the parameters in the rocket vicinity changed very little. In the paper by Gringauz *et al.* (1981, Ref. 3) an attempt was made to show that precipitation of electrons with E > 8 keV between injected pulses could be initiated by the whistler radiation of injected electron beams. The data on the particle and wave measurements (in particular, the data related to the electron beam injection along the geomagnetic field line) permit to reveal the main mechanism of waves emission in the whistler frequency range and explain the set of phenomena described in this paper.

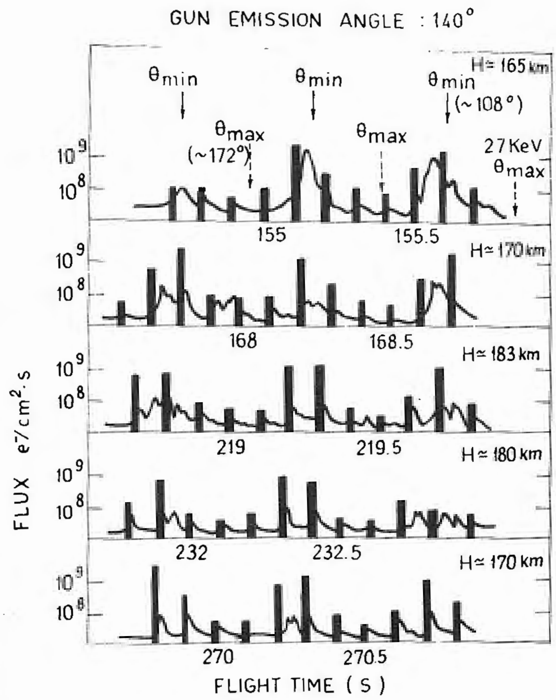

Figure 1: Fluxes of electrons (E > 8 keV) measured aboard the rocket during several series of electron pulses injected downwards (launch of February 15, 1975) and bursts of precipitated electrons in pauses between injected pulses.

2. EXPERIMENTAL DATA

In the ARAKS experiments the second rocket was launched on February 15, 1975 during the recovery phase of the moderate geomagnetic storm.

The program for the electron gun operation was rather complicated (Ref. 1). In particular it included the injection of electron pulses ($I_e \simeq 0.5$ A gun current, $E_0 \simeq 27$ keV initial energy of electrons) with varying pulses duration of 20 ms and intervals between pulses of tens of ms. This paper deals only with this part of the gun operation program.

Rocket instruments included an electron detector directed upwards with a lower energy threshold of 8 keV and an aperture angle of $\delta = \pm 45^o$. The nose cone separated from the rocket and flying ahead (and above) with respect to the rocket at the distance of several kilometres had a wideband wave receiver (electric component of waves; frequency range 0.1÷5 MHz).

During injection of each electron pulse (for both rockets) wide-angle detectors measured the fluxes of electrons with energies >8 keV which were in good agreement with the results of calculations of injected electrons scattered by the atmosphere (Gringauz *et al.*, 1981, Ref. 4).

Fig. 1 shows the electron fluxes measured by the wide-angle detector for the injection of several series of electron pulses downwards on flight of February 15, 1975 (pitch-angles of the injection Θ changed between 172^o and 108^o; this corresponds to downward injection since Kerguelen Island is in the southern hemisphere). The black columns represent the fluxes measured during the electron gun operation. One can see in the pauses some intensive bursts of precipitating electrons.

Fig. 2 is the same as Fig. 1, but for upward injection ($\Theta \sim 3^o \div 58^o$) of a serie of pulses. A certain "broadening" of signals in the pauses is caused by atmospheric scattering of injected electrons; there is no precipation of electrons in the pauses.

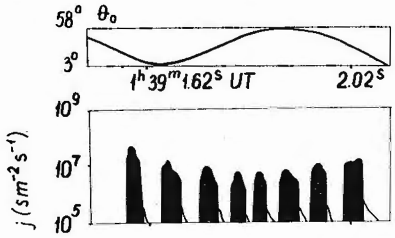

Figure 2: Fluxes of electrons (E > 8 keV) measured aboard the rocket during upward injected pulses (launch of February 15, 1975).

Fig. 3(a) shows part of Fig. 1 on an expanded scale and the changes of Θ due to rocket rotation are shown on the top. Fig. 3(b) depicts strong bursts of wave radiation received on the nose cone in the frequency range $\Omega_i << \omega < \Omega_e$ (where Ω_i and Ω_e are gyrofrequences of ions and electrons, respectively), *i.e.* in the whistler range, which are in correlation with the bursts of electrons precipitation in the pauses. Bursts of electrons with E > 8 keV were recorded by wide-angle detectors only during the flight of February 15, 1975 and only for the injection of downward electrons. The first rocket of ARAKS was launched on January 26, 1975 under quiet geomagnetic conditions and the second - on February 15, 1975 in the recovery phase of the moderate geomagnetic storm.

Only for frequencies $\omega < \Omega_e$ there is a correlation between bursts of wave signals in the pauses and bursts of electrons fluxes recorded in the pauses; at other plasma frequencies such a correlation has not been found.

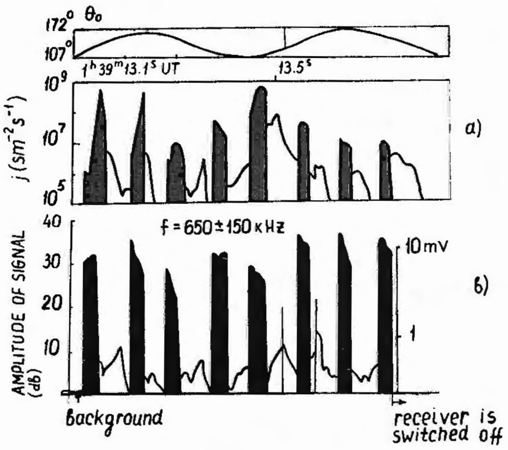

Figure 3: Bursts of electrons (E > 8 keV) observed at the rocket between electron pulses injected downwards (launch of February 15, 1975) and bursts of radiation in the whistler range simultaneously received at separated nose cone.

To obtain a signal for the whistler range (Fig. 3b) it was selected from a wide band signal of 0.1÷5 MHz by use of a filter with $\Delta f = \pm 150$ kHz tuned to the whistler signal maximum, $f \simeq 650$ kHz.

Fig. 4 shows frequency spectra of the wave radiation $\omega < \Omega_e$ obtained for the signal during pulse of electron gun (Figs. 3(a), 3(b) and 3(c)) at different angles Θ as well as in the pause (Fig. 3d) for the injection of electron beam downwards. These spectra are generated by use of the method of recirculating spectral analysis (Naidenov, 1973, Ref. 5).

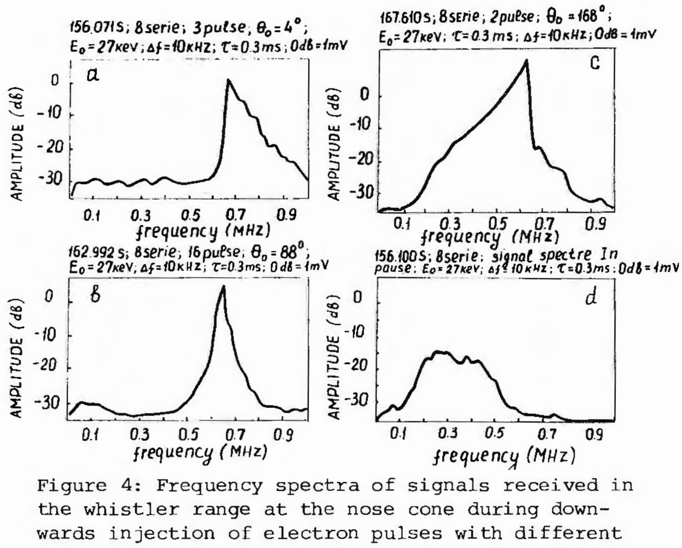

Figure 4: Frequency spectra of signals received in the whistler range at the nose cone during downwards injection of electron pulses with different injection angles (a, b and c) and in the pause between injected downwards pulses (d).

3. DISCUSSION

The absence of electron precipitation and of wave bursts $\Omega_i << \omega < \Omega_e$ in the pauses between injections of electrons upwards, the simultaneous existence of precipitating electrons with energies >8 keV and of waves of the whistler range in the pauses between downward injections, all this leads to the idea that this precipitation of electrons is stimulated by the wave-particle interaction (Gringauz *et al.*, 1980, Ref. 2).

The fact that the experiment on February 15, 1975 was carried out at the phase of the geomagnetic storm recovery in a subauroral region ($L \sim 4$), allows us to believe that precipitating electrons were electrons of the ring current.

Indeed, as is seen from Figs. 4(a), (b) and (c) during the electron beam injection the spectrum of radiation with the maximum at 650 kHz appeared. In case of a wave packet with f = 650 kHz the region where $\omega < \Omega_e$, is located at $\sim$2000 km and extends along field lines by several hundreds of kilometres. In this region mirror points of magnetospheric trapped charged particles are placed. The estimates of some physical conditions occurring in propagation of the wave packet from the region $\omega < \Omega_e$ to the region $\omega \lesssim \Omega_e$ (these estimates were made according to Kenell and Petschek, 1970, Ref. 6) in particular, show that this fact helps a wave-particle resonance to be developed in the region of mirror points (Ref. 4).

These estimates also indicate that for the experimentally measured values of the wave electric field the precipitation of trapped electrons into the loss cone should be considerable, about 5×10^8 cm^{-2}s^{-1} with E > 8 keV and with a reasonable number density of trapped electrons of 10^{-1} cm^{-3} in the mirror point region (of quasi-trapped electrons of the ring current in our case). Due to the absorption of whistlers energy by the plasma electron component in the upper ionosphere strongly non-isothermal plasma forms ($T_e >> T_i$). For a wave packet the electron component heating may be estimated in quasi-linear approximation (Ivanov, 1977, Ref. 7).

$$(\overline{\Delta v_\perp})^2 \sim \Omega_e^3 (B_1/B) C^2 \tau_1/\omega_{pe}^2,$$

$$B_1 \sim \omega_{pe} E_1/\left[\omega(\Omega_e \cos\alpha - \omega)\right]^{1/2}$$

where E_1, B_1 is the wave amplitude of an electric and magnetic component ($E_1 \sim 1$ mV/m is the measured value of the amplitude), B is the geomagnetic field intensity; τ_1 is the wave radiation duration (τ_1 is equal to duration of an injected pulse). According to the estimates, $(\overline{\Delta v_\perp})^2 \sim 10^8 \div 10^9$ cm s^{-1}, that is, the electron energy may increase by an order of magnitude (or more), it is electron energy increase up to several eV $(\overline{\Delta v_\parallel})^2$ also increases due to the diffusion over the velocity space).

The first attempts to consider the mechanism of low-frequency radiation generation in the ARAKS experiment was made by Lavergnat *et al.* (1980, Ref. 8). The authors assumed that non-linear heatings of HF waves near the plasma frequency excited by plasma-beam interaction give rise to low-frequency electrostatic waves. In the time of writing this paper the results of the spectral analysis of LF-signals which are given in Fig. 4 were not yet obtained. The mechanism suggested by Lavergnat *et al.* can not explain all the data observed and Fig. 4 among them.

The absence of stimulated electron precipitation in the pauses during upward electron beam injection (Fig. 2) is an indication that in this case the radiation which could stimulate precipitation does not reach the region of mirror points and gyroresonance.

When possible generation mechanisms of the radiation observed are considered the above is an argument in favour of the electron-cyclotron mechanism:

$$\omega - \Omega_e = \vec{k}\cdot\vec{V}$$

$$\omega < \Omega_e \to \vec{k}\cdot\vec{V} < 0,\ k\uparrow\downarrow V,$$

that is in the case of upward electron beam injection whistlers are propagating downward and cannot stimulate ring current electron precipitation.

Another argument that favours the electron-cyclotron mechanism of wave generation is obtained in consideration of three frequency spectra (Figs. 3a, b, c). All of these spectra measured during electron injection at different pitch-angles have intense maxima at $\omega \sim \Omega_e/2$ which may possibly be explained by wave-plasma resonance. The condition of resonance is $V_\parallel \approx C/N$ where $V_\parallel$ is electrons velocity of injected pulse and N is the refractive index for whistlers:

$$N^2 = 1 - \frac{\omega_p^2}{\omega(\omega - \Omega_e\cos\alpha)} \sim \frac{\omega_p^2}{\omega(\omega - \Omega_e\cos\alpha)}$$

where $\alpha = \sphericalangle(\vec{k}, \vec{B})$; the plasma frequency ω_p may be determined by the plasma density in the BPD region in the rocket vicinity (Galeev *et al.*, 1976, Ref. 9) and/or neutralizing the rocket charge electron flux flux moving to the rocket, or in the undisturbed ionosphere.

From the condition $V \approx C/N$ we have

$$\omega_{1,2} = \frac{\Omega_e\cos\alpha}{2}\left[1 \pm \left(1 - \frac{4\omega_p^2 V^2}{\Omega_e^2 C^2 \cos^2\alpha}\right)^{1/2}\right]$$

whence for $V_\parallel \sim C\Omega_e/2\omega_p$ the roots of the equation coincide

$$\omega_1 \approx \omega_2 \approx \Omega_e\cos\alpha/2$$

For $\omega = \Omega_e/2$ resonance takes place at whistler modes for both the Čerenkov:

$$\omega = \vec{k}\cdot\vec{V}(\vec{k}\uparrow\uparrow\vec{V}),$$

and cyclotron radiations

$$\omega - \Omega_e = \vec{k}\cdot\vec{V}(\vec{k}\uparrow\downarrow\vec{V})$$

(at the same frequency).

Note that the presence of the radiation maximum in case of cyclotron mechanism of waves generation at frequency $\Omega_e/2$ (where Ω_e is the emitting electrons gyrofrequency) of given type is also implied by Kimura (1967, Ref. 10). The absence of electron precipitation during the upward injection proves that the intensity of the Čerenkov radiation alone is insufficient to stimulate particle precipitation.

Though the radiation is downward for the electron-cyclotron emission mechanism when the electrons have been injected upwards the whistlers should nevertheless be recorded on the nose cone above the rocket (which was the case in our experiment). The matter is that the distance 1 to 10 km between the nose cone and the rocket was covered by beam electrons in about 10^{-5} to 10^{-4} s, and so short a delay in a wave signal appearance with respect to the beginning of injection was impossible to measure. After that time the beam was already above the nose cone and the conditions for reception of the radiation in case of the upward injection were favourable.

Explanation should also be given to the differences of whistler spectra at different injection pitch-angles during the injection process (Figs. 4a, b, c). Invariability of spectral maximum location agrees with the suggested mechanism of wave generation while differences in the spectral form may be explained as follows. The nose cone was above the rocket during the experiment and was near or within the flux of electrons neutralizing the rocket charge and moving downward to the rocket. Some of the waves received on the nose cone interact with these downward moving electrons and may lead to Doppler shifts.

When the direction of K changes with respect to velocity of neutralizing flux electrons from $K \uparrow\downarrow \vec{v}$ to $\vec{K} \uparrow\downarrow \vec{v}$ to Doppler shifted frequency is $\omega = \Omega_e + \vec{K}v \gtrless \omega (\Omega_e > \omega)$ for cyclotron mechanism of waves generation when pulses were injected upwards and $\omega' < \omega$ for the same mechanism when pulses were injected downwards; ω' being the frequency of waves measured on the nose cone).

Finally we are to deal with characteristics of waves bursts recorded in pauses during the downward injection. Their frequency spectrum (Fig. 4d) is appreciably different with respect to spectrum for waves measured during pulse (Figs. 4a, b, c). From our point of view these bursts of waves in pauses are generated in the electron gyro-resonance region $\omega < \Omega_e$ and the mechanism of their generation is related to the process of whistler ($\vec{K}_o$) decay into whistler $\vec{k} = -\vec{k}_o$ and ion acoustic oscillations $k_s = 2\vec{k}_o$ (see Galeev and Sagdeev, 1973, Ref. 11), that is to the process of parametric back-scattering (coherent Brillouin-Mandelshtam). As already mentioned in the gyro-resonance (h < 2000 km) region ionospheric electrons become considerably heated (from 0.1 eV up to several eV) and the plasma becomes non-isothermal ($T_e >> T_i$), hence the effect of whistler decay is probable. The growth rate of decay may be determined (Ref. 11) as:

$$\gamma = \left[K_s^2 \, K_o \, V_g / 8\omega_s (B_1^2 / 2\pi n \, M)\right]^{1/2},$$

where $\omega_s = 2K_oC_s$; $C_s(T_e/M)^{1/2}$; M is the mass of the ions. For the magnetospheric plasma $\gamma = 10^{-1}$ to $10^2 \ s^{-1}$. This value of γ is large enough as compared to the collision frequency ν_{ei} ν_{en}; the time $1/\gamma$ is sufficiently large for whistlers to be observed in the pauses between electron injections.

4. CONCLUSIONS

1. During the downward injection of electron pulses in the ARAKS experiment of February 15, 1975 ($E = 27$ keV, $I_o = 0.5$ A, $h \approx 160$-185 km) whistlers were generated (via the electron-cyclotron mechanism).

2. Above the rocket in a region of about h < 2000 km these whistlers caused a pitch-angle diffusion of quasi-trapped ring current electrons and their precipitation.

3. The decay of whistlers with the Brillouin-Mandelshtam back-scattering and acoustic wave generation may occur in the $\omega < \Omega_e$ region. Whistlers due to this back-scattering were received on the nose cone in the pauses between the downward injected electron pulses. All that may satisfactorily explain the phenomena discussed in the paper.

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