**Air Force Research Laboratory**

# Nonlinear Plasma Effects of Electron Beams Injected in the Ionosphere: Observations and Theory

AFRL HERITAGE | 1917–2017

100 YEARS OF U.S. AIR FORCE SCIENCE & TECHNOLOGY

**Evgeny Mishin**

**Space Vehicles Directorate**

**Air Force Research Laboratory**

***Integrity ★ Service ★ Excellence***

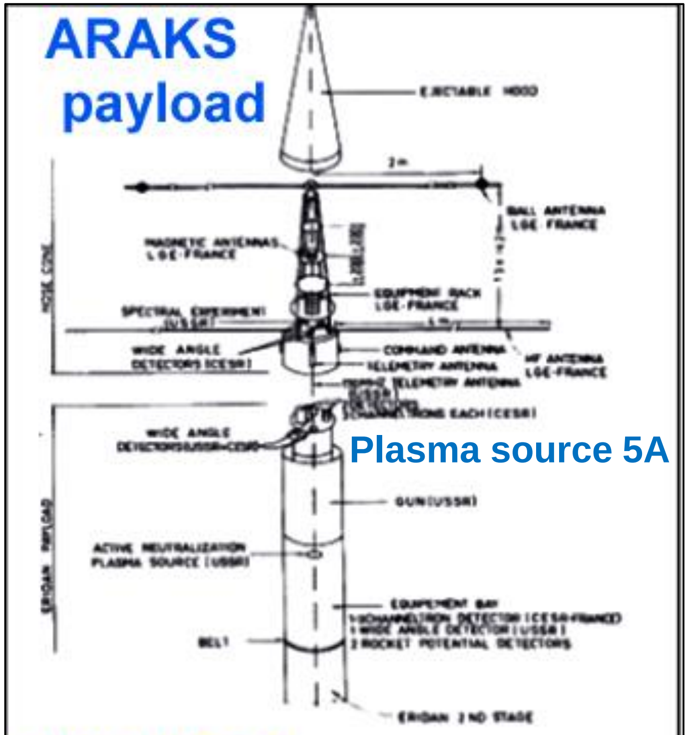
**Active experiments in space: Past, present, and future**
**Santa Fe, NM, 10-15 September 2017**

# OUTLINE

- ➢ **Unexpected (nonlinear) effects in *ARAKS, Zarnitsa-2, Echo, Polar-5, …* rocket experiments with electron beams**
  - Artificial Aurora and near-rocket glow
  - Artificial radio emission
  - Suprathermal electrons
  - Elevated electron temperature
  - Beam scattering and prompt electron echo (PEE)
- ➢ **Beam-Plasma discharge theory**
  - Threshold (*beam energy, current, pitch angle, and ne*
  - Saturation: B*eam-trapping and Strong Langmuir Turb*
  - Optical and radio emissions from the BPD region
  - Artificial auroral rays and natural (Enhanced) aurora
- ➢ **Summary**

- Based on E. Mishin et al. (1989), *Interaction of electron fluxes with the ionospheric plasma*, Hydrometeoizdat, Leningrad (in Russian).
- Galeev, A., E. Mishin, R. Sagdeev, V. Shapiro, and V. Shevchenko (1976), Discharge in the near-rocket region during electron beam injections in the ionosphere, *Sov. Phys. Doklady*.

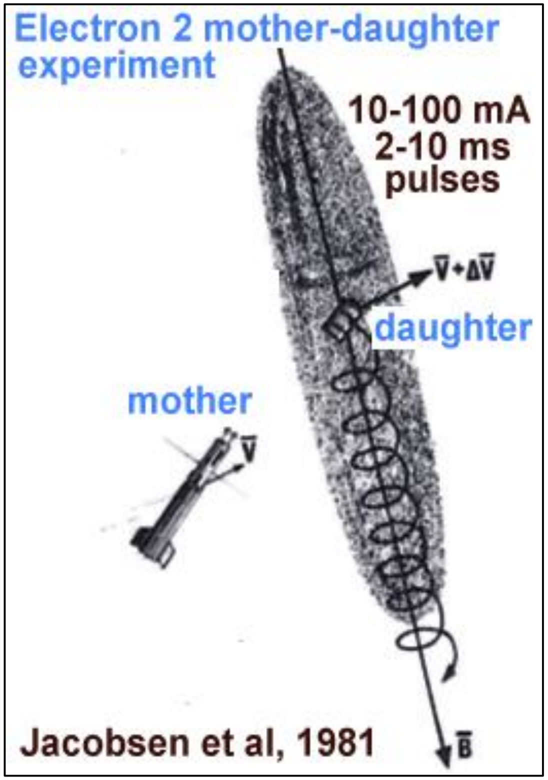
# ARAKS, ECHO-7, Electron 2, Polar 5



**ARAKS payload**

Plasma source 5A

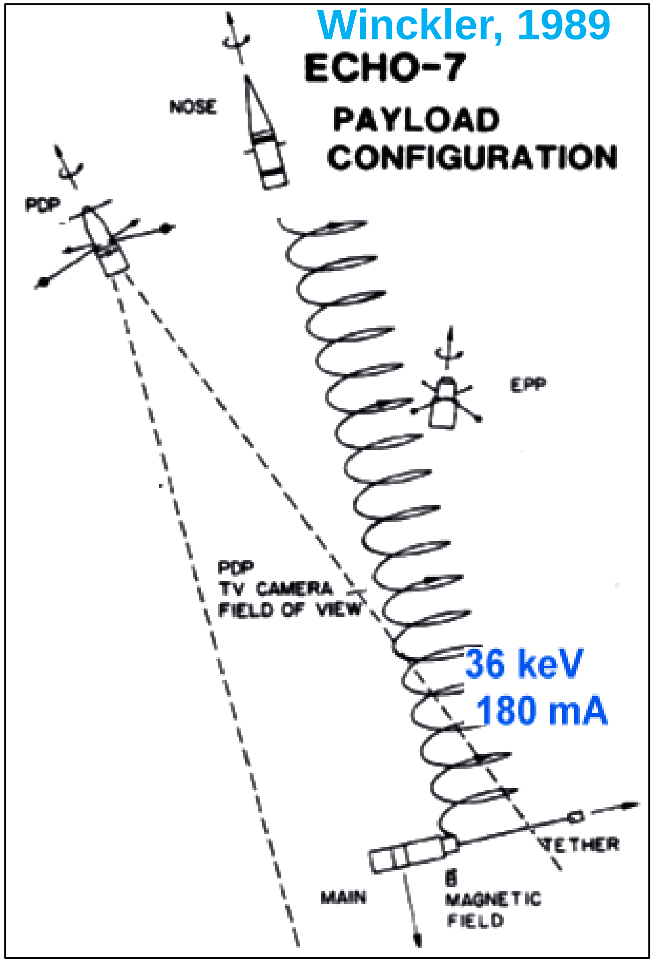
current 0.5 A
pitch-angles 0-90 deg downward
0- 50 deg upward
energy 15 and 27 keV
pulses 20 and 40 ms



Electron 2 mother-daughter experiment

Jacobsen et al, 1981

Similar to Polar 5 [Grandal et al., 1980]



Winckler, 1989

ECHO-7
PAYLOAD CONFIGURATION

36 keV
180 mA

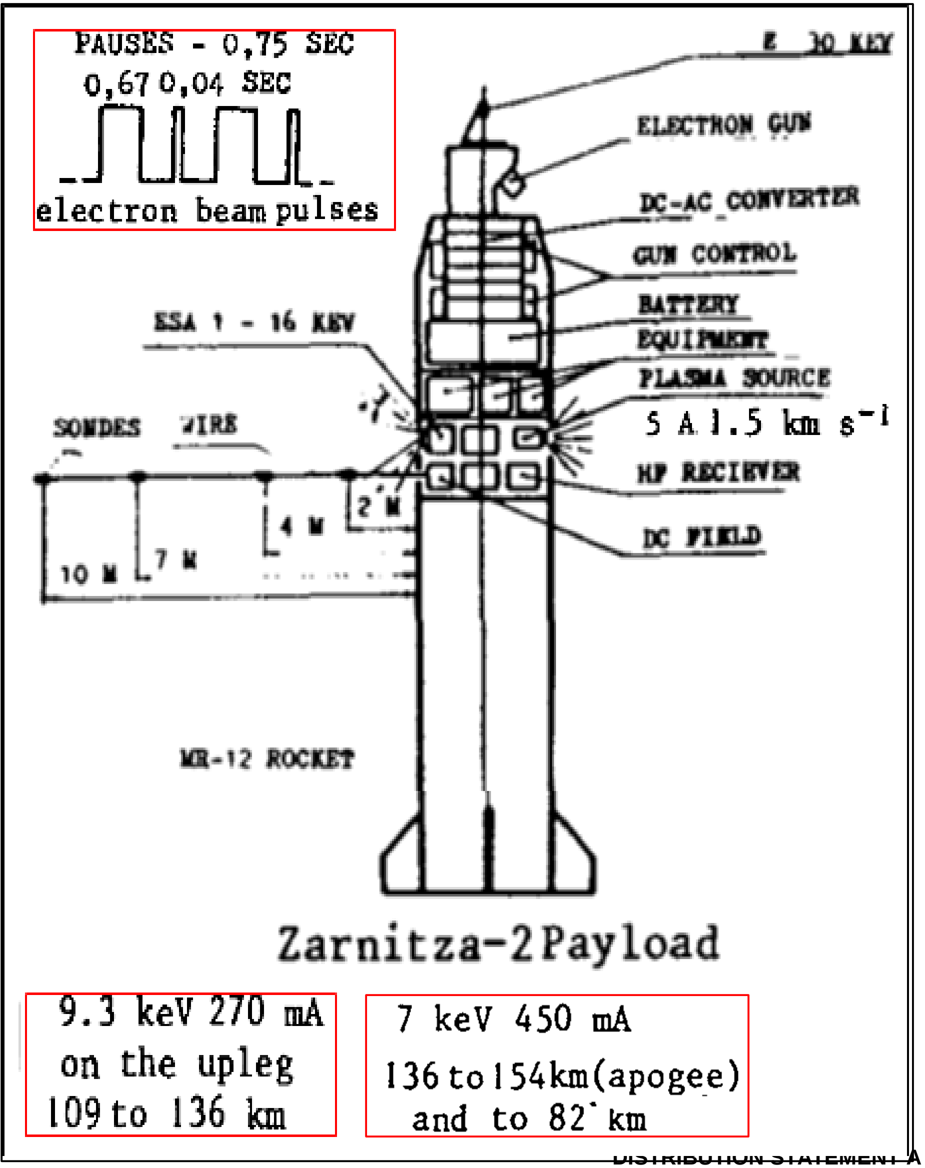
- On-site UHF radio receivers

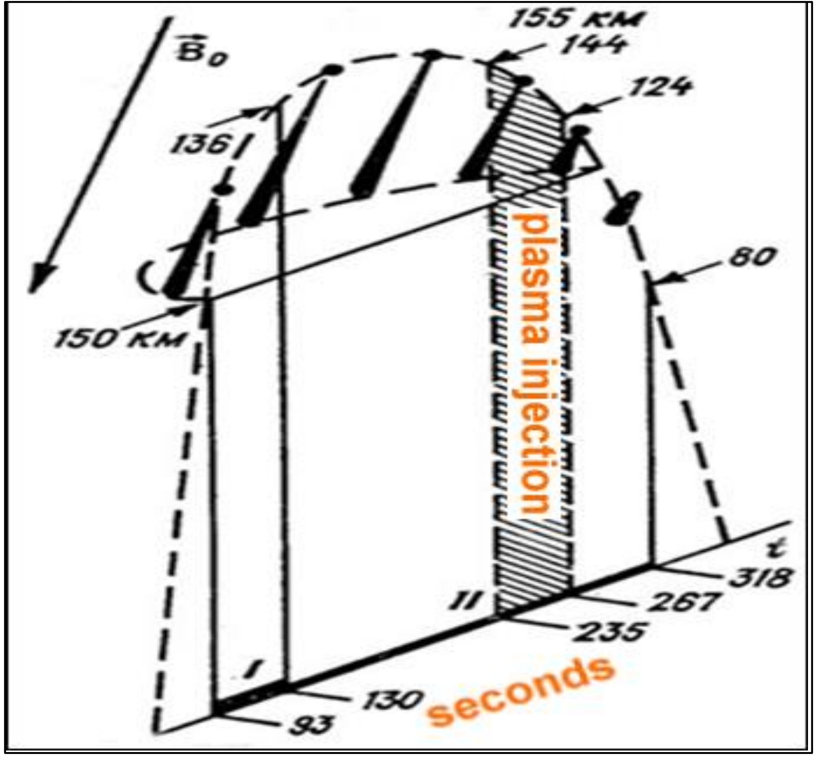
“mother” -“daughter(s)” experiments

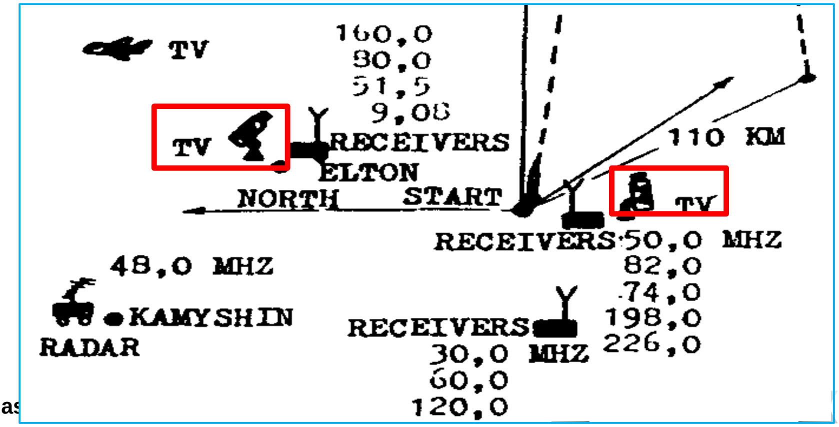
# Zarnitsa-2 (Aurora-2)

Dokukin et al., 1981

Dokukin et al., 1981

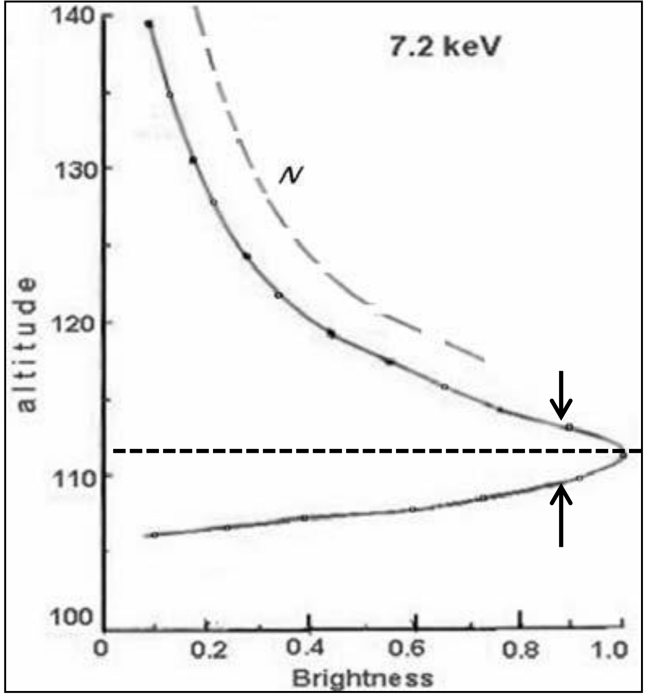






# Collisional (single-particle) interaction in the E/F-region ionosphere

**Beam (primary) electrons excite & ionize neutral particles via collisions (*Beam-Atmosphere Interaction*)**



**Luminosity altitude-profile calculated for $\varepsilon_b$ = 7.2 keV by Monte Carlo method. The dashed line shows MSIS neutral density.**

- **Peak altitude and thickness are explicitly determined by the electron beam energy $\varepsilon_b$**

**Energy dissipation rate**

**(Bethe's formula)**

$$\frac{d\varepsilon_b}{dz} \approx -\varepsilon_b / l_b \propto N(z)$$

$$l_b\,[\mathrm{km}] \approx 5\,\frac{N_{[120km]}}{N}\sqrt{\varepsilon_b\,[\mathrm{keV}]}$$

**Flux of suprathermal (secondary) electrons**

$$\Phi(\varepsilon) \propto \varepsilon^{-3.5}$$

**~6 --300 eV**

**defines brightness and colors of auroral glow, e.g., the red-to-blue ratio**

$$Q_\lambda = N_j \int \sigma_\lambda(\varepsilon)\Phi(\varepsilon,\vartheta)\,d\Omega\,d\varepsilon$$

neutral density

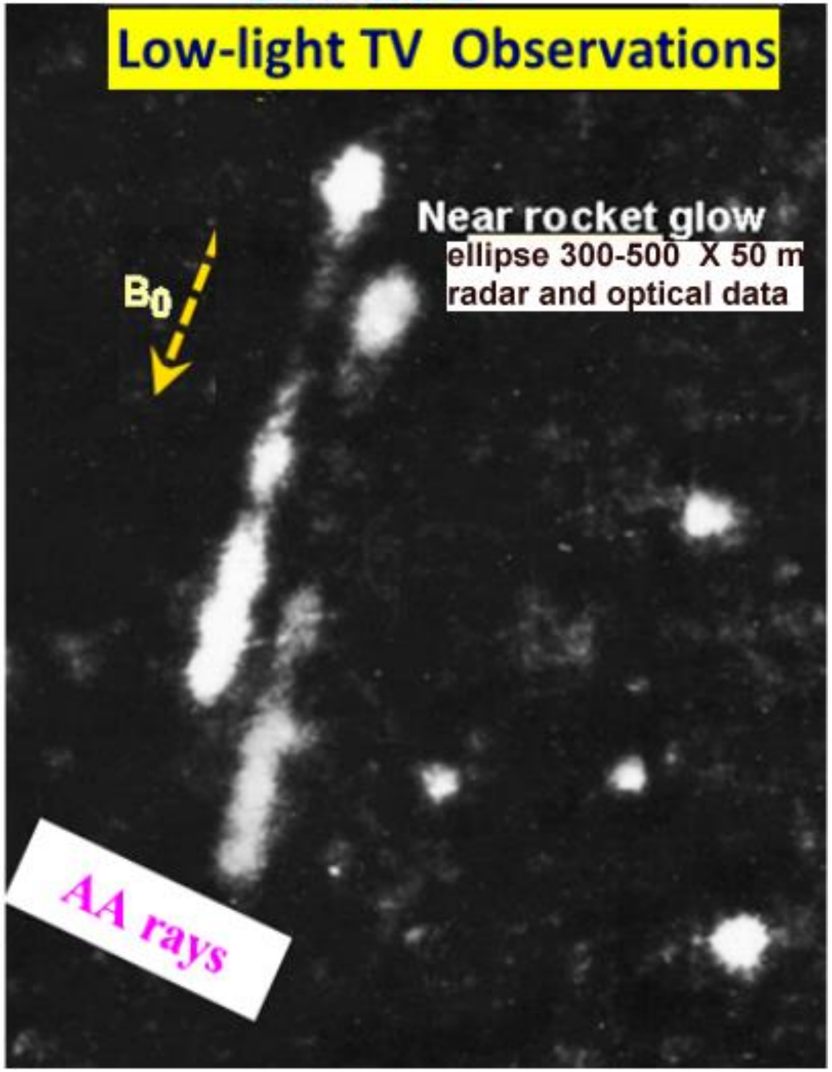
excitation cross-section

electron flux

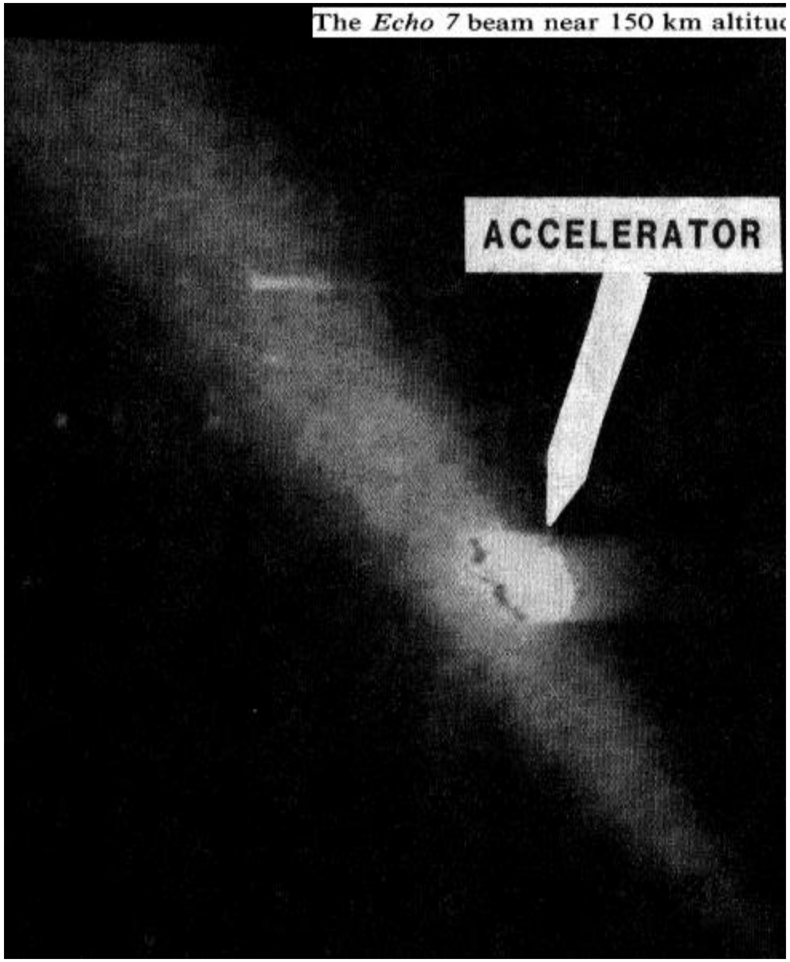
**Excitation/ionization rate**

# Optical emissions

Zarnitsa-2

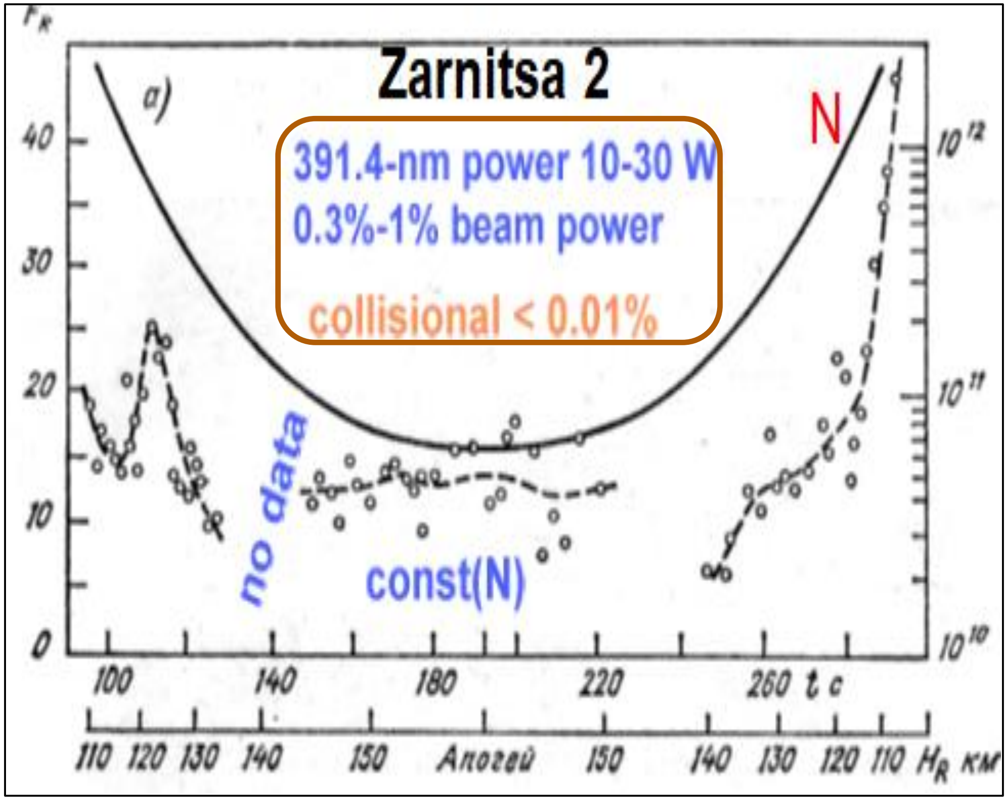


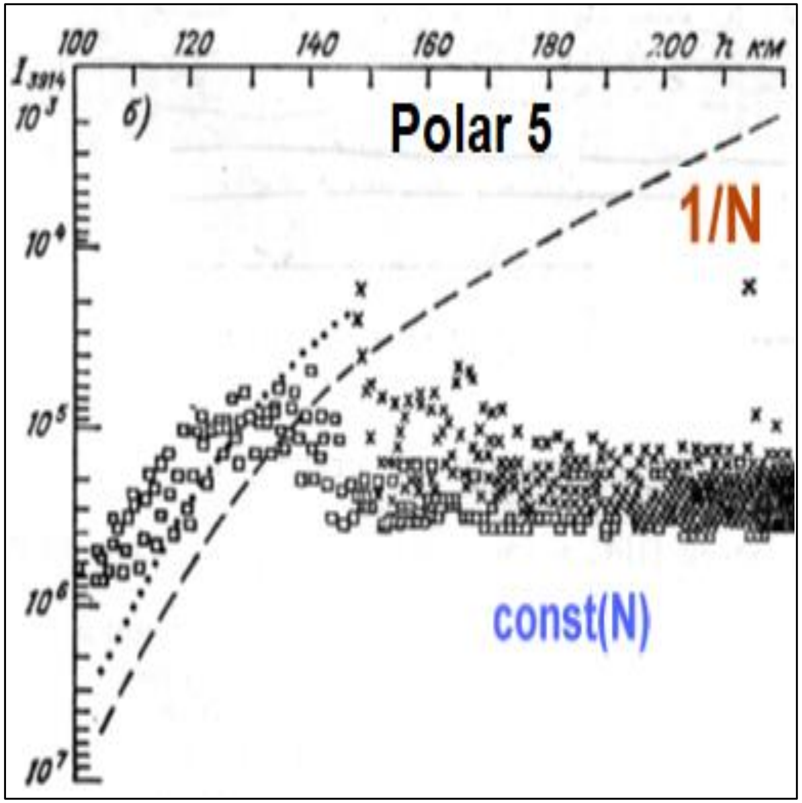
ECHO-7



# Near-rocket glow vs. altitude

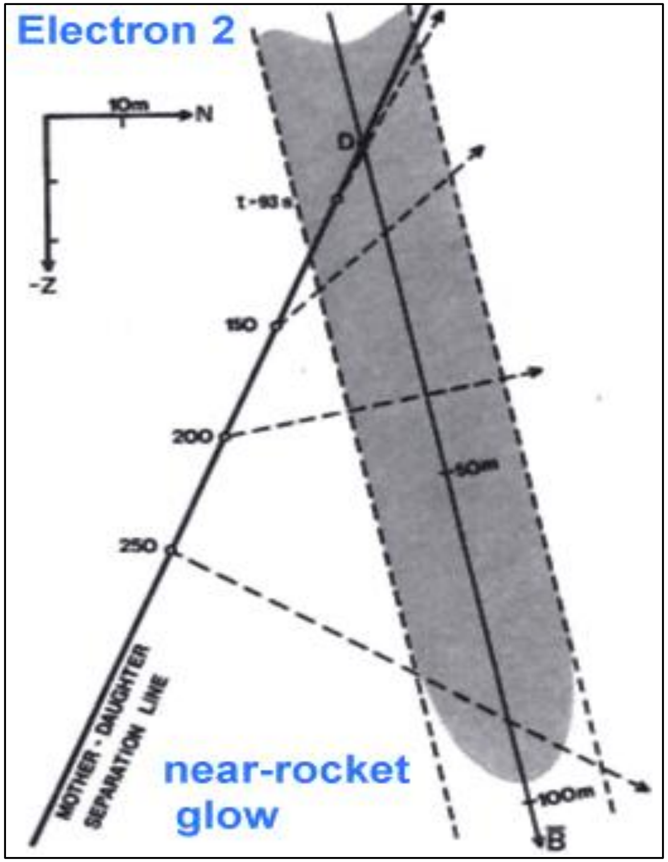
**Beam induced 391.4 nm luminescence as a function of altitude: const @ h>140 km**



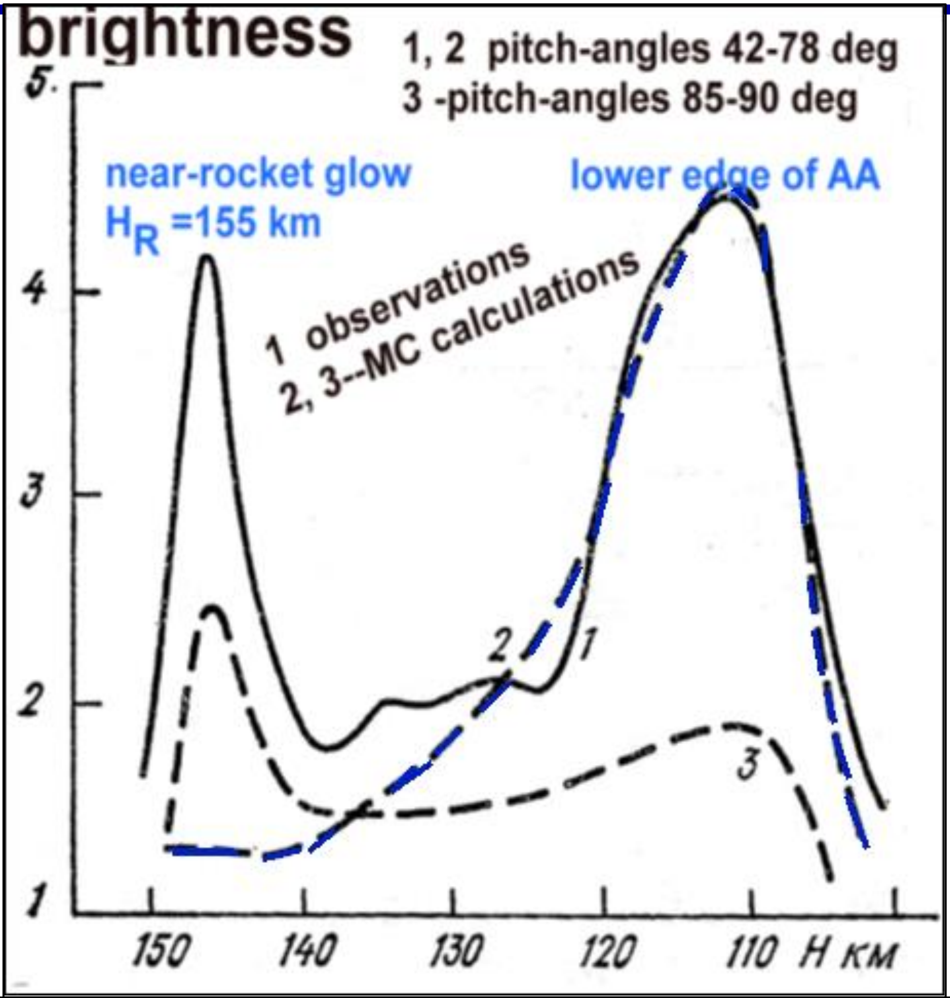


❖ Greatly exceeds Monte Carlo (single-particle) values near the rocket

# Near-rocket glow



Shape & dimensions are similar to Zarnitsa-2



- Greatly exceeds Monte Carlo (single-particle) values near the rocket

# Beam Plasma Discharge

The HF ($\omega_n \gg \nu_e$) breakdown criterion or

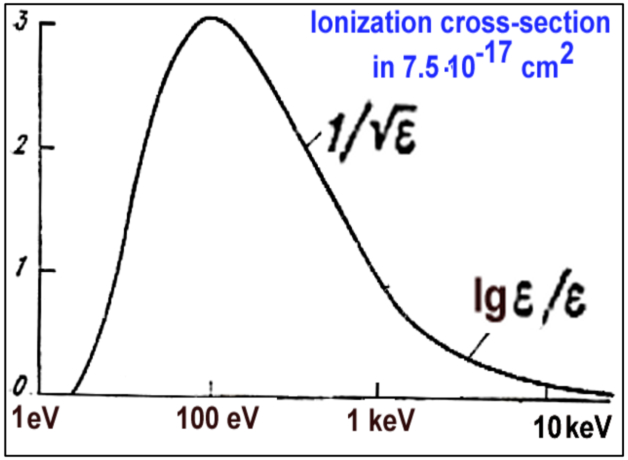
Townsend condition

**electron lifetime** $\tau_{\rm loss} > \tau_{\rm heating}(\varepsilon \sim \varepsilon_{ion}) + \tau_{\rm ionization}$

**heated electrons**

**elastic collisions**

collisional heating $\varepsilon_{ion} \sim \nu_e(\varepsilon)\dfrac{e^2E_0^2}{3m\omega_0^2}\tau_{\rm heating}$



**The ionosphere is a weakly ionized plasma** $\boxed{\omega_{p0} > \omega_{ce}}$

In BPD, the waves are excited by the beam

First, beam-plasma instability (BPI) must develop

$$\gamma_b(n_b, n_0) > \frac{\nu_e}{2} \propto N_n$$

Let's $n_b^*$ is the threshold beam density for BPI

At $n_b > n_b^*$, BPD is self-sustained if

**avalanche**

$$n_e\overbrace{\nu_{ion}(T_e)}^{\text{heated bulk}} + \overbrace{n_{tail}\nu_{ion}^{tail}}^{\text{accelerated}} > n_b\nu_{ion}(\varepsilon_b)$$

# Beam Plasma Discharge near a rocket

BPI is much faster than the macroscopic processes

$$\tau_{BPI} \ll \tau_{\text{ionization}}, \ \tau_{\text{heating}}, \ \tau_{\text{loss}}$$

- Steady state $W = \left\langle \frac{|E^2|}{8\pi} \right\rangle = \alpha_b n_b \varepsilon_b$

$\alpha_b$ depends on the BPI nonlinear saturation

Let's neglect ionization by the accelerated tail electrons

- Townsend condition

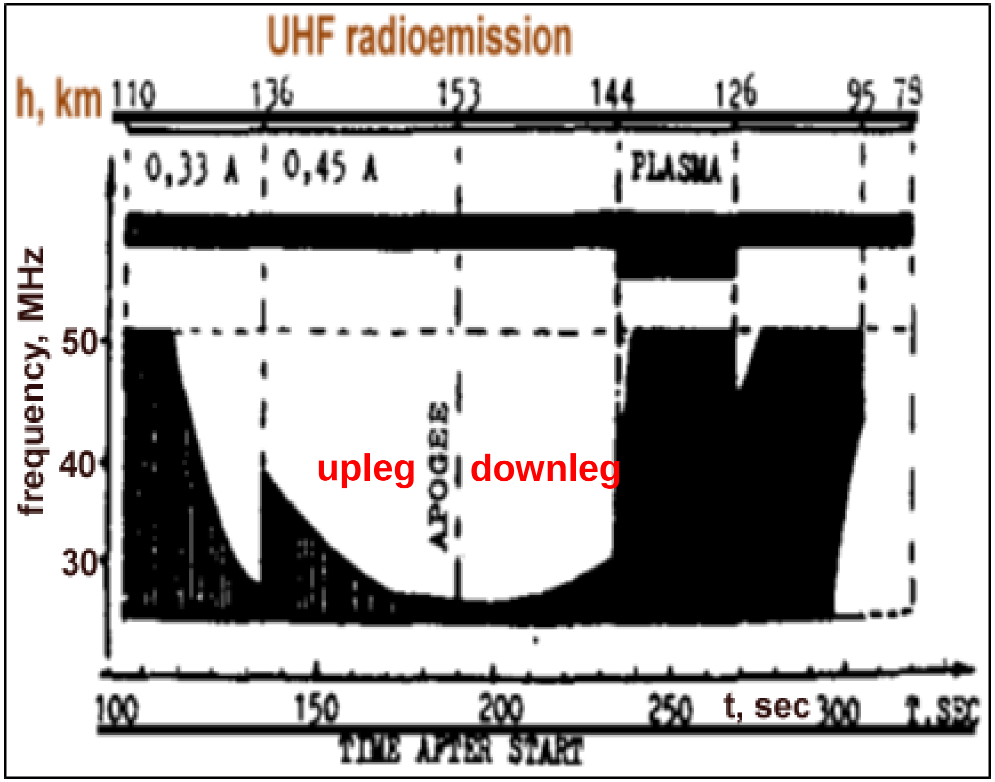
$$\tau_{\text{heating}} \sim \frac{(3-5)}{\nu_e(\varepsilon_{ion})} \frac{n_e \varepsilon_{ion}}{\alpha_b n_b \varepsilon_b} < \tau_{\text{loss}} = \frac{\overset{\text{BPD radius}}{\rho_\perp}}{\underset{\text{rocket speed } \perp \text{B}_0}{V_{R\perp}}}$$

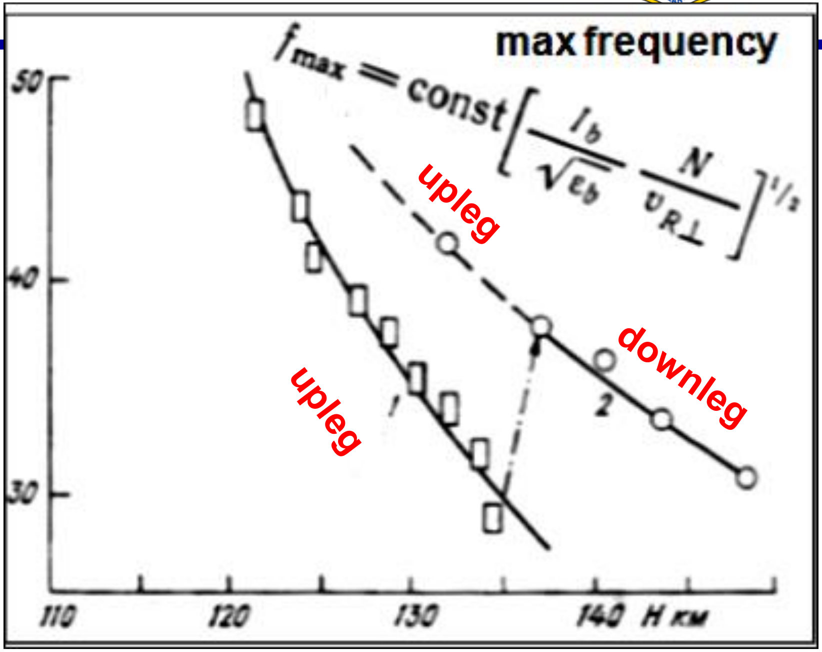
collisional

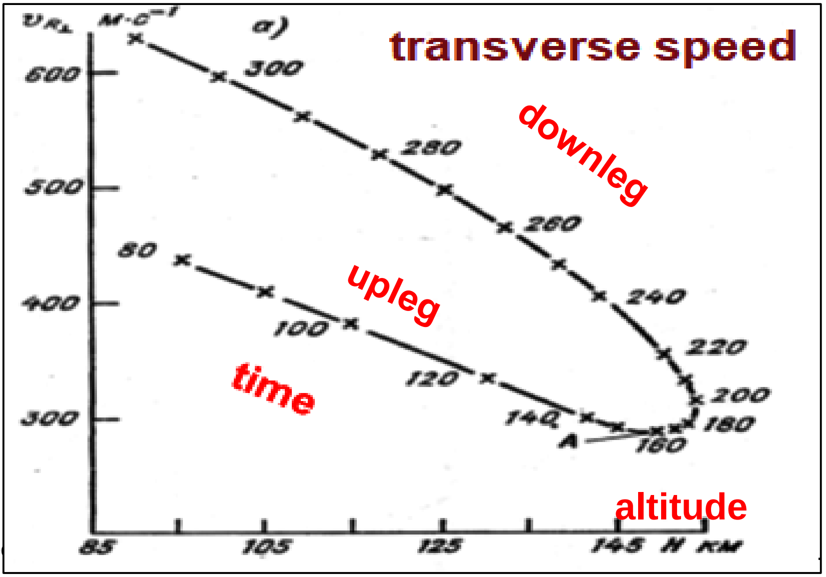
- The BPD maximum density

$$\boxed{n_e \sim n_b \nu_e(\varepsilon_{ion}) \frac{\alpha_b \varepsilon_b}{(3-5)\varepsilon_{ion}} \frac{\rho_\perp}{V_{R\perp}} \propto I_b \frac{N_n}{V_{R\perp}}}$$

# Zarnitsa-2: UHF radio emission







**power flux (1-2) $10^{-20}$ W/m$^2$Hz**

**power 30-100 W**

**1% - 3% beam power**

**Dokukin et al., 1981**

# Beam Plasma Interaction

Beam structure

- The beam is not "locked" by the spatial charge (virtualcathode) at the beam currents

$$I_b \ll I_c = v_b \varepsilon_b / e = 30 \left( \frac{\varepsilon_b [\mathrm{keV}]}{10} \right)^{3/2} [\mathrm{A}]$$

**Injection II $B_0$**

- If $n_b^{(0)} \gg n_0$, the beam expands due to electrostatic repulsion until $n_b(z_*) \leq n_0$ at $z > z_* \sim \frac{v_b}{\omega_{p0}}$

- The beam radius and effective pitch-angle at $z_*$

$$\rho_\perp(z_*) = \left( \frac{I_b}{I_c} \right)^{1/2} \frac{v_b}{\omega_{p0}}$$

$$\theta_c = \frac{\omega_{ce}}{\omega_{p0}} \left( \frac{I_b}{I_c} \right)^{1/2} \ll 1$$

- For injections at $\theta_0 \gg \theta_c$, electrostatic repulsion ends at $z_{**} \sim \frac{v_b}{\omega_{p0}} \cdot \theta_c$

resulting in a hollow cylinder

$$\rho_{ce} - \Delta\rho \leq \rho \leq \rho_{ce} = \frac{v_b}{\omega_{ce}} \sin \theta_0$$

# Beam Distribution Function

- The beam distribution function

$$f_b(\mathrm{v},\rho) = n_b(\rho)\begin{cases} 0 \quad at \quad \rho > \rho_\perp \\ f_{||}\left(\frac{v_z - u_b}{\Delta u}\right) f_\perp\left(\frac{v_\perp - v_{b\perp}}{\Delta v_\perp}\right) at\ \rho \le \rho_\perp \end{cases}$$

- **Bump-in-tail in || direction and beam of “oscillators” in ⊥ direction (el. ring)**
- **Instabilities of a radially bounded beam at small and large injection pitch-angles**

- **BPD diameter $R_{\mathrm{BPD}}$ is the wave excitation region $\perp \mathbf{B}_0$**

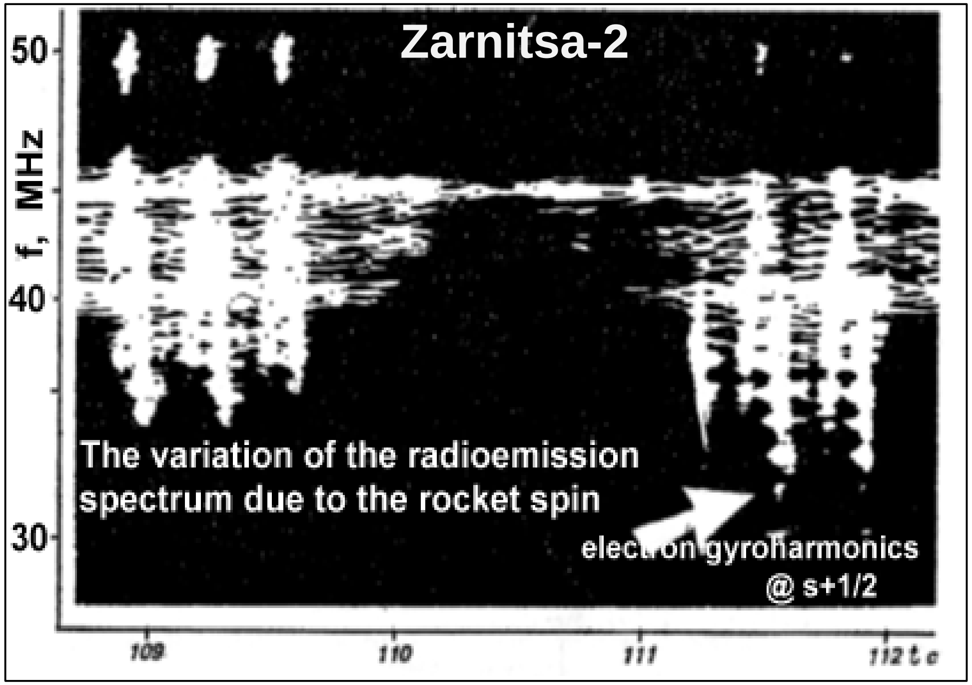
**Much greater than the beam diameter**

- Narrow beam, $\rho_\perp \ll u_b/\omega_{p0}$ at $\theta_0 \le \theta_c$

$$R_{\mathrm{BPD}} \sim \left(\frac{I_c}{I_b}\right)^{1/4} \frac{u_b}{\omega_{ce}} \gg \rho_{ce}$$

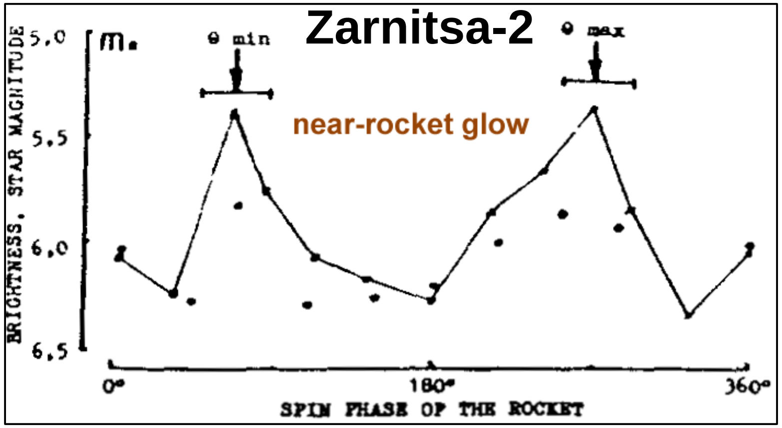
- **Linear theory: *Alekhin, Karpman, Ryutov, Sagdeev*, 1972**
- **Lab. experiments: *Jost et al.*, 1982; *Bernstein et al.*, 1983**

# Modulation by the rocket spin

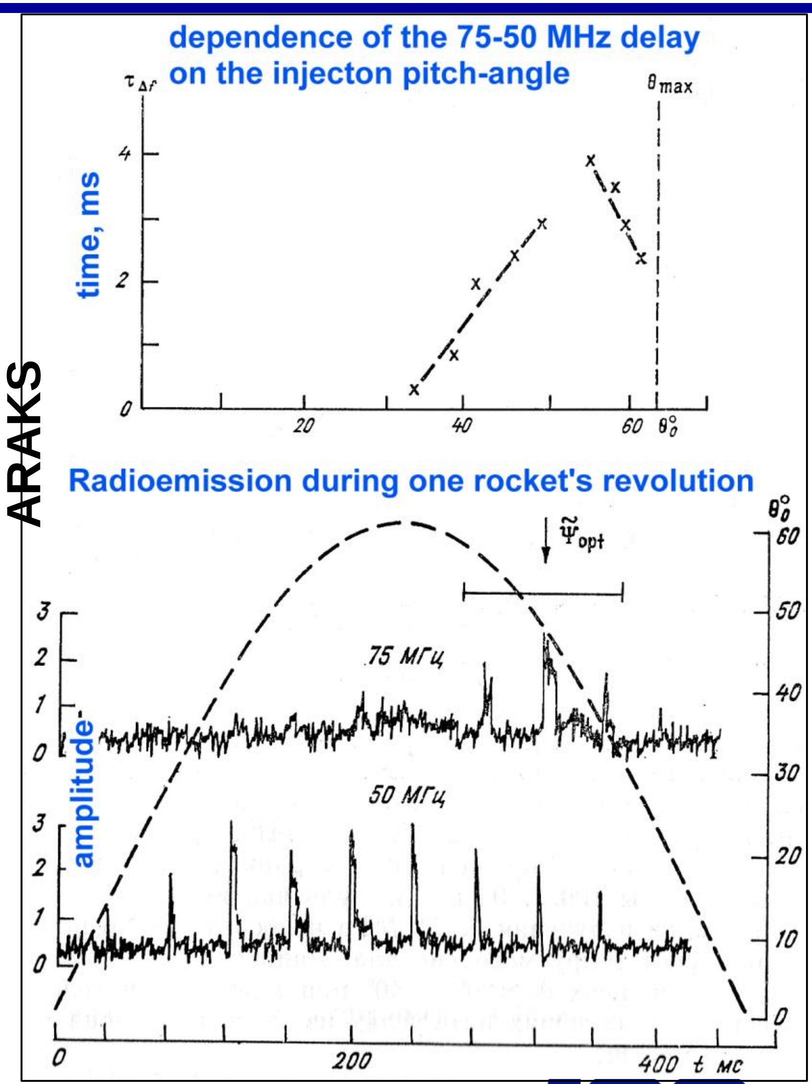

Zarnitsa-2

The variation of the radioemission spectrum due to the rocket spin

electron gyroharmonics @ s+1/2


Zarnitsa-2

near-rocket glow


ARAKS

dependence of the 75-50 MHz delay on the injecton pitch-angle

Radioemission during one rocket's revolution

**Mishin and Ruzhin, 1980**

# BPD initial stage

- Bump-in-tail instability at $\Delta u/u_b < (n_b/n_e)^{1/3}$

$( J_1(\xi_j) = 0 )$

$$\gamma_h \sim \left(\frac{n_b}{n_e}\right)^{1/3}\left(1+\left(\frac{\xi_j}{k_0\rho_\perp}\right)^2\right)^{-1/3}$$

Wide beam

$$\gamma_h \sim \omega_{p0}\left(\frac{n_b}{n_0}\frac{\omega_{p0}}{\omega_{ce}}\right)^{1/2}$$

Narrow beam

Saturation due to trapping of the beam electrons

$$W_0 = \frac{|E_0|^2}{8\pi} \sim n_b\varepsilon_b\cos^2\theta_0\left(\frac{\gamma_h^0}{\omega_{p0}}\right)^{1/2}$$

$$l_\| \sim l_h^0 \sim 4\pi\frac{u_b}{\gamma_h^0} \ll \frac{u_b}{\nu_b}$$

$W_0 \gg n_0 T_e^0 \rightarrow$ Aperiodic instability $\quad \tau_{heating} \sim \Omega_{pi}^{-1}$

saturated by trapping of the bulk electrons $\quad T_e \rightarrow W_0/n_0$

[DeGroot and Katz, 1973]

# BPD development

- Quasi-oscillatory process: Rise→Saturation→ →Heating→Suppression (due to conversion)→Rise, etc.
- At each step, the beam propagates through the "suppression" zone farther from the rocket

- $T_e^{\text{heat}} > \varepsilon_{ion}$ at

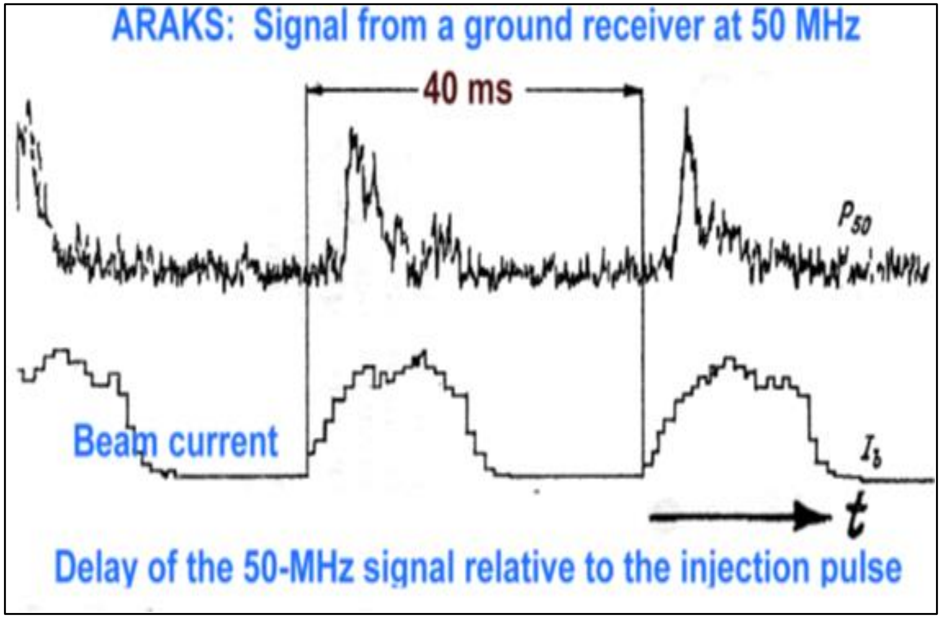
$$I_b > I_* = \left(\frac{\omega_{p0}}{2\omega_{ce}}\right)^{3/2}\left(\frac{\varepsilon_b}{10}\right)^{3/4}\sin^{3/2}\theta_0$$

- Townsend condition

$$\nu_{ion}(T_e^{\text{heat}}) \; > \; \tau_{\text{loss}}^{-1} = \frac{V_{R\perp}}{R_{BPD}}$$

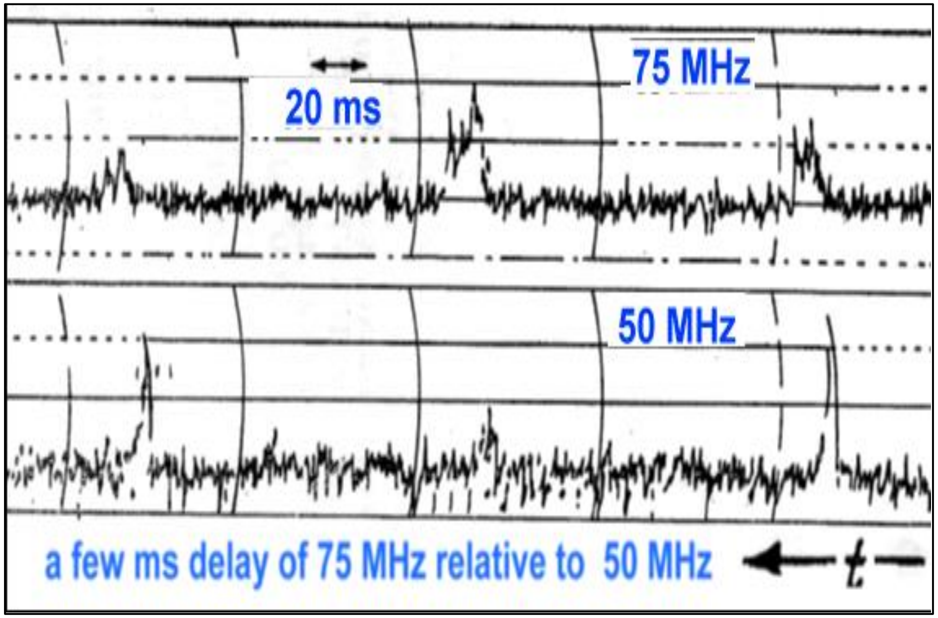
$$N_n > N_{thr} = 3\cdot 10^{10}\left(\frac{10}{\varepsilon_b}\right)^{1/2}\frac{\varepsilon_{ion}}{T_e^{\text{heat}}}B_0[\text{G}]V_{R\perp}[\text{km/s}]$$

# ARAKS : UHF radio emission



ARAKS: Signal from a ground receiver at 50 MHz

Delay of the 50-MHz signal relative to the injection pulse



a few ms delay of 75 MHz relative to 50 MHz

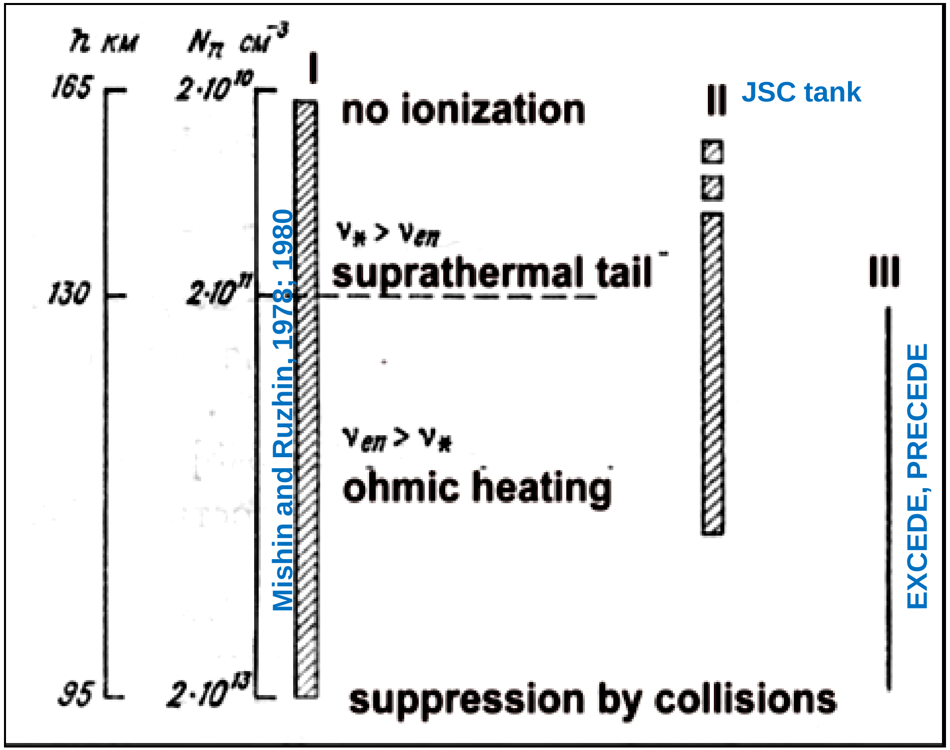
power flux (1-2) $10^{-20}$ W/m$^2$Hz

power 30-100 W
1% - 3% beam power

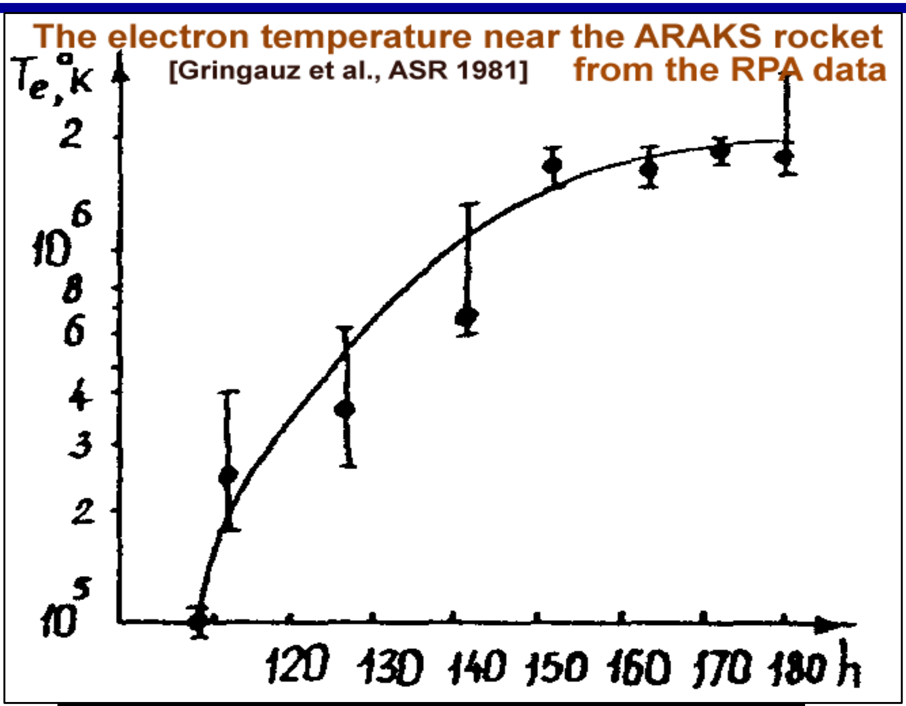
- **Consistent with the BPD ionization rate**

**Mishin and Ruzhin, 1980**

# BPD



Altitude and neutral density range over which BPD is expected [Linson, 1982]


The electron temperature near the ARAKS rocket from the RPA data

[Gringauz et al., ASR 1981]

- Greatly-elevated electron temperature

$$\text{Steady state at } n_e > n_* = n_b \frac{\varepsilon_b}{\varepsilon_{ion}} \sim 10^3 n_b$$

# Strong Langmuir Turbulence

## SLT

$$n_b^{(th)} \approx 10^{-6}\left(1+\frac{2\nu_e\,\varepsilon_b}{3\omega_p\,T_e}\right)n_e$$

- Waves are trapped inside density cavities
- Collapsing cavities transfer the wave energy toward short scales
- In saturation, the wave energy is

$$W_{SLT} \cong \sqrt{\frac{3m}{M}\frac{\gamma_b}{\omega_p}}\,n_e T_e \ll W_\infty$$

- Short-scale waves are absorbed by plasma electrons, leading to non-Maxwellian suprathermals

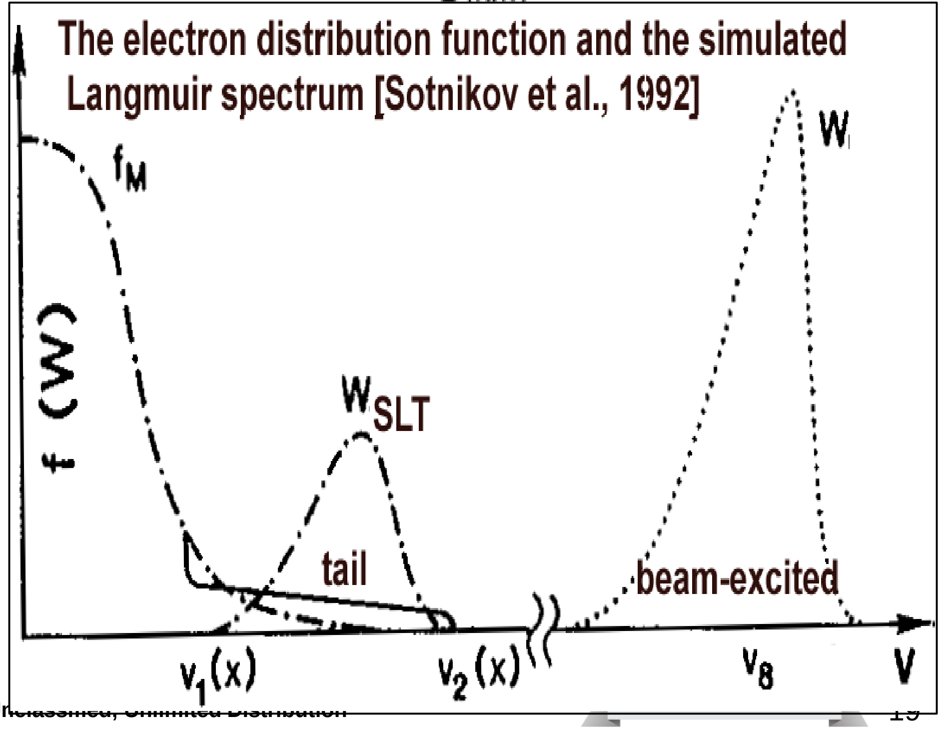
$$F_a(\varepsilon_\parallel) \simeq \frac{2p_a-1}{v_{\min}}\,n_a\left(\frac{\varepsilon_{\min}}{\varepsilon_\parallel}\right)^{p_a}$$

$(p_a \simeq 0.8\text{-}1)$

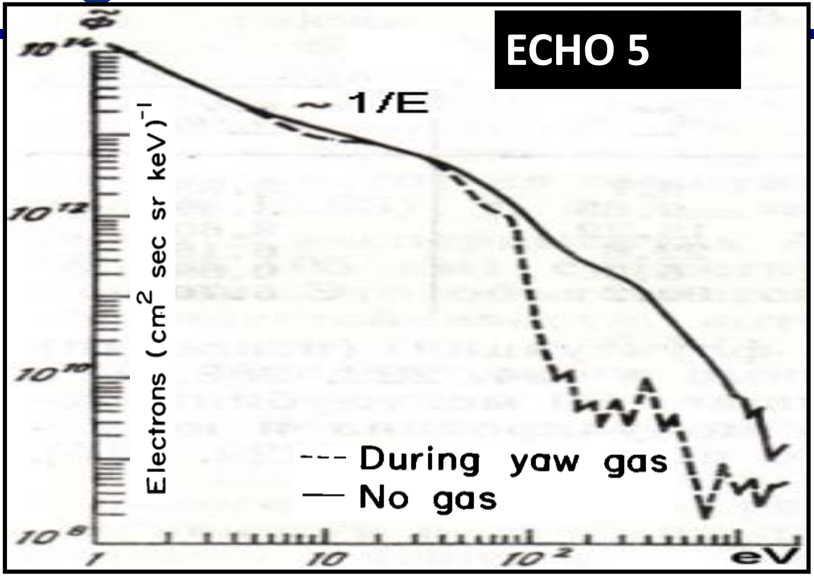
**Ionization by accelerated electrons**

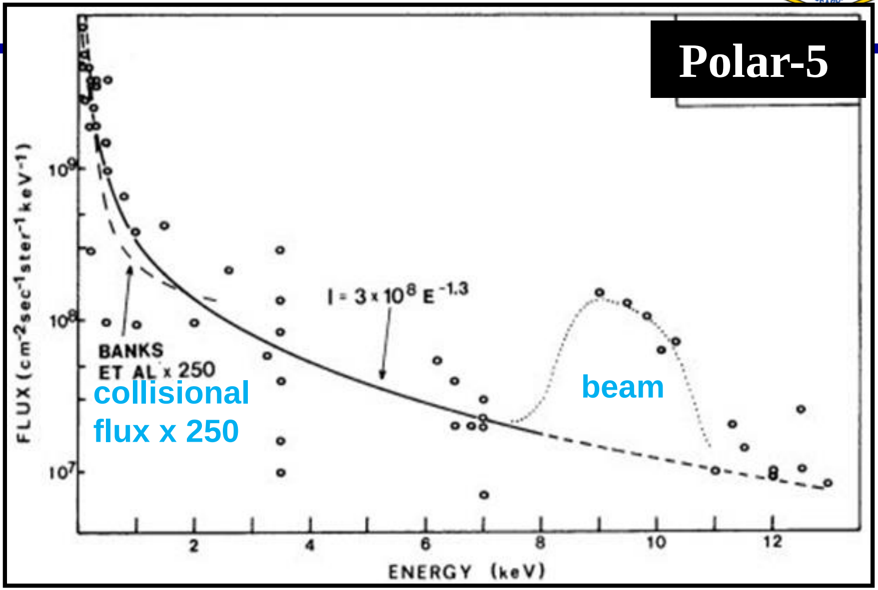
$$q_{ion}^{(t)} \simeq 10\,\nu_e(T_e)\,n_b\,\frac{T_e}{\varepsilon_{ion}}\left(\frac{\varepsilon_b}{\Delta\varepsilon_\parallel}\right)^2$$

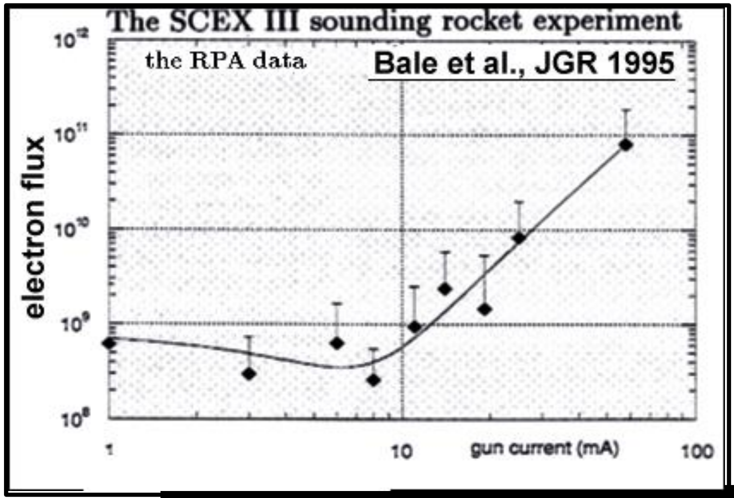
z (km)

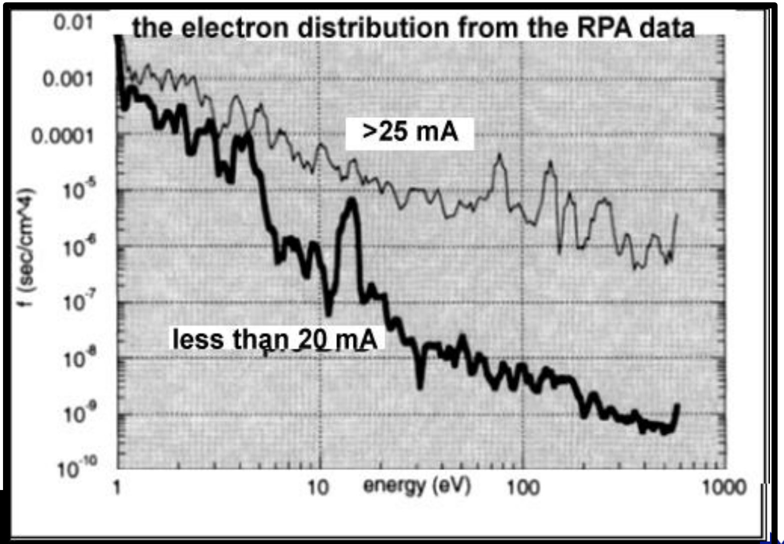

The electron distribution function and the simulated Langmuir spectrum [Sotnikov et al., 1992]

# Suprathermal Electrons



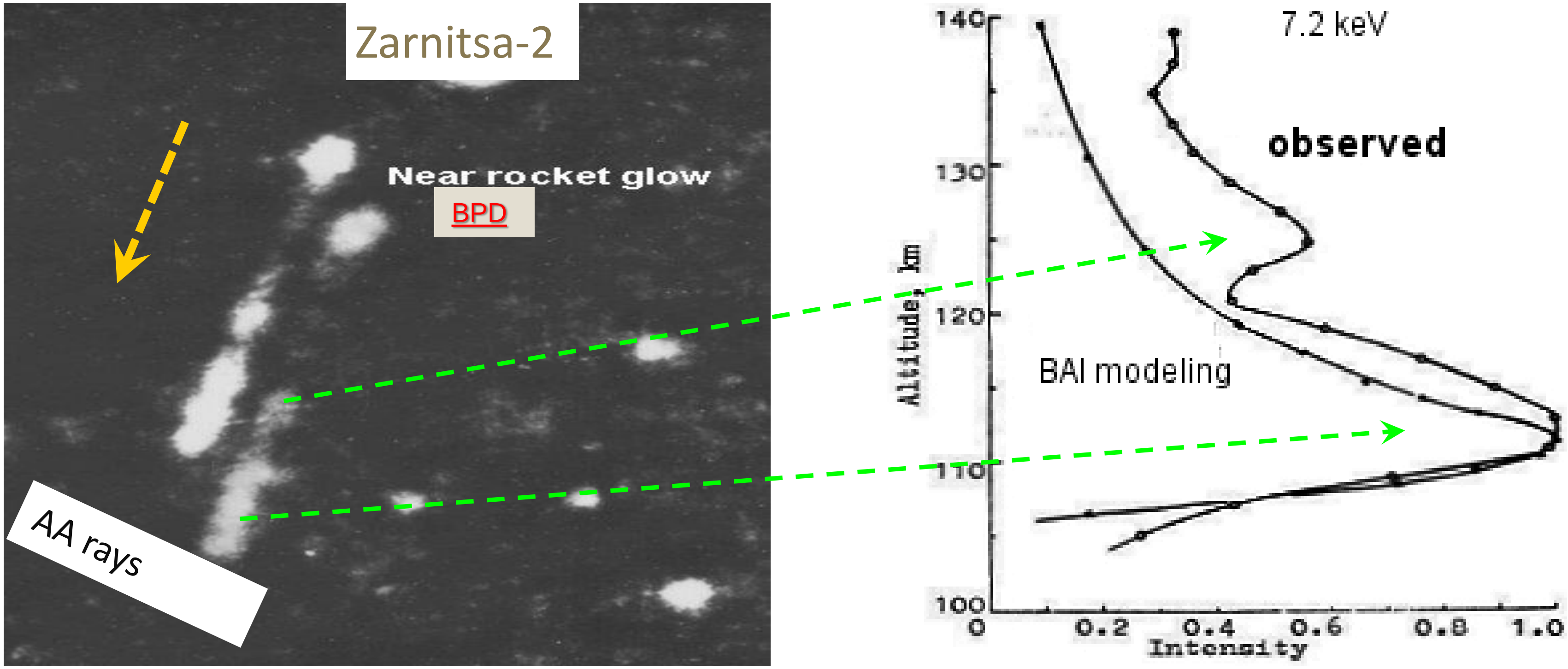






- Flat suprathermal spectra
- Many more suprathermal electrons than collisional values

# Artificial Aurora Rays



**Mishin et al., 1981**

# SLT Auroral Rays

## ➢Effects of collisions on SLT

$$\Gamma_b \gg \nu_e > \frac{m}{M}\omega_p$$

**As the collapse rate is smaller than $\Gamma_b$ , the beam can excite waves *but* the trapped waves are damped faster than collapsing. As nonlinear transfer is reduced, the Langmuir wave energy grows until collapse will be possible.**

the limiting collision frequency

$$\nu_* = \omega_p \left(\frac{m}{M}\frac{\Gamma_b}{\omega_p}\right)^{1/2}$$

**Volokitin and Mishin , 1979**

Wave energy density

$$W_L/n_eT_e \simeq \frac{3M}{m}\left(\frac{\nu_e}{\omega_p}\right)^2$$

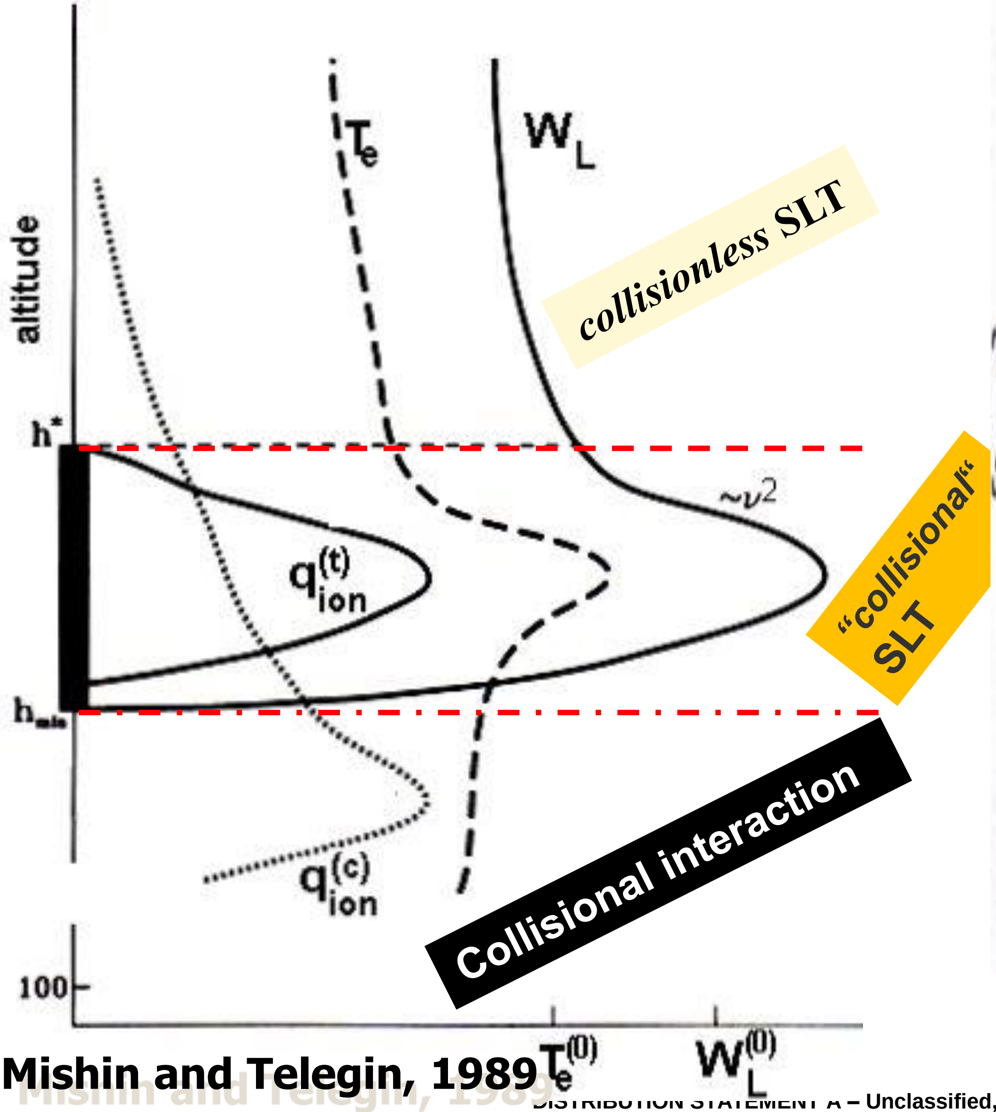
Ionization by accelerated electrons

$$T_e \approx \sqrt{3\varepsilon_{ion}\frac{W_L}{n_e}}$$

$$q_{ion}^{(t)} \simeq 10\ \nu_e(T_e)\ n_b\ \frac{T_e}{\varepsilon_{ion}}\left(\frac{\varepsilon_b}{\Delta\varepsilon_{\|}}\right)^2$$

# Plasma Turbulence Layer

**Schematic of altitude-profiles**



*collisionless* SLT

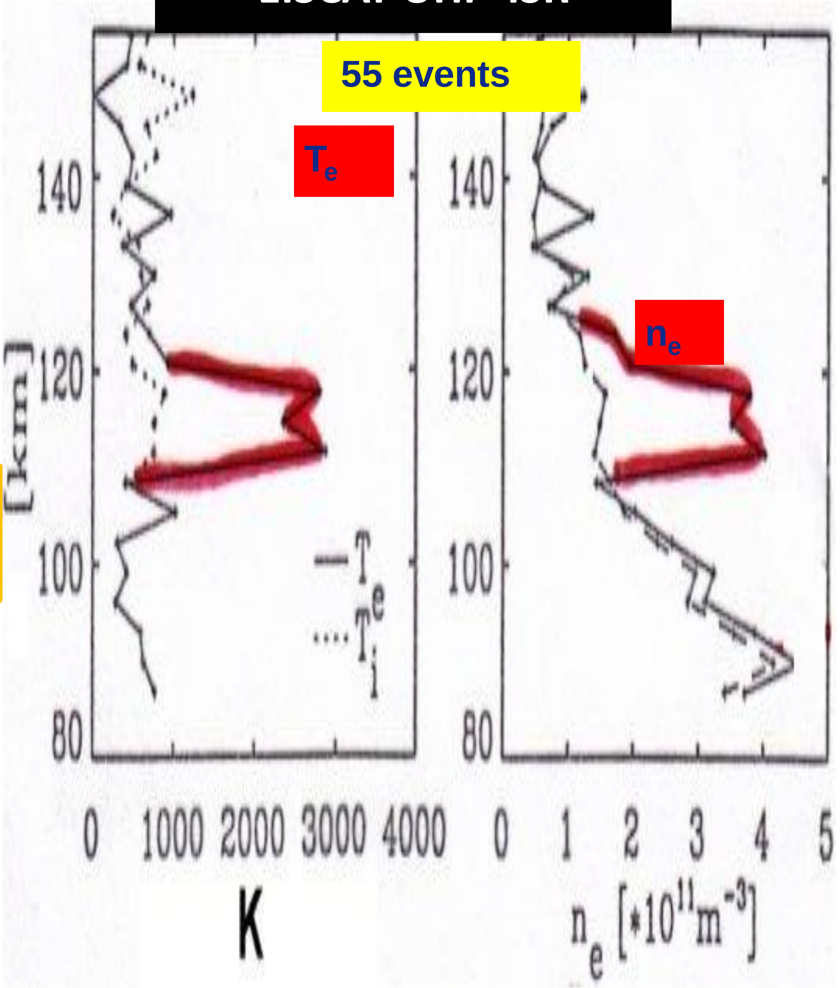
"collisional" SLT

Collisional interaction

Mishin and Telegin, 1989

Mishin and Telegin, 1989

**EISCAT UHF ISR**



55 events

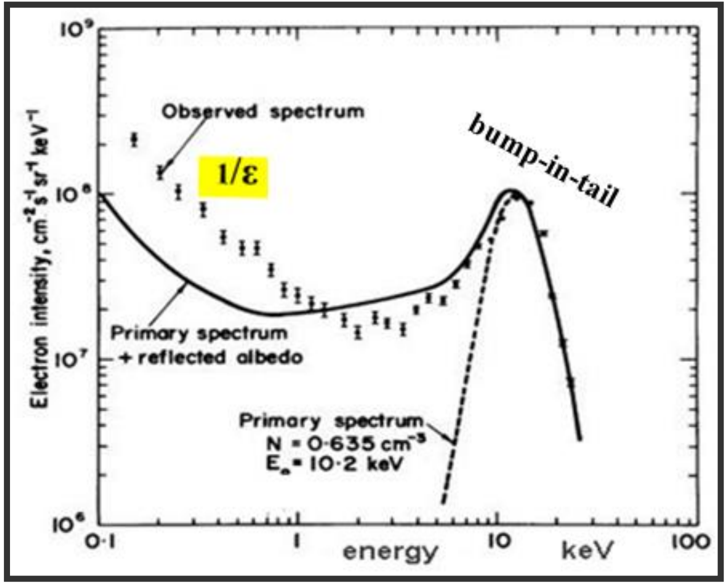
$T_e$

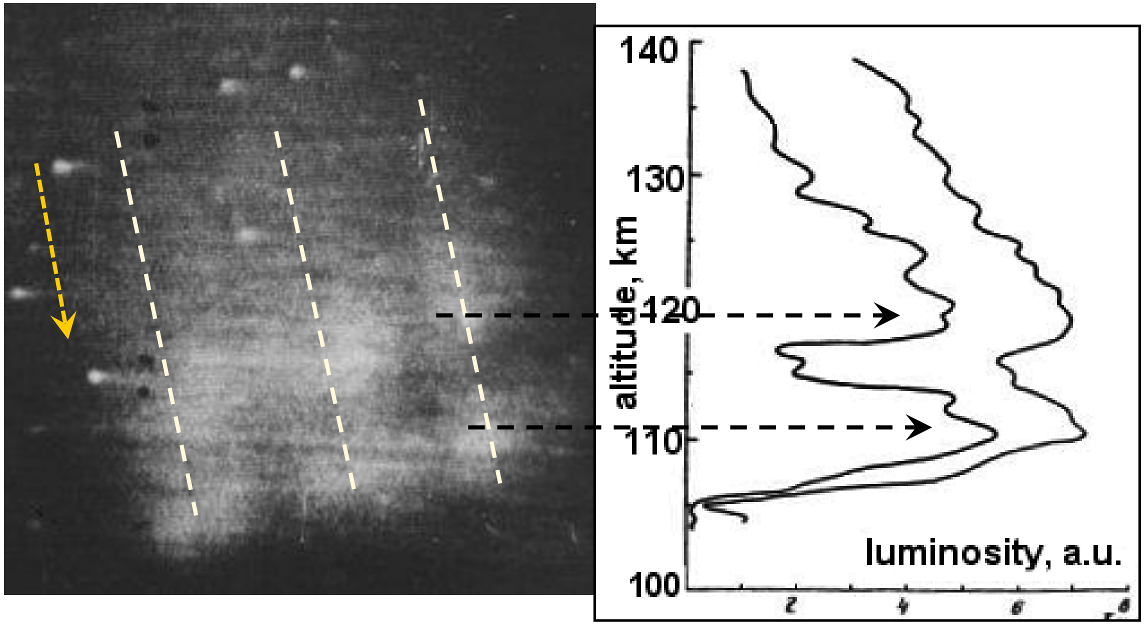
$n_e$

Schlezier et al., GRL 1997

Schlezier et al., GRL 1997

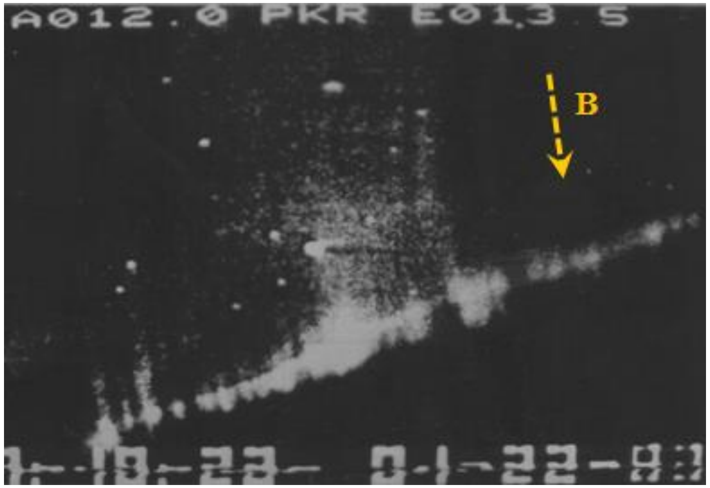
# Enhanced Aurora





Double-peaked auroral rays

Dzyubenko et al., 1980

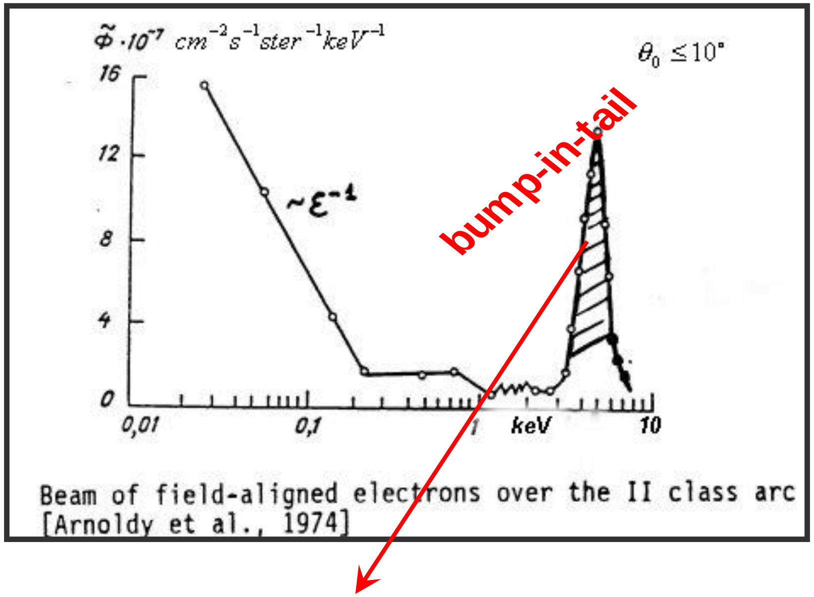


sharp upper boundary

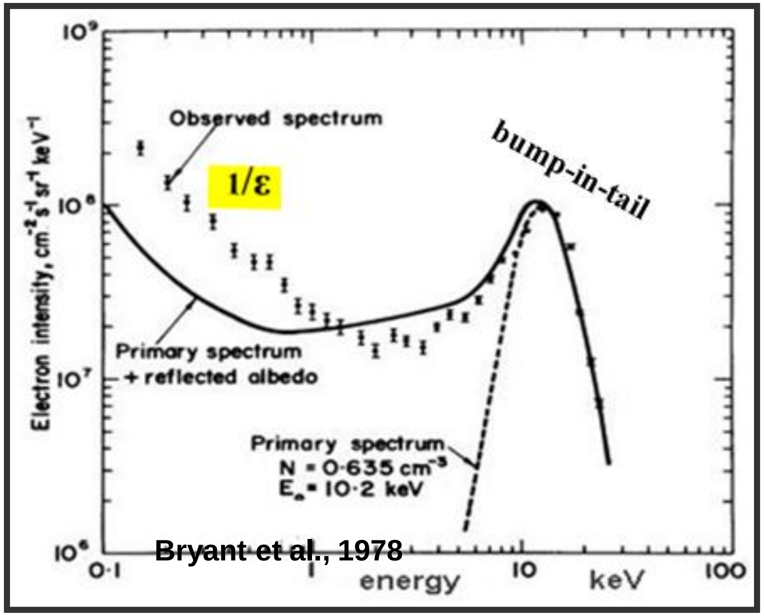
Hallinan et al., 1995

# Beam-Plasma Instability

**Natural Auroras**



Beam of field-aligned electrons over the II class arc [Arnoldy et al., 1974]



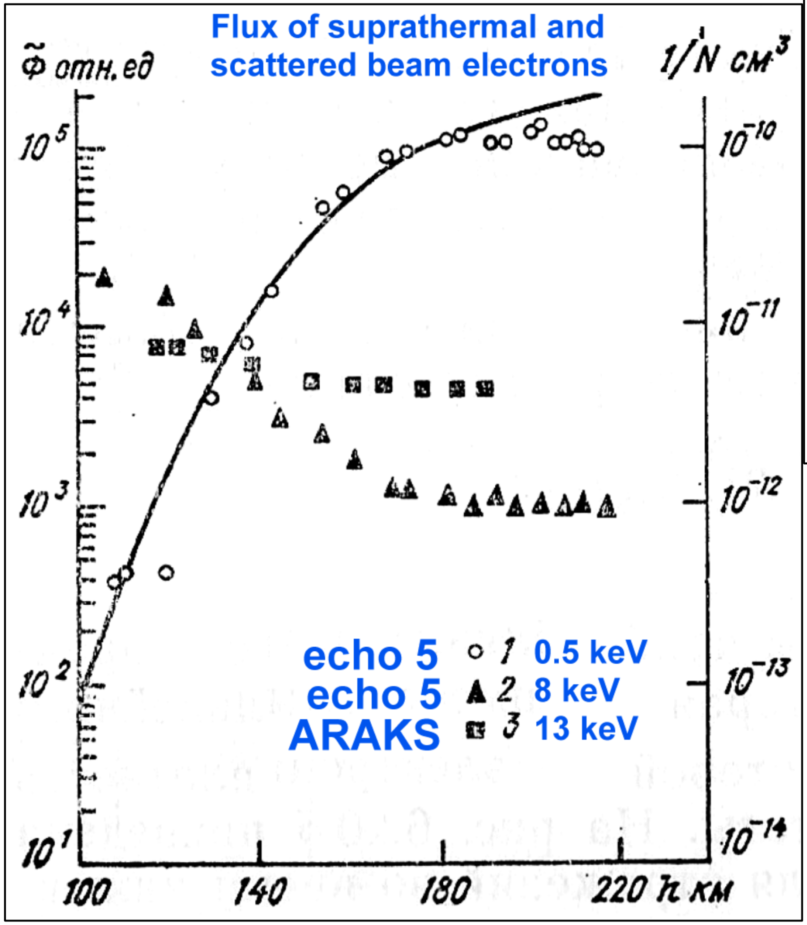
Bryant et al., 1978

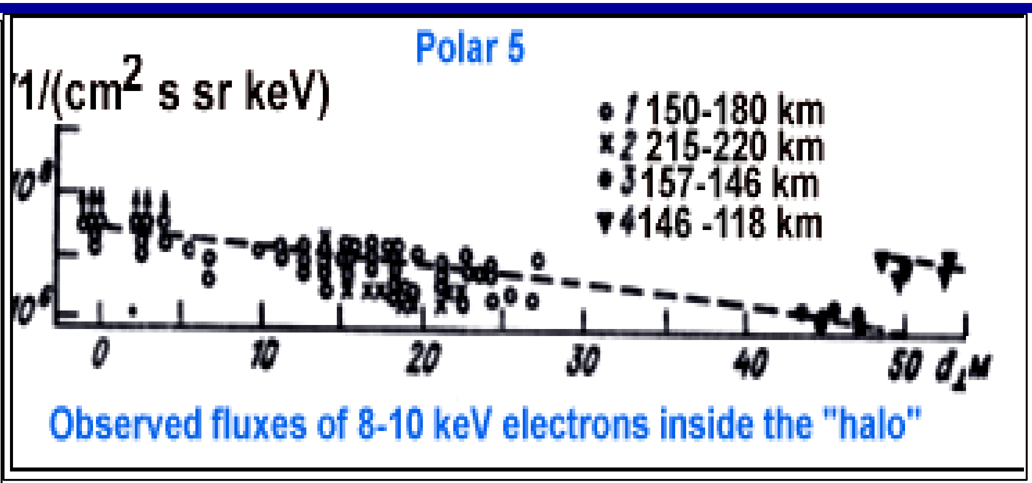
**Inverse Landau damping**

$$\Gamma_b \sim \omega_p \frac{\pi n_b}{n_e}\left(\frac{\varepsilon_b}{\Delta\varepsilon_{\|}}\right)^2 - \nu_e(T_e)$$

AFRL HERITAGE | 1917–2017

# Beam scattering near the rocket





- ❖ Greatly exceeds collisional scattering near the rocket

- ❖ Prompt Electron Echo ( PEE) [Hendrikson et al., 1975; Winckler et al., 1975; Maehlmn et al., 1980; Wilhelm et al., 1985] with time delays < 100 ms during upward beam injections

# Prompt Electron Echo SLT model

$$\frac{\partial\langle f\rangle}{\partial t}+\mu v\frac{\partial\langle f\rangle}{\partial s}-\frac{1-\mu^2}{v}\frac{v^2}{2B}\frac{\partial B}{\partial s}\frac{\partial\langle f\rangle}{\partial \mu}=\langle S\rangle$$

$$\langle f\rangle=\frac{1}{2\pi}\int_0^{2\pi} f(\phi)d\phi$$

$\mu=\cos\theta$, $s$ is the coordinate along the geomagnetic field

$$\langle S\rangle_{ep}=\nu_{eff}\frac{\partial}{\partial\mu}[(1-\mu^2)\frac{\partial f}{\partial\mu}]$$

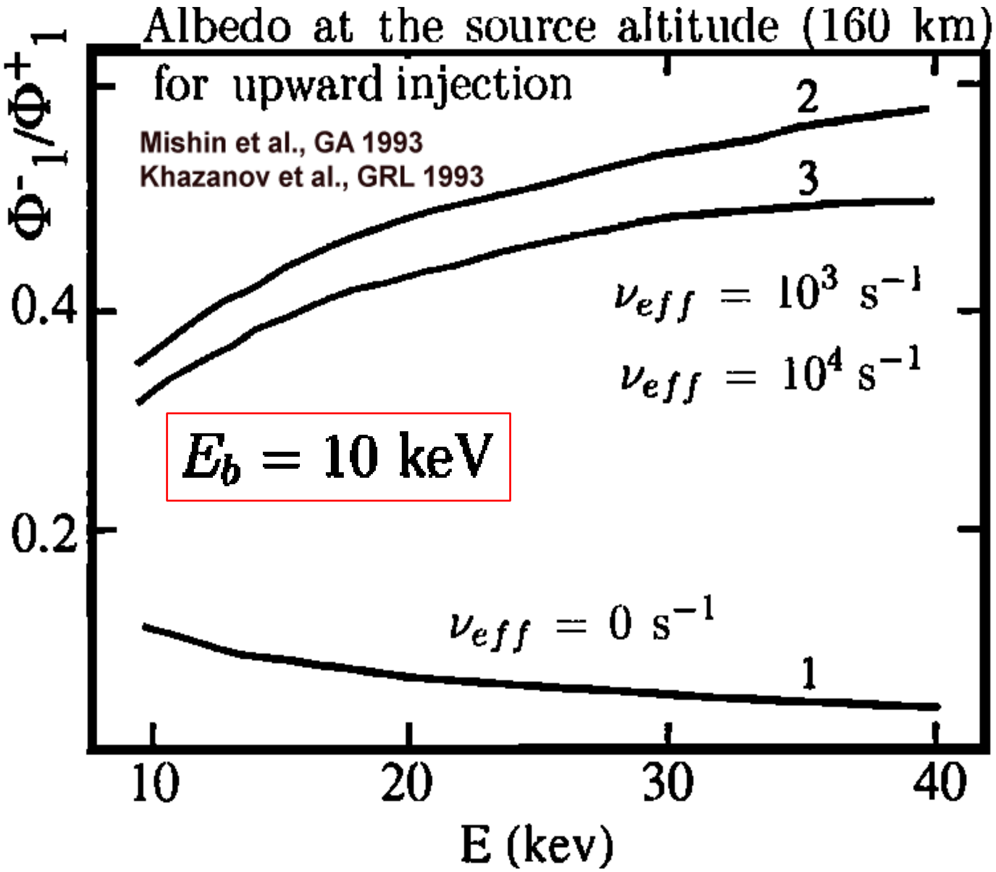
$$\nu_{eff}=\omega_p\left(\frac{W_L}{n_eT_ek_Lr_D}\right)\left(\frac{T_e}{E_b}\right)^{3/2}\simeq\omega_p\left(\frac{n_b}{n_e}\right)^{1/2}\left(\frac{u}{\Delta u}\right)\left(\frac{T_e}{E_b}\right)^{3/2}$$

$$\boxed{k_L\gg k_o=\omega_p/v_o}$$

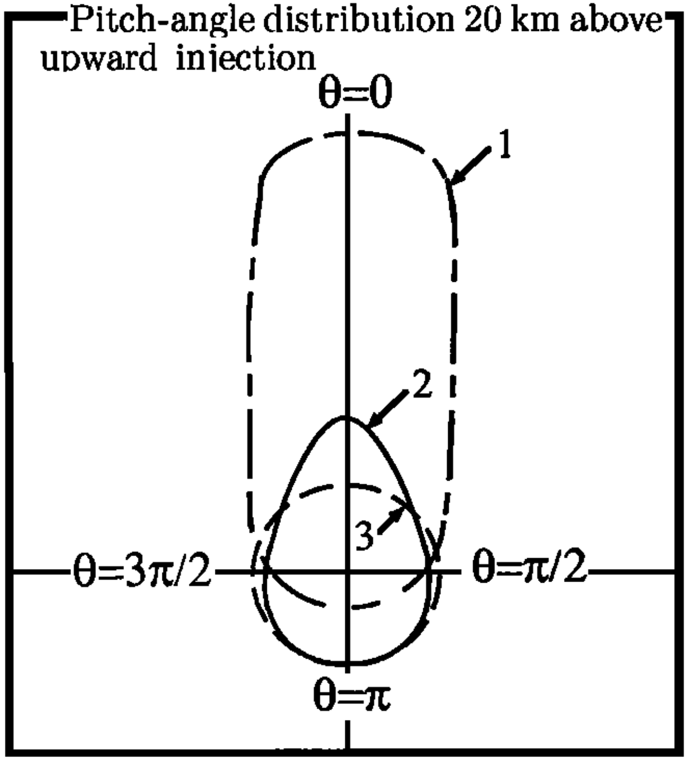
$$\Phi^+(E)=\int_0^1\mu\psi(E,\mu)d\mu$$

**Mishin et al, 1989**

# PEE calculations


Albedo at the source altitude (160 km) for upward injection

Mishin et al., GA 1993
Khazanov et al., GRL 1993


Pitch-angle distribution 20 km above upward injection

$$\Phi^+(E) = \int_0^1 \mu\psi(E,\mu)d\mu$$

# Strong LT in auroral plasma

Flat accelerated electron spectrum

$$\boxed{n_b^{(th)} \approx 10^{-6}\left(1+\frac{2\nu_e\,\varepsilon_b}{3\omega_p\,T_e}\right)n_e} \rightarrow \text{SLT} \rightarrow \boxed{F_a(\varepsilon_\|) \simeq \frac{2p_a-1}{v_{\min}}n_a\left(\frac{\varepsilon_{\min}}{\varepsilon_\|}\right)^{p_a}}$$

$(p_a \simeq 0.8\text{-}1)$

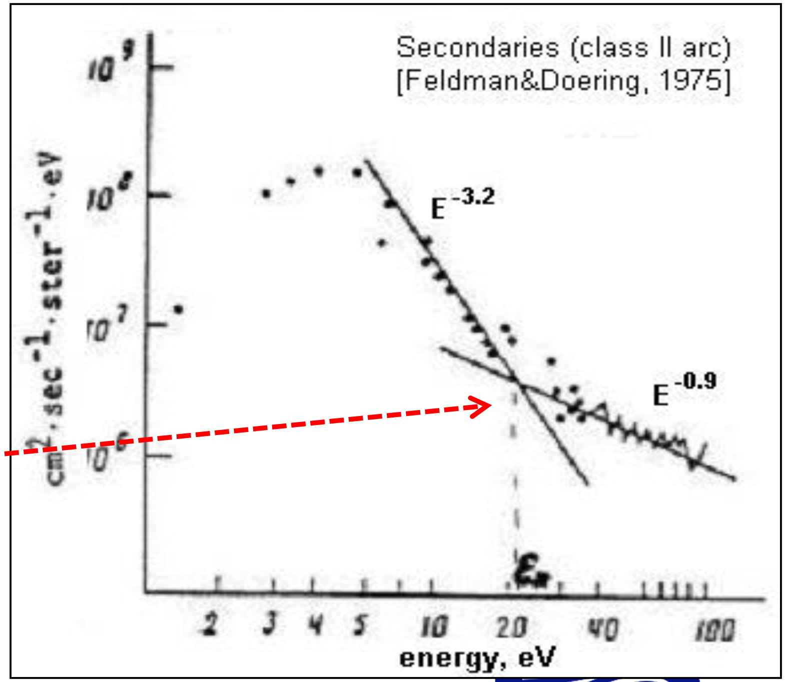
Joining condition

$$\boxed{F_a(\varepsilon_{\min}) = F_0(\varepsilon_{\min})}$$

➢**Acceleration of *secondary* electrons**

$$\boxed{\varepsilon_{min} \simeq 30(W_L/n_sT_e)^{-2/5}[\mathrm{eV}]}$$

$n_s$ is the density of secondary electrons



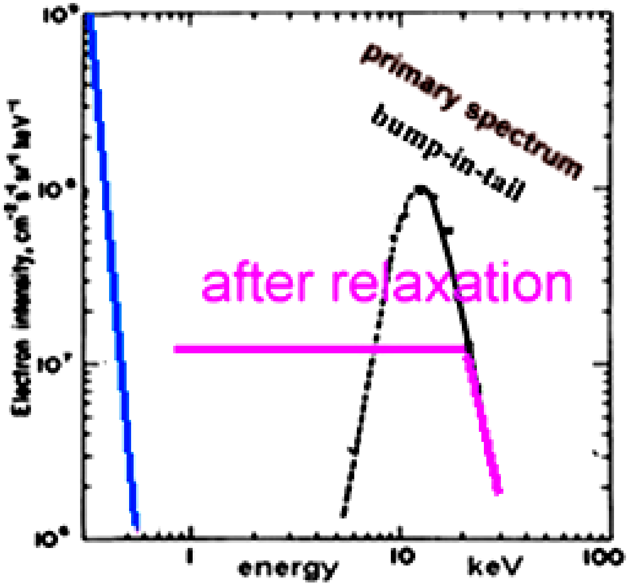
**Mishin & Telegin, 1989**

Mishin & Telegin, 1989

# SUMMARY

- ✓ Limited survey of nonlinear beam-plasma interactions during active experiments with electron beam injections in the ionosphere is given.
- ✓ Artificial aurora and near-rocket glow, artificial radio emission, accelerated and albedo electrons, rocket potential and electron temperature near a rocket, and telemetry damping.
- ✓ Theory of beam-plasma discharge
- ✓ Enhanced aurora

# Collisionless Beam Plasma Interaction



**Inverse Landau damping**

$$\Gamma_b \sim \omega_p \frac{\pi n_b}{n_e}\left(\frac{\varepsilon_b}{\Delta\varepsilon_\parallel}\right)^2 - \nu_e(T_e)$$

**Langmuir waves gain energy at the expense of the beam**

$$n_b \frac{d}{dt}\langle\varepsilon\rangle_b \simeq -\frac{d}{dt}\sum\nolimits_k W_k \simeq -\Gamma_b W_r$$

**Relaxation length**

$$l_r \simeq \frac{\Delta v_\infty}{\gamma_b^\infty}\frac{n_b\varepsilon_b}{W_r}$$

**QL-saturated wave energy (no wave-wave coupling)**

$$W_\infty \cong 0.1 n_b \varepsilon_b \frac{\varepsilon_b}{T_e} \gg n_e T_e$$