METHODS AND FIRST RESULTS OF PLASMA NON-ISOTHERMAL
PARAMETERS MEASUREMENTS IN METEOR TRAILS

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There is no reliable experimental evidence so far of either the presence or absence of non-isothermal effects in newly-formed meteor trails. Neither is there a common opinion on the most effective mechanism of electron cooling. According to the laboratory experimental data (BIDIN and DEMKOV, 1982), collisions of atomic and molecular particles of all kinds having velocities of 10-70 kms^{-1} often yields 1eV electrons and not infrequently some have energies reaching several electron-volts. These highest energy electrons will be referred to as superhot electrons.

The mechanisms leading to electron energy losses in meteor trails are numerous (thermal conduction by ionospheric plasma electrons, diffusive cooling, elastic and non-elastic collisions of superhot electron with trail ions and neutral atmospheric particles), but each role is different. Diffusive cooling losses do not exceed 10-20% of the general electron energy. During the nighttime, thermal conductivity of ionospheric gas can be ignored. In meteor trails with linear electron densities $\alpha < 10^{12}$ el/cm, the plasma can be considered only slightly ionized and the electron cooling due to ion collisions may be ignored. If the conditions mentioned above are fulfilled, the energy balance equation for the electron component of the meteor trail plasma looks like:

$$\frac{3}{2} kn_e \frac{dT_e}{dt} = - \sum_n (L^\circ_{en} + L^*_{en}) \ , \qquad (1)$$

where n_e, T_e are concentration and effective temperature of electrons in trail, k is the Boltzman constant, and L°_{en}, is the electron cooling rate due to elastic losses and L^*_{en} is the non-elastic losses of energy through collisions with neutral atmosphere particles (atoms and molecules). Equation (1) was numerically solved for conditions covering the height interval of 80-115 km. The calculations included elastic collisions of electrons with N_2, O_2 and O; rotational and vibrational excitation of N_2 and O_2 molecules; electronic $^1\Delta g$ and $^1\Sigma g^+$ excitation of O_2 molecules and ^1D level of oxygen atoms as well as the O_* atomic fine structure excitation. The corresponding formulas for L°_{en} and L^*_{en} are taken from STUBE and VARNUM (1972) and PRASAD and FURMAN (1973). Fig. 1 shows calculated results (over the height interval 90-100 km) for the electron thermalization time τ_T which is defined as the time required for the temperature to decrease from the initial value T_{eo} down to a level 1.1 times greater than the neutral atmosphere particle temperature T_n. The numbers near the curves give the assumed value of electron temperature to neutral particle temperature ratio $a = T_{eq}/T_n$ upon which calculations of τ_T were based. So, if a = 50, then at the heights of 90, 93, 95, 100 and 205 km, electron thermalization takes place in 3, 7, 9, 22.6 and 54 ms. The effective electron temperature decrease from $T_e = 50T_n$ to $T_e = 10T_n$ takes place very quickly with a time shorter than the ion thermalization time. Considerable moderation of trail plasma electron component cooling rate occurs when the values $T_e/T_n < 10$.
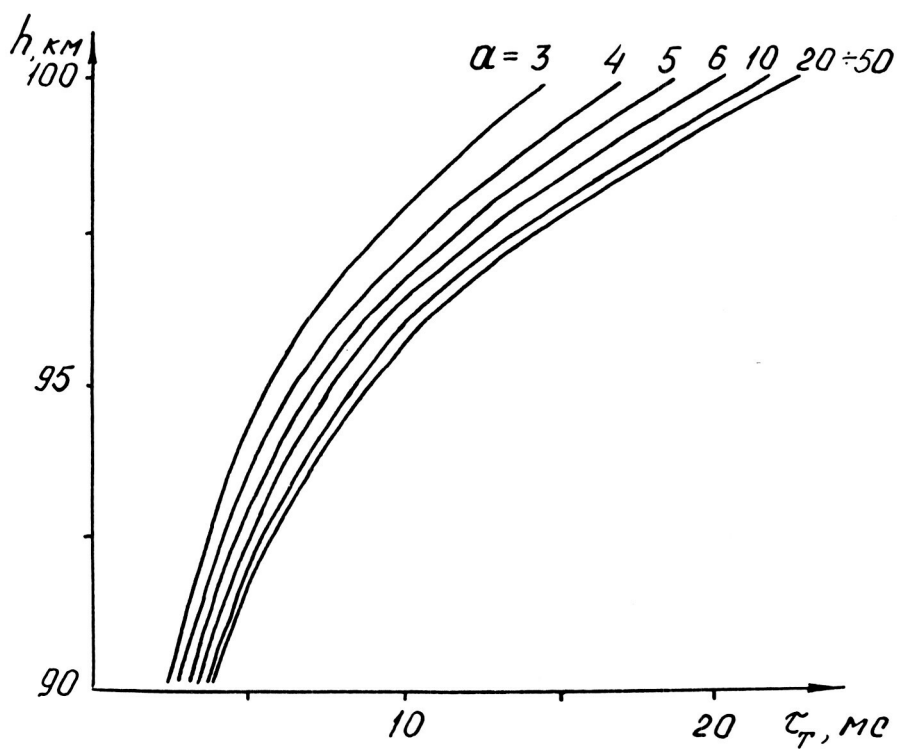
Fig. 1   Dependence of thermalization time τ_T on height and initial effective temperature a of electrons in a meteor trail.

Let us write down the signal power scattered by an unsaturated non-isothermal meteor trail as follows (AMINOV and TOKHTASJEVE, 1973; AMINOV et al., 1976):

$$P_r = P_{r_1} \, f(r_1) \, I^2 \qquad (2)$$

where

$$I = \left| \frac{1}{\sqrt{2}} \int_{x_1}^{x_o} \frac{\alpha}{\alpha_1} \exp\left(i \, \frac{\pi}{2} \, x^2 - \left(\frac{4\pi r_o}{\lambda} \right)^2 \xi(t) - \left(\frac{2\pi r_o}{\lambda} \right)^2 \left[1 - \left(\frac{r_1}{r_o} \right)^2 \right] \right) dx \right| ; \qquad (3)$$

$$\xi(t) = \frac{Da_o}{r_o^2} \left[\frac{1}{2} \, t + \frac{1}{2T_n} \int_o^t T_e(\eta) d\eta \right] ; \quad t = \frac{\sqrt{R_1 \lambda}}{2v} (x_o - x) ; \qquad (4)$$

$$f(r_1) = \exp\left[-2 \left(\frac{2\pi r_1}{\lambda} \right)^2 \right] ;$$

with α = linear trail electron density, Pr_1 = signal power scattered from a trail when $\alpha = \alpha_1$ and calculated by the Lovell-Clegg formula; D_{ao} = coefficient of ambipolar diffusion in the isothermal meteor trace; r_o = initial trail radius, R_1 = slant distance to the reflecting point in the trace, v = meteor body velocity, and λ = radar wavelength. The index 1 denotes the value corresponding to the reflecting point.

If the changes of α along the trail as well as the height dependence of D_{ao}, r_o and ξ are all neglected, then the diffraction integral (3) is simplified:

$$I = \left| \frac{1}{\sqrt{2}} \int_{x_1}^{x_o} \exp\left[i \, \frac{\pi}{2} \, x^2 - \left(\frac{4\pi r_o}{\lambda} \right)^2 \xi(t) \right] dx \right| \qquad (5)$$

To analytically calculate the diffraction pattern of the radioecho from unsaturated meteor trails, it is necessary to simplify the function $\xi(t)$. In order to do this, Equation (1) was replaced by two simple model differential equations having analytical solutions. One of the solutions gives a more rapid and another - a slower time decrease as compared with the results of the numerical solution Equation (1). For the first model we have

$$\left(\frac{4\pi r_o}{\lambda} \right)^2 \xi(t) = \frac{\tau_\phi}{\tau_D} (x_o - x) + \frac{\tau_p}{\tau_D} \cdot \frac{\alpha^*}{2} \left(1 - \exp\left[- \frac{\tau_\phi}{\tau_p} (x_o - x) \right] \right) \qquad (6)$$

for the second

$$\left(\frac{4\pi r_o}{\lambda}\right)^2 \xi(t) = \frac{\tau_\phi}{\tau_D}(x_o - x) + \frac{\tau_p}{\tau_D}\left(\frac{1}{1-C} - \frac{1}{1 - C\left[-\frac{\tau_\phi}{\tau_p}(x_o - x)\right]}\right) \quad (7)$$

In the formulas (6) and (7), the following notations are introduced:

$$\tau_\phi = \frac{\sqrt{R_1 \lambda}}{2v} \; ; \; \tau_D = \frac{\lambda^2}{16\pi^2 Da_o} \; ; \; \tau_p = \frac{1}{B} \; ; \; C = \frac{\sqrt{a^*} - 1}{\sqrt{a^*} + 1} \quad ,$$

$a^* = T_e^*/T_n$. The physical meaning of the parameter B is defined below.

The influence of non-isothermal effects in a meteor trail plasma on the amplitude and form of radioecho depends upon the correlation of characteristic time of formation of the Fresnel first zone τ_ϕ, the electron effective temperature relaxation time τ_D and the time constant of the signal amplitude decrease L_D. When compared to the isothermal case, the diffraction pattern distortions increase with increasing reflecting point height. But when the reflection height and radar wavelengths are fixed, they increase with a decrease of the trail slant range.

Numerical integration of the formula (5) considering the dependence given by (6) was made to choose optimal conditions for detection of non-isothermal effects in meteor trails, which in turn allow measurement of the *main parameters* a^* and B for the non-isothermal plasma. The theoretical analysis permits the following conclusions. Despite the small values of the thermalization time τ_T of superhot electrons in newly-formed meteor trails, non-isothermal effects contribute to the considerable weakening of trail scattered signals and to specific diffraction pattern distortions. The first maximum of the diffraction pattern shifts slightly, but if its position is not used in amplitude and time characteristic processing (as is usually done), then errors in determining speed by all the other extremes are negligible and do not exceed 1-2%. The depths of the minima of the diffraction pattern all increase (Fig. 2). Fig. 3 (a, b, c) shows the amplitude ratios for several extrema as a function of $\Delta = \tau_\phi/\tau_D$ for both the isothermal (dashed curves) and non-isothermal *solid curves*) cases. It can be seen that relationships of the first and second maxima to the first minima possess a strong and rather characteristic dependence on Δ. The amplitude ratios, A/D and C/D, though not shown, are also characterized by a similar dependence on Δ.

The existence in the observational amplitude-versus-time characteristics of the mentioned peculiarities enables one to select those that are of interest for a more detailed analysis by optimization *methods* (KOSTYLEV and KOSTYLEV, 1980). Thanks to the sufficient accuracy of determining a whole range of meteor parameters, the use of these methods makes it feasible to estimate the main parameters of the non-isothermal electrons component in meteor trails - a^* and q = B/100 with a relative r.m.s. error of $\langle\sigma a^*\rangle/a^* \approx 25\%$ and $\langle\sigma q\rangle/q \approx 45\%$.
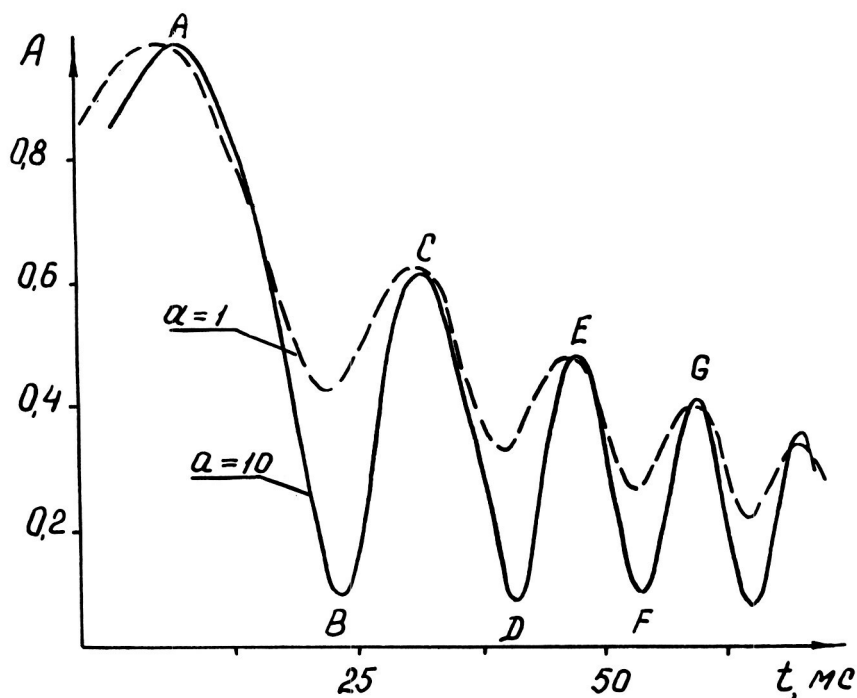
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Fig. 2   Amplitude and time characteristics, with (a = 10) and without
(a = 1) non-equilibrium temperature effects, calculated for the
following parameters values:

$$D = 11.9 \ m^2 s^{-1}; \quad V = 40 \ km \ s^{-1}; \quad Z = 33°$$

$$r = 1.4 \ m; \quad q = 4.34; \quad \lambda = 9.375 \ m; \quad R = 185 \ km$$
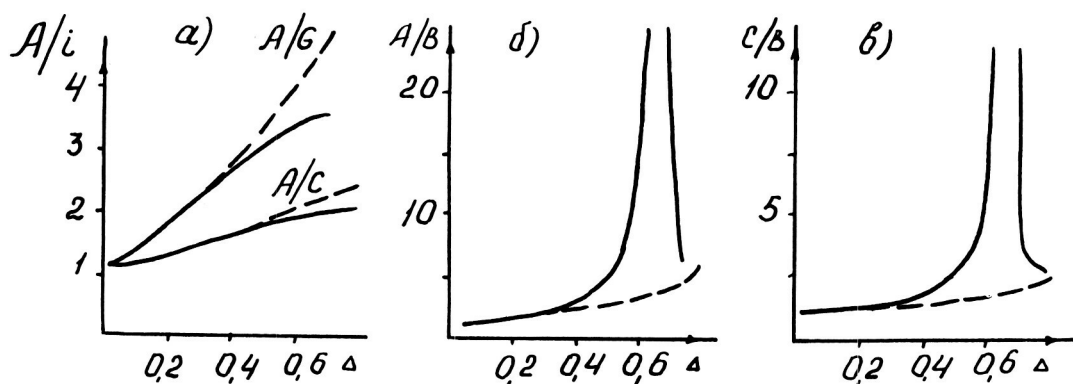

Fig. 3   Dependence of diffraction pattern extremum ratios on the
parameter Δ with (——) and without (---) non-equilibrium
temperature effects.

The model of meteor trail formation used in the calculations allows for variation of (a) the ambipolar diffusion coefficient and initial radius along the trail, (b) the position of the reflecting point on the ionization curve and (c) meteor body deceleration and seems adequate enough to describe real meteor phenomenon (KOSTYLEV, 1983).

Fig. 4 shows a histogram of the distribution of derived a^* values. Echoes recorded at night during the period of the Geminids in 1983 and Perseids in 1978 were selected for optimization methods processing. The mode of a^* shown by this distribution equals 4.7. The height dependence of the measured values of the number $q = B/100$ is shown in Fig. 5. Also shown is the theoretical dependence for mode (7) with $q = 0,014 \langle\delta\rangle \nu^\circ_{en}$, where $\langle\delta\rangle$ is the part of energy lost by superhot electrons per one collision with an atmospheric particle and averaged over the temperature interval $T_n < T_e < T_e$ and ν°_{en} is the effective frequency of electron collisions with neutral atmosphere components with $T_e = T_n = 200°K$. For the calculation $\langle\delta\rangle = 1,1 \times 10^{-3}$ was used. Using the derived value of the parameter q, we get the following values of ν°_{en}: 1.4×10^5 and $1.2 \times 10^5 s^{-1}$ at the heights of 94 and 96.5 km. The paper Middle Latitude Ionosphere Empirical Models, (Moscow, 1981), gives the ν°_{en} values as 1.4×10^5 and $0.9 \times 10^5 s^{-1}$ for the same altitudes. The coincidence is quite satisfactory.

In conclusion, it may be said that in trails produced by meteors with velocities of 35-60 kms, the initial effective temperature of electrons is at least 5 times as high as that of the neutral atmosphere particles. This provides a real possibility for radar measurement of an important structural parameter of ionosphere, the electron collision frequency, in the 90-105 km interval.

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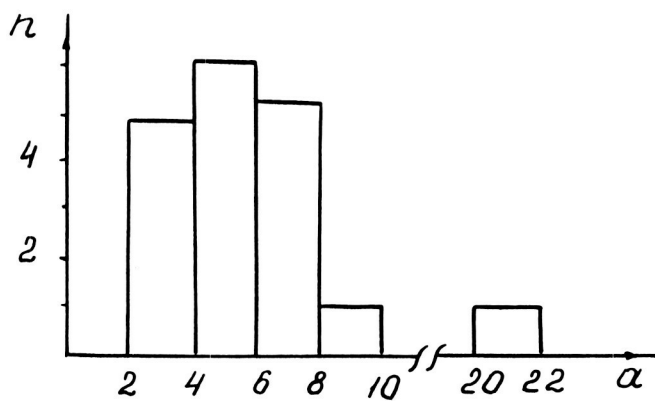
Fig. 4   Distribution of value $a^* = T_e/T_n$ for the Geminids - 83 and Perseids - 78.
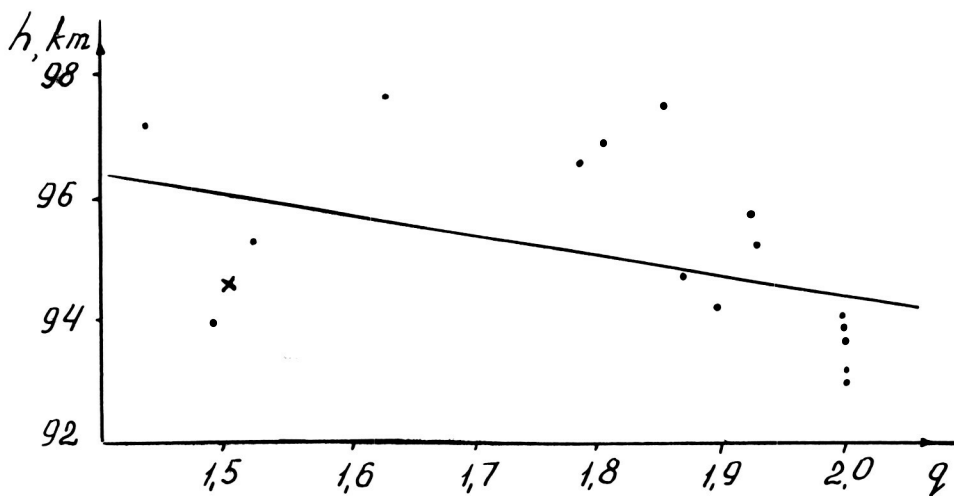

Fig. 5   Parameter q theoretically (——) and experimentally obtained dependence on height.