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ATMOSPHERIC-PROFILE IMPRINT IN FIREBALL ABLATION-COEFFICIENT

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During the past two decades three different projects for registration of meteoric fireballs were put into operation using multistation photographic technique. They have yielded data on several hundreds of fireball trajectories, some of them with deep atmospheric penetration down to heights of 20 kilometers. The immediate results of multistation photograph of a fireball are the relative distances along the trajectory, l_{obs}, and the heights, h_{obs}, measured at each shutter time-mark, t, (shutter breaks of the image). The precision of one value of l_{obs} is of the order of several tens of meters. There are usually many tens of independent points (breaks) available for long fireball trajectories with independently measured l_{obs} and h_{obs}. We need a good theoretical relation for a least-squares solution of $l=l(t)$ or $h=h(t)$, where l is the theoretically given distance along the trajectory and h the height. Until recently there were no adequate formulae expressing theoretically the distance along the fireball trajectory, l, as function of t. We have been able to find such formulae and moreover to find their general form for any atmospheric profile used.

The motion and ablation of a single non-fragmenting meteor body can be expressed by the following set of differential equations first presented by HOPPE (1937):

$$\frac{dv}{dt} = - \Gamma A \rho_d^{-2/3} \rho m^{-1/3} v^2 \tag{1}$$

$$\frac{dm}{dt} = - \frac{\Lambda A}{2\zeta} \rho_d^{-2/3} \rho m^{2/3} v^3 \tag{2}$$

$$\frac{dh}{dt} = - v \cos z_r \tag{3}$$

where v is the velocity, m the mass, h the height of the meteoroid, ρ the air density at any time instant t. The parameters are: Γ the drag coefficient, Λ the heat-transfer coefficient, A the shape factor: $A = S m^{-2/3} \rho_d^{2/3}$, where S is the head cross-section and ρ_d the density of the meteoroid, ζ is the energy necessary for ablation of one unit of mass and z_R is the angle between the fireball trajectory and the vertical. The ablation coefficient, is defined by

$$\sigma = \frac{\Lambda}{2\zeta\Gamma} \tag{4}$$

and the shape-density coefficient, K, by

$$K = \Gamma A \rho_d^{-2/3} \tag{5}$$

To solve the system of equations (1) to (3), we have to assume a density profile of the atmosphere. Until now everybody working in the field of physical theory of meteors and its application to observations solely used the assumption of exponential decrease of the air density with height corresponding to an isothermal atmosphere:

$$\rho = \rho_c \exp(-bh) \tag{6}$$

where b, the air density gradient, was assumed constant as well as the zero-level air-density, ρ_c. Moreover, the solution of the system (1) to (3) was known only in the form of $v=v(\rho)$:

$$\bar{E}_1(\frac{1}{6}\sigma v_\infty^2) - \bar{E}_1(\frac{1}{6}\sigma v^2) = \frac{2K\rho m_\infty^{-1/3}\exp(\frac{1}{6}\sigma v_\infty^2)}{b\cos z_R} \tag{7}$$

where v_∞ is the initial velocity (before entering the atmosphere) and m_∞ is the initial mass and $\bar{E}_i(x) = \int_\infty^x \frac{\exp(u)du}{u}$ is the exponential integral. Thus numerical differentiation of directly observed distances along the fireball trajectory, l_{obs}, was necessary to get v_{obs} for application of formula (7) to observations. Such an indirect method yielded ablation coefficients and initial velocities with standard deviations much larger than corresponding to the accuracy of the measured distance, l_{obs} so the accuracy of the observed quantities was far from being utilized fully.

Recently we have proposed a solution of the system (1)-(3) in a closed form expressing $l=l(v(t))$:

$$t - t_o = -\frac{2}{b\cos z_R}\int_{v_o}^{v}\frac{\exp(\frac{1}{6}\sigma x^2)dx}{x^2[\bar{E}_1(\frac{1}{6}\sigma v_\infty^2) - \bar{E}_1(\frac{1}{6}\sigma x^2)]} \tag{8}$$

$$l - l_o = \frac{1}{b\cos z_R}\ln\left[\frac{\bar{E}_1(\frac{1}{6}\sigma v_\infty^2) - \bar{E}_1(\frac{1}{6}\sigma v^2)}{\bar{E}_1(\frac{1}{6}\sigma v_\infty^2) - \bar{E}_1(\frac{1}{6}\sigma v_o^2)}\right] \tag{9}$$

Here v_o, l_o are the velocity and the distance at the point $t_o=0$ from where the relative time is counted. The integration variable is denoted x. The equations (8) and (9) hold under the assumption (6). The observed values, l_{obs} and h_{obs} for each independent time instant, t, can be fitted to equations (8) and (9) by the least-square method and the parameters l_o, v_o, v_∞, σ can be determined.

In applying our formulae (8) and (9) to observations of fireballs we started to suspect much greater importance of the air density profile for the resulting values of the parameters than it was assumed previously, when the simplistic approach to the air density profile with a constant air density gradient was assumed as correct. Our solution of (1) to (3) for a general air density profile has the form

$$t - t_o = \int_{l_o}^{l} v^{-1}dl \tag{10}$$

$$\frac{\bar{E}_1(\frac{1}{6}\sigma v_\infty^2) - \bar{E}_1(\frac{1}{6}\sigma v^2)}{\bar{E}_1(\frac{1}{6}\sigma v_\infty^2) - \bar{E}_1(\frac{1}{6}\sigma v_o^2)} = \frac{\int_h^\infty \rho\, dh}{\int_{h_o}^\infty \rho\, dh} \tag{11}$$

where h_o is the height at the time instant t_o. Among other parameters v_∞ and σ can be determined by the least-square method to fit the observations to (10) and (11).

Details on both solutions (8), (9) and (10), (11) can be found in two recent papers (PECINA and CEPLECHA, 1983, 1984) together with outlines of the numerical procedures and of the computer programs used. The ablation coefficients and initial velocities computed for 10 Prairie Network and one European Network fireballs for the isothermal atmosphere (1962) and for the seasonal atmosphere (1966) are compared in Table 1. Graphical comparison of ablation coefficients computed for the isothermal atmosphere and for the seasonal atmosphere are plotted in Figure 1. The following results are evident.

a) The computed ablation coefficient is strongly dependent on the atmospheric model used. Differences by using a simplistic isothermal atmosphere are up to factor of two.
b) The standard deviations when using a seasonal atmosphere are significantly smaller than for the simple isothermal model.
c) The initial velocity differs also far outside the standard deviations for the majority of cases and the values from the seasonal atmosphere are better. This has astronomical significance in computing the orbits.

The main conclusion is evident. The generous assumption of simple atmospheric model used up to now for theoretical considerations of meteoroid penetration into the atmosphere and for computational applications to fireballs yields incorrect results. At least, the density profile of "Monthly atmospheres" should be used (CIRA, 1972) for any future theoretical and experimental applications to get any reliable data on ablation coefficients and initial velocities of fireballs with good dynamic data. Analysing ablation coefficients computed for many fireballs of different structure and composition of their meteoroids, we could better recognize different types of bodies and their average characteristics. Then, using the average statistical value of the ablation coefficient for each separate structural and compositional group of fireballs, we could determine details of the instant air density profile of the Middle Atmosphere at the particular moment of any fireball with good dynamic data and moreover the local disturbance by large meteoric bodies. And in this direction we want to contribute to studies of the Middle Atmosphere in the near future.

REFERENCES

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Table 1. Comparison of ablation coefficient, σ, and initial velocity, v_∞, computed with constant air density gradient, b, and with seasonal air density profile.

Fireball Number	σ s^2/km^2		v_∞ km/s		Height Interval km
	* $\rho = \rho_0 \exp(-bh)$	Seasonal Atmosphere	* $\rho = \rho_0 \exp(-bh)$	Seasonal Atmosphere	
PN39057	0.0229 ±.0009	0.0195 ±.0005	14.339 ±.006	14.350 ±.002	74 36
PN39060	0.007 ±.003	0.018 ±.002	31.94 ±.06	31.81 ±.04	91 50
PN39065	0.0362 ±.0009	0.0316 ±.0006	17.303 ±.009	17.332 ±.004	68 34
PN39078	0.0634 ±.0031	0.0604 ±.0013	10.975 ±.011	10.982 ±.003	62 41
PN39404	0.0396 ±.0007	0.0303 ±.0007	15.319 ±.006	15.346 ±.004	79 28
PN39405	0.0465 ±.0017	0.0451 ±.0009	14.406 ±.011	14.385 ±.003	70 44
PN39434	0.0269 ±.0009	0.0146 ±.0007	14.289 ±.004	14.317 ±.002	69 27
PN39469A	0.0132 ±.0020	0.0176 ±.0016	26.39 ±.04	26.42 ±.02	95 56
PN39729C	0.0107 ±.0004	0.0109 ±.0002	27.890 ±.029	27.823 ±.009	72 43
PN39820A	0.0208 ±.0003	0.0212 ±.0002	24.617 ±.006	24.611 ±.003	80 39
EN290181	0.059 ±.006	0.031 ±.004	11.578 ±.011	11.611 ±.004	64 33

*Different average values of b were used corresponding to different height intervals for particular fireballs and to the U.S. Standard Atmosphere (1962).

Seasonal atmosphere were taken from U.S. Standard Atmosphere Supplements (1966).

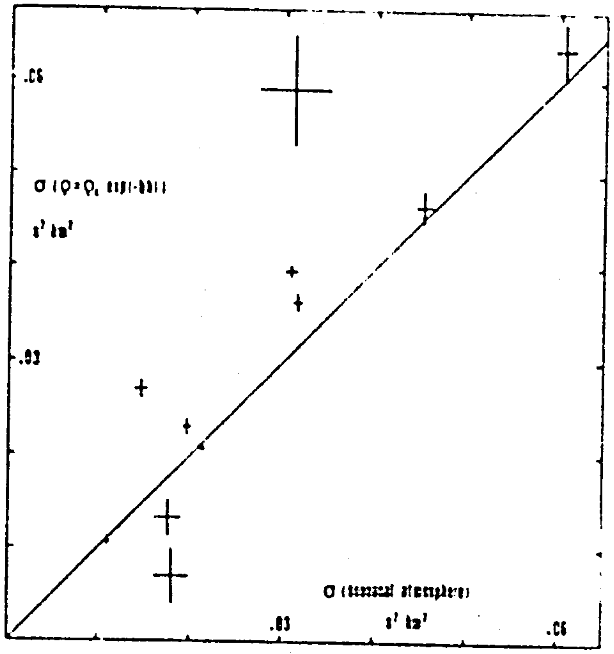

Figure 1. The average ablation coefficient, σ, computed from the simple isothermal atmospheric model ($\rho = \rho_0 \exp(-bh)$) is plotted against the average ablation coefficient computed from the seasonal atmospheric model. Bars are the standard deviations. The 45° line marks equal values of σ from both computations.