II

METEORS

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The Physics of Meteors

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Abstract. Interaction of a meteoroid penetrating the atmosphere can be described through its motion, ablation, luminosity, ionization and the geometry of its trajectory. A theoretical description may be based on the so called "single body theory", generalized to allow for discrete fragmentation. Such a concept is fully able to simulate the motion and ablation (mass loss) of meteoroids from millimeter to meter sizes recorded through photographic techniques (the best precision of such observations is better than ±10 m in observed heights). Observed distances and heights as a function of time can be fit to this model with the intrinsic precision of the geometrical data. The majority of meteoroids follow the "single-body theory" closely: large values of the ablation coefficients derived from observations favor continuous fragmentation under very low dynamical pressures as the main process of ablation. The rest, some 20 to 30%, can be described by one or more discrete fragmentation points in addition to continuous fragmentation. Dynamic pressures at these gross-fragmentation points are also very low, if compared with the strength of stony meteorites.

On the other hand, luminosity and ionization are not as well understood. Existing detailed spectral records show mostly radiation in form of emission lines of ablated meteoroid material with excitation temperatures in the range of 3000 to 5000 K. Additional theoretical modeling is called for.

Photographically documented meteorite falls can be used for computation of luminous efficiencies, because the terminal mass and bulk density are known in these cases. Recently, photographs of the Lost City meteorite fall were remeasured with special attention to visible trails of fragments. The new analysis revealed two main discrete fragmentation points that are in perfect agreement with the geometrically resolved trails based on the dynamics. Moreover, Adolfsson (1996) found an artificial periodic signal originating from the switching shutter and after removing this signal, he was able to find an initial rotation period of 3.3±0.3 s and also the rotation phase of the Lost City meteoroid. A solution for the motion, ablation and rotation of the Lost City meteoroid is now completely self-consistent throughout the whole photographed trajectory and yields an initial mass of $m = 163 \pm 5$ kg. The luminous efficiency was found to be 6.1% at $v = 13$ km/s (for 4500 K), this is $\sim 10\times$ larger than the values determined from artificial meteors, i.e., from masses of 1 g fired downward from high-altitude rockets by shaped-charge.

1. Introduction

This paper is a survey of the present status of the research field known as "Meteor Physics". This is not a well chosen term, invented many decades ago to divide the purely descriptive approach of meteor observation, from studies of the interaction of a meteoroid with the atmosphere and the processes giving rise to meteors. Before sufficiently precise observing techniques were available, the attempt to develop the subject of Meteor Physics was completely speculative. The recording of meteors with photographic cameras and later using radars and TV cameras, substantially changed this situation,

- giving us precise geometrical data on meteoroid atmospheric trajectories
- converting theoretical concepts into ready tools explaining meteoroid motion, ablation, luminosity, and ionization.

Getting spectral records during a meteoroid's flight through the atmosphere also added another very valuable dimension to our knowledge. But all theoretical concepts of the meteoroid motion – so far presented – are based on "simple physics", if I may use a part of the title of Burns' paper presented at this Colloquium. Simple physics means that only exchange of energy and conservation of momentum of a meteoroid driving forward into the atmosphere are used to derive the basic equations of the so called *single body theory*, sometimes called Hoppe's theory in memory of Prof. J. Hoppe from Jena University in Germany. He was the first to present an analytical solution to the basic differential equations in the form of velocity as a function of time (Hoppe, 1937). This happened in late thirties, while the formulation of the single body problem was presented in the twenties and early thirties by Öpik (1922, 1933, 1937). This concept was further developed by Levin (1961) and Broshten (1983), but the general solution of the basic equations was still missing. The 'Ionization part' of the theory presented by Kaiser (1953, 1955) shortly after the second world war survived with few changes up to now. Nemchinov & Setzer (1995) recently developed some new insights into the meteor ionization problem. *This all may be merely because simple physics fits the most precise observations available with residuals corresponding to geometric and dynamic precision of such observations.* On the other hand one should not expect to derive too much on physical processes from such simple-physics concepts.

Of course this is all *not completely so simple.* There is one phenomenon, known through all these years, which complicates the application of single body theory to observations of meteors, and this is *fragmentation.* Two basic fragmentation phenomena were recognized in the past

- *continuous fragmentation*, which is the main process of meteoroid ablation
- *sudden fragmentation* at a point, also referred to as gross fragmentation or discrete fragmentation.

The term 'meteoroid ablation' used in meteor physics should be understood as referring to all mass leaving the body, i.e., without distinction if realized in form of gas, or of droplets or of solid fragments. We cannot distinguish the form of ablation just only from our observations – except discrete fragmentation – and more sophisticated physics has to be used for the interpretation to distinguish what part of the ablation belongs to what form of ablation. We know that most ablation occurs in small fragments, because the ablation coefficients we compute for individual meteoroids from their precise photographic observations are much larger values than the values corresponding to evaporation, or to sublimation, or to spraying of droplets from the meteoroid surface. Meteor wake is one of the direct evidences of continuous fragmentation of meteoroids into very small fragments (McCrosky, 1958). However, the final stage of at least some of the ablated material must be in the form of a hot gas, because the radiation from meteors consists mostly of emission lines of atoms of the meteoroid material. We know this from spectral records. Temperatures of the gas are typically between 3000 and 5000 K depending on the velocity and the part of the trajectory. Recently, Borovicka (1993, 1994a,b) found that a few spectral lines with anomalous brightnesses and behavior belong to a second independent constituent of meteor spectra with temperatures of the order of 10000 K and that this higher energy constituent is getting more important with increasing velocity. However, this more energetic radiation is a minor constituent in the visible region and evidently belongs to some parts of the radiation volume closer to the shock wave.

How much light is radiated compared to the total kinetic energy or to kinetic energy of the ablated mass? This goes on to be one of the most speculative parts of the physical theory of meteors. Luminous efficiencies used by many authors are based mostly on very old computations (Öpik, 1933, 1955) with experimental calibration for masses of about 1 gram (Ayers et al., 1970). These values are assumed to be a function of velocity only, although there are physical arguments that luminous efficiencies should significantly depend on several other values, e.g., the mass of the body and the density of the atmosphere. Halliday et al. (1978, 1981), when modeling trajectories of fragments of the Innisfree meteorite fall (the third ever photographically recorded fireball with meteorite falls) found a dependency of the luminous efficiency on the mass and he also found that the values of the luminous efficiency are larger than those traditionally used to derive meteoroid masses. A recent study of Lost City (Ceplecha, 1996) yielded luminous efficiency of about 6% at 13 km/s, while the values used for the majority of Prairie Network meteors were below 1% at the same velocity. I present here a strong warning not to use the so called "photometric masses" based on luminous efficiencies without the full knowledge of how they were derived, and if using them, an appropriate statement should be made in any published material. Given sufficiently precise data on photographic, radar, or TV meteors, masses derived from the motion of the body – called "dynamic masses" – are clearly preferable, especially if the fragmentation effects are accounted for.

2. Very large meteoroids

In recent years attention was increasingly paid to very large bodies that could reach the Earth's surface with a good part of the initial kinetic energy preserved, making an explosive crater, and potentially causing a lot of troubles to our biosphere. Some researchers used hydrocodes, treating the body as a fluid of homogeneous properties. For bodies larger than 10 m in size there are no available observations, and only theoretical argumentation can be presented, for or against explosion ascribed to a large dynamic pressure, occurring at the very terminal part of the trajectory, when the pressure is equal to the homogeneous strength of – say – a solid stone. But for bodies below 10 m size we can check such concepts through observations. E.g., Hills & Goda (1993) recently published such a model going down to sizes of 10 cm. Comparing photographic observations with their concept of one discrete explosion of a meteoroid at a very high pressure, we see that real meteoroids crumble mostly gradually and with 10 to 100 times less forces applied than corresponding to the strengths of meteorites (Ceplecha 1995). As an example, the recent Peekskill meteorite fall (Brown et al., 1994) recorded by camcorders (first such a case ever) demonstrated clearly that tremendous discrete gross-fragmentation took place under pressures of 7 to 10 Mdyn/cm^2 These values are about 30 times lower than the actual strength of the recovered stony meteorite in Peekskill. Natural bodies – meteoroids – undergo collisions in interplanetary space making these bodies full of cracks and weaker inner layers. Such a body crumbles earlier in the atmosphere and under lower pressures than in the case of a hypothetical material with the homogeneous strength of a compact stone. Photographic observations of meteoroids of from 10 cm to over meter sizes disproved concept of Hills & Goda (1993) for these sizes. If such a concept were valid for larger bodies, there still would remain to find out, at what sizes the well known fragmentation mechanism of smaller meteoroids changes into the hypothetical regime of explosion of larger meteoroids.

On the other hand, work on large bodies done in recent years by Nemchinov and his group in Moscow in cooperation with Sandia National Laboratories, is very promising in respect to theoretical modeling of large and also small meteor radiation (Nemchinov, 1995; Nemchinov et al., 1994, 1995). Their model is based on detailed numerical computation of the aerodynamic flow around the body with inclusion of ablation process and of products of this process in the radiation volume. It takes into account also fragmentation at very low dynamic pressures in accord with observations. All atoms important in radiation of meteors were considered – including the ablated atoms of the meteoroid material – and their quantum states put into this model. The authors are able to visualize theoretically not only an atmospheric shock wave and its high energy radiation of air, but also an intermediate mixture zone, where most of the low temperature radiation takes place. And this is what we actually observe in meteor spectra in visible light.

Preliminary results were published recently by Nemchinov (1995) during the Workshop on Satellite Observation of Meteoroid Impacts into the Atmosphere in Albuquerque. These results well explain radiation and ablation of even smaller bodies observed by photographic technique. Namely the theoretically derived values of ablation coefficients and luminous efficiencies correspond roughly to the already mentioned values derived from Lost City (Ceplecha, 1995). Even if all this is very preliminary, we may soon have a more sophisticated model – not just the simple-physics model – but hard to check on with the present precision of our observations. Moreover, Nemchinov's model (1995) predicts the change of radiation regime: if one goes from 1 m sizes to 10 m sizes, the radiation changes from low temperature emission lines of ablated material to high temperature radiation of compressed air. The exact size at which this transition of the radiation type takes place, depends also on velocity.

Satellite observations of meteoroids are very effective in getting data on the largest meteoroids in visible and infrared pass-bands (sizes from several meters up to over 10 m). This is not only due to global coverage (in contrast to very limited space observed by photographic fireball networks), but also due to high technology used for recording these events (McCord et al. 1995; Tagliaferri, 1995).

3. Progress in simple-physics models

The main topic of this chapter and of the whole paper may be expressed by asking what substantial knowledge has been added to the single body theory in recent years and what made this "simple-physics" theory working so well and to be capable in explaining practically all enough precise photographic observations, and with not many questions left over. I stress here that this is valid for observations with geometrical precision of ± 10 m in heights or in distances flown by the body along its trajectory. If experimental data would once achieve ± 1 m precision, then certainly many new questions would arise and new solutions, based on more sophisticated physical insights would certainly be presented and checked on by such observations.

The first substantial addition to the single body theory was presented by Doug ReVelle (1979), when he tried to follow the body motion with theoretical predictions of the main parameters of the problem, i.e. with predictions of the drag and ablation coefficients as function of time. He had chosen small time intervals and kept these parameters constant inside such a small interval, and integrated numerically the basic differential equations step by step. This way he omitted the time derivatives of the changing coefficients. This intrinsic assumption latter on proved to be quite reasonable.

The second substantial change and a very significant step forward in our interpretation of photographic observations, was analytical solution of the problem presented by Pecina & Ceplecha (1983, 1984) about a decade ago. This solution expresses distance flown by the body along its trajectory as function of time. The distance along trajectory as well as the heights are quantities directly derived from observations. This solution also doesn't use any assumption on how the atmospheric pressure changes with height, just it takes the actual values. Such a solution has a great advantage of being expressed fully and explicitly by the parameters of the problem.

The third substantial addition to the single body theory – initiated by Dick McCrosky – is a generalization by allowing for discrete fragmentation, i.e. a sudden gross-fragmentation at a point (Ceplecha et al., 1994). This concept was checked by using photographic observations and by implementing several independent methods. Their results proved that this concept of discrete fragmentation yields consistent results and is valid for vast majority of those precisely recorded meteors, which could not be explained by single body theory.

Mathematical details of the gross-fragmentation theory are in the original paper (Ceplecha et al., 1993). Only general outline of the solution is presented here just to show how many and what parameters and with what precision are determinable from photographic observations.

Solution for discrete fragmentation can be represented by equation:

$$l = l(t, v_{\infty 1}, v_{\infty 2}, \sigma_1, \sigma_2, v_0, l_0, t_0, \frac{m_{01}}{m_{02}}) \tag{1}$$

Parameters of equation (1) are determined by making

$$\Sigma[(l_{obs} - l)^2] = \text{ a minimum value} \tag{2}$$

where l is the theoretically computed distance along the trajectory as function of time and the parameters, l_{obs} is the observed distance along the trajectory at a given time-mark, t is the relative time, v is the velocity, m is the mass, σ is the ablation coefficient, and where the subscripts have the following meaning: 0 denotes values at the discrete fragmentation point, 1 denotes values before the discrete fragmentation point, 2 denotes values after the discrete fragmentation point, and *obs* denotes observed values.

Examples of how this gross-fragmentation model works can be found elsewhere (Ceplecha et al., 1993; Ceplecha, 1995).

4. Luminous efficiency

The dynamic behavior of a meteoroid passing through the atmosphere is much better known than the production of light. The theoretical concept of discrete fragmentation fits well all precise observations available. On the other hand, luminosity and ionization are not so well understood. The meteor luminous efficiency, τ, is defined very simply as the fraction of kinetic energy of the mass loss transformed into light during the meteoroid ablation in the atmosphere:

$$I = \tau \frac{v^2}{2} \frac{\mathrm{d}m}{\mathrm{d}t}. \tag{3}$$

Here v is meteor velocity in [m s^{-1}], $\mathrm{d}m/\mathrm{d}t$ is the mass loss rate in [kg s^{-1}], and I is the luminosity [W]. The luminous efficiency is dimensionless. Usually, we are not able to measure the meteor luminosity in absolute units. Instead, we measure the brightness of meteors in magnitudes by comparisons with stars, and we measure it also only in a limited and given spectral range, mostly in panchromatic pass-band from about 3600 Å to 6600 Å. We convert these magnitudes to a distance of 100 km from the source and call them absolute magnitudes of a meteor.

Photographically documented meteorite fall can be used for computations of luminous efficiencies, because the terminal mass and bulk density are known from the laboratory measurements on the recovered meteorites. Recently, the original photographs of the Lost City meteorite fall (McCrosky et al.1971) – the best documented meteorite fall ever – were remeasured by Keclíková (Ceplecha et al., 1993, 1996) at the Ondrejov Observatory with special attention to visible trails of individual fragments.

The new analysis of dynamics of the Lost City body was done by Ceplecha using the discrete fragmentation model and latter on completed by Adolfsson

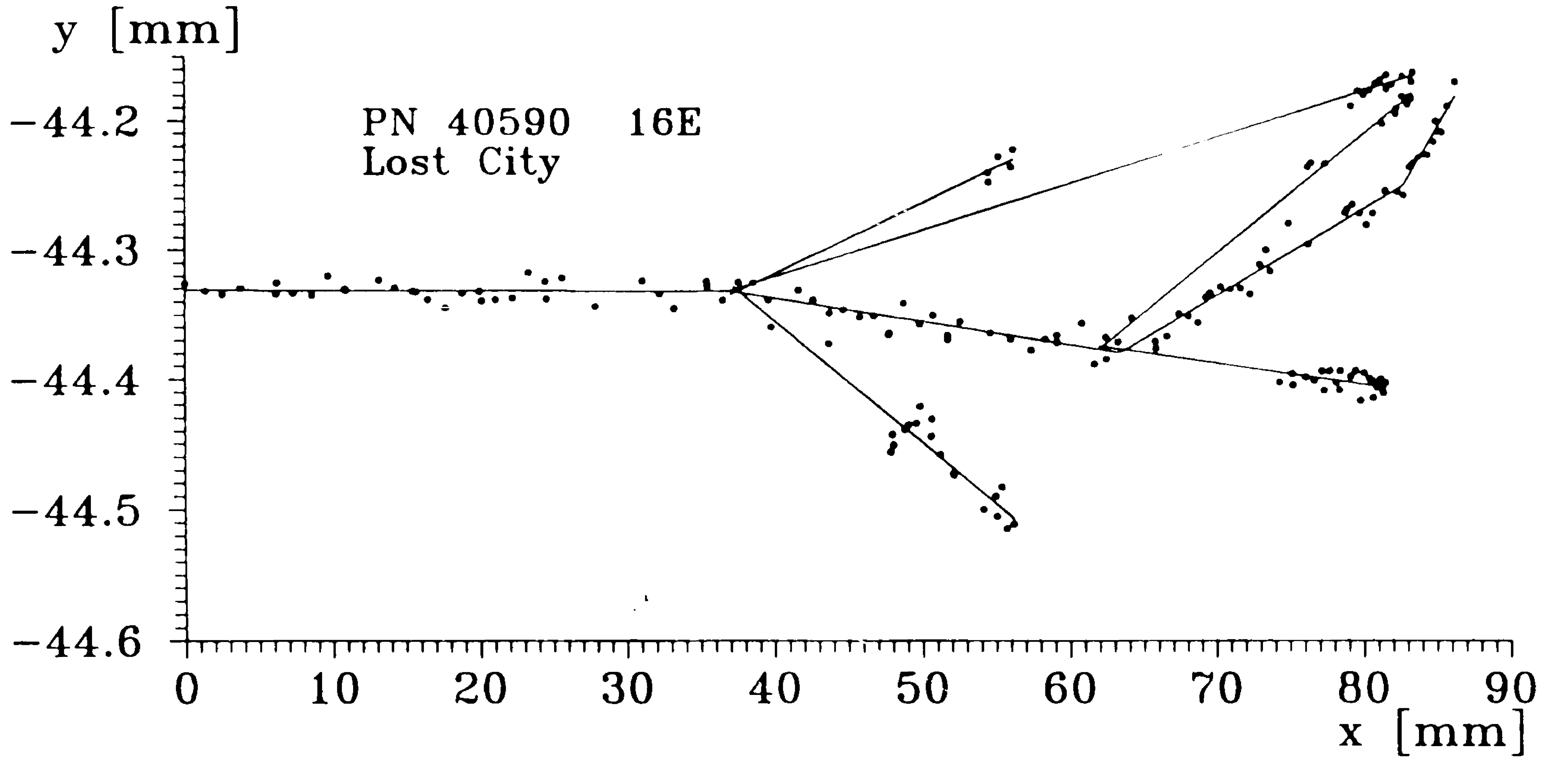

Figure 1. Splitting trail of the Lost City fireball. This is the direct image as seen on the film except the y-axis is greatly enlarged to visualize the separation of individual fragments. Dots are the directly measured points on individual trails: least square fits of straight lines to these point define trails of individual fragments. The trail of the main piece terminates at the largest x.

using his model of meteoroid rotation (Ceplecha et al., 1996). The new analysis revealed two main fragmentation points also dynamically, and this was in perfect agreement with intersections of geometrically resolved trails of individual fragments (Fig. 1). The fragmentation model fitted nicely the observed distances as function of time with standard deviation of ± 23 m for one observed point, when both of the fragmentation points were considered for two independent and partly superposing solutions.

As a referee of a paper by Gustafson & Adolfsson I sent my Lost City solutions to the authors as a part of my comments and explanations on other more general problems. Soon Adolfsson (1995) surprised me by proposing that an artificial signal in timing of the time-marks for the Lost City fireball may be present in the data. His suspicion proved to be right. The found instrumental periodic signal originated from using an old style mechanical telephone commutator for controlling frequency of the switching shutter of the camera (McCrosky & Ceplecha, 1996). The repetition rate of it was 1.3 seconds, almost exactly the value, Adolfsson found from frequency analysis of residuals of my new solution for the Lost City. The resulting amplitude was 11 m, which corresponds to 0.0008 s of periodic error in timing. After removing this signal by assigning corresponding corrections of relative time for each time-mark, the discrete fragmentation model fitted then significantly better to observations with this correction, and standard deviation for one measured point turned to be ± 21 m (Fig. 2)

In the same paper, Adolfsson (1996) proposed also a new method of analyzing a possible rotation of a flat meteoroid just from its motion, i.e. from distances flown along the trajectory. (Flat shape of the Lost City meteoroid was used already by McCrosky et al. (1971) for explanation of the difference between photo-

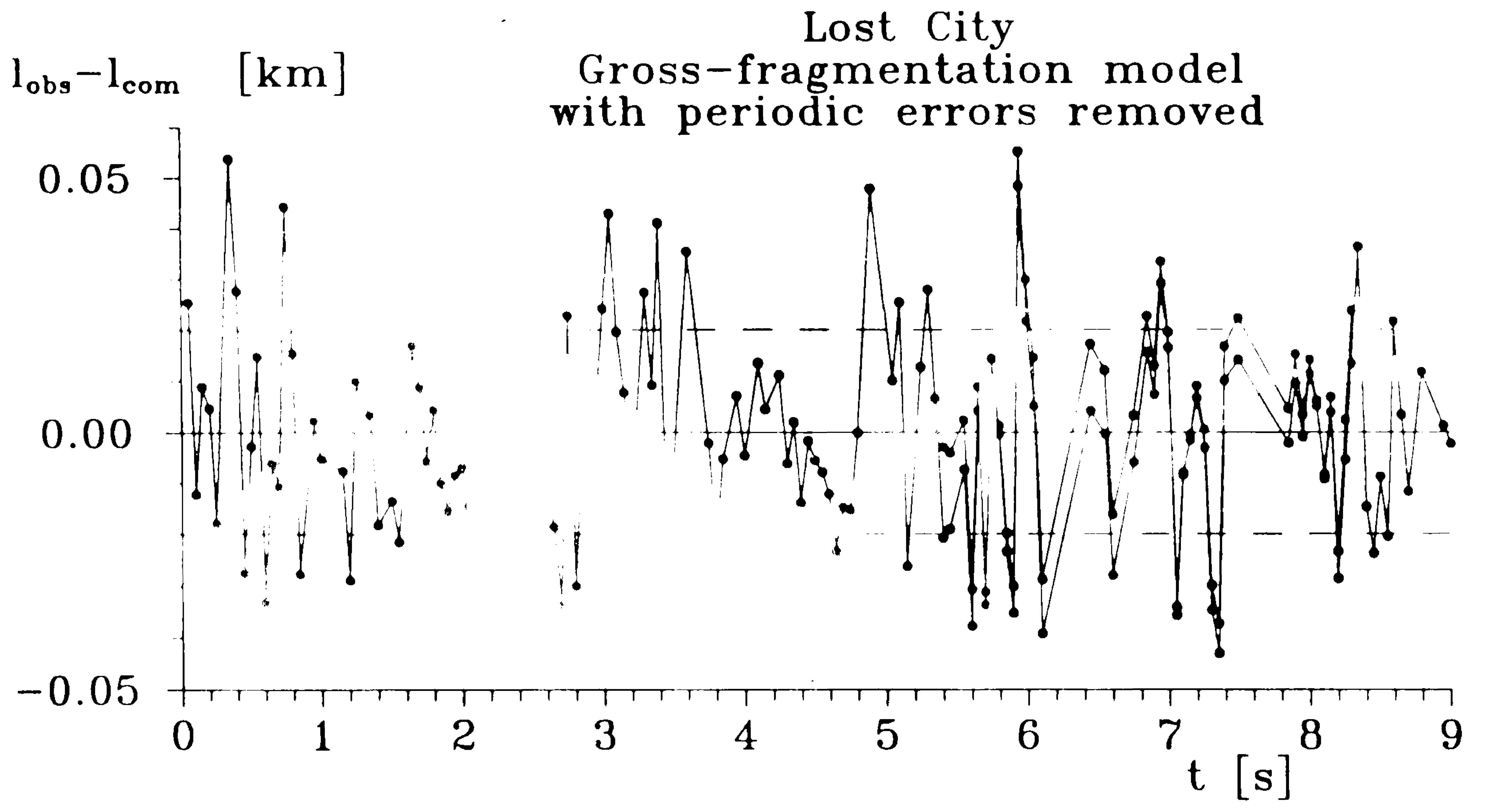

Figure 2. Residuals $l_{obs} - l_{com}$ for Lost City fireball using gross-fragmentation model. ($l_{com} \equiv l$ in eq. (1)). The positions of dynamically derived gross-fragmentation points correspond to geometrically observed fragmentation points. Standard deviation for one observed point is denoted by dashed lines.

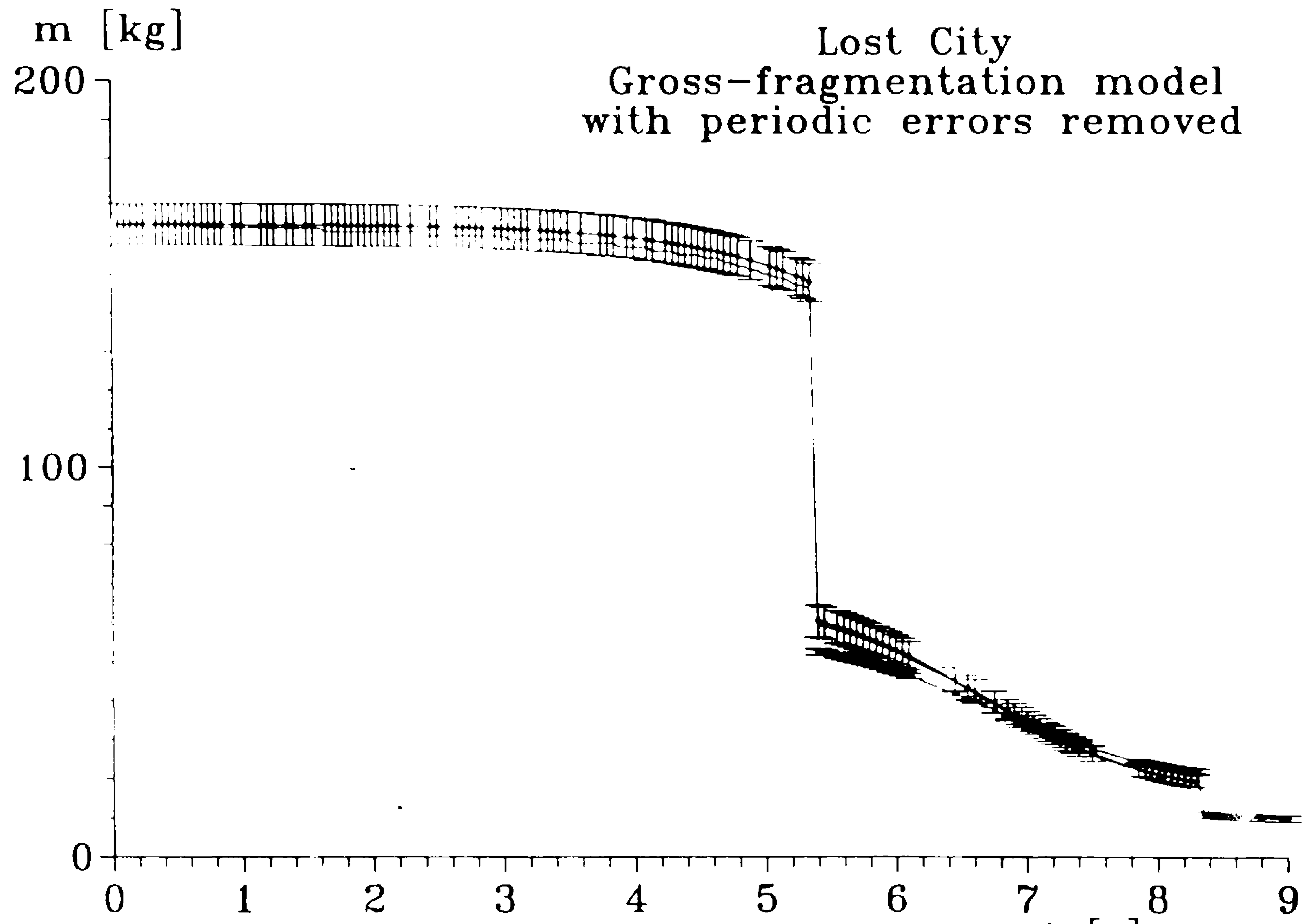

Figure 3. Mass (dynamically determined) with its standard deviations as function of time for the main meteoroid of the Lost City fireball resulting from the gross-fragmentation model. Masses from both independent solutions inside their overlapping part are in a very good agreement. Deceleration of the main body changes abruptly at the fragmentation points.

metric and dynamic mass). Adolfsson applied his method to my time-corrected solutions of the Lost City fireball: he found an initial rotation of the Lost City body with a period of 3.3 ±0.3 seconds, and a rotational phase with maximum head cross-section perfectly corresponding to the position of the first fragmentation point (Table 1).The resulting standard deviations were again smaller, i.e. now only ±18 m for one measured point. So there was nothing systematic left to be explained for the Lost City fireball, all perfectly fits inside standard deviations to Lost City observed distances and heights as function of time. Now, we can say that the solution for motion, ablation,original rotation and shape of the Lost City meteoroid is completely self-consistent throughout the whole trajectory photographed and that it yields an initial mass of $m = 163 \pm 5$ kg. The computed dynamic masses should be considered as calibrated by the main recovered meteorite (Fig. 3).

Table 1. Model of continuous and gross fragmentation (Ceplecha et. al., 1993), and of rotation of meteoroids (Adolfsson, 1996) applied to observed distances and heights as function of time.

Precision of two independent least-squares fits on partly superposing time intervals (135 measured points):	
standard deviation	
for one measured point	± 21 meters
including rotation	± 18 meters
initial velocity	14.1485 ± 0.0012 km/s
ablation coefficient from	0.0146 ± 0.0004 s^2/km^2
to	0.0114 ± 0.0003 s^2/km^2
initial mass	163 ± 5 kg
terminal mass	9.79 ± 0.86 kg
the largest recovered meteorite	9.83 kg
ΓA	1.10 ± 0.04 (c.g.s.)
initial rotation period	1 rotation per 3.3 ± 0.3 s
flatness	2.1 ± 0.4
maximum head cross-section at	$h = 40.7 \pm 1.1$ km
Drag coefficient Γ	0.7 ± 0.1
the first gross-fragmentation at	$h = 40.74 \pm 0.08$ km
	59.0% ± 1.9% of mass stripped off
the second gross-fragmentation at	$h = 21.89 \pm 0.25$ km
	49.9% ± 2.3% of mass stripped off
luminous efficiency at $v =$ 13 km/s	$\log \tau = -11.4 \pm 0.2$
luminous efficiency at $v =$ 4 km/s	$\log \tau = -12.1 \pm 0.3$
(c.g.s. units with $I = 1$ for 0 stellar magnitude)	
for 4500 K:	
it corresponds to 6.1% of total kinetic energy of mass loss at 13 km/s	
it corresponds to 1.2% of total kinetic energy of mass loss at 4 km/s	

In this case, we can compute the luminous efficiencies for Lost City from known velocity and known mass-loss as function of time (Fig. 4, Table 1, Ceplecha 1996). We should consider these values of luminous efficiencies also as calibrated by the recovered meteorites. They resulted as 6.1% at 13 km/s, a

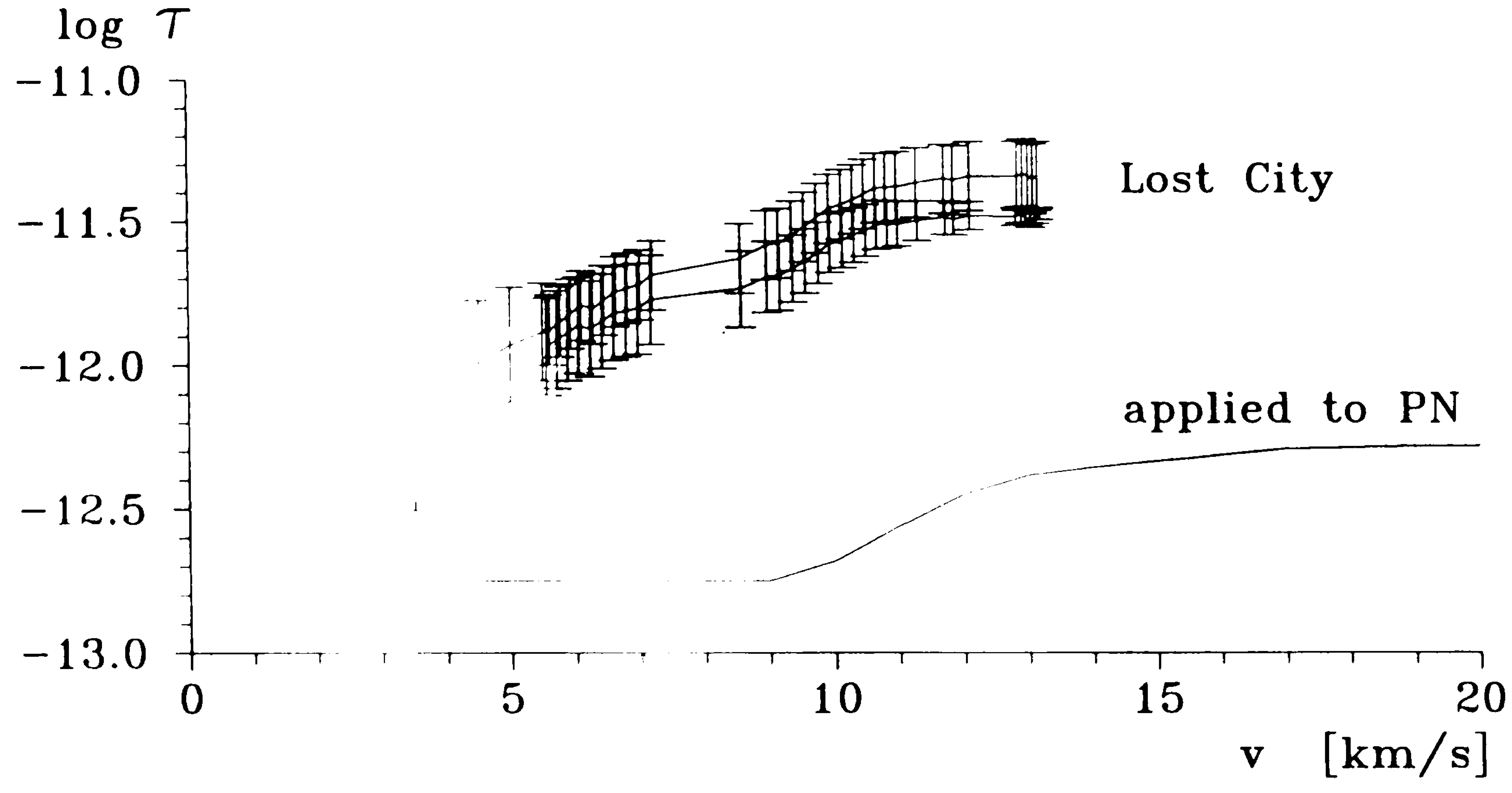

Figure 4. Logarithm of luminous efficiency, log τ, as function of velocity, v. The error bars are the standard deviations inside the used model. The line denoted as "applied to PN" represents the values used for determining photometric masses of PN as well as of EN fireballs so far (Ceplecha, 1975; Ceplecha & McCrosky, 1976). Units are that of light intensity $I = 1$ for 0 magnitude of A0 star. Transformation to Watts: for 4500 K multiply by 1530 W.

value about 10× larger than values determined from shaped-charge experiment by Ayers et al.(1970). These experiments consisted of firing about one gram masses – mostly iron – with velocities of 11 to 16 km/s from high altitude rockets down to the surface and recording artificial meteors by several observational techniques (using also panchromatic pass-band). Thus bodies of masses of the order of hundreds of kilograms are evidently much more efficient in producing visible light during the atmospheric flight than smaller meteoroids are.

5. Ionization

Ionization processes are not included in this paper. Conversion of kinetic energy into ionization is only partly similar to conversion into optical radiation. A poster at this Colloquium by Pecina (1995) presents some new insights into using radar observations for dynamical solution of a meteoroid trajectory. Problems with precision in determining meteor orbits from New Zealand radar experiment were presented at this Colloquium by Baggaley (1995), who will soon start a more sophisticated instruments at the same location. The reality of large amount of hyperbolic orbits among very faint meteors coming out of these measurements may thus be an artifact of precision of the data. The more precise measurement may resolve this question. An accompanying television observation at the same location is nevertheless still recommendatory as a check of radar data. Also fragmentation processes studied by radar are presented at this Colloquium as a poster by Šimek (1995). New theoretical insights into ionization problems were presented recently by Nemchinov & Setzer (1995). Detailed presentation of meteor ionization processes prepared by Elford will be published in a "Meteor Chapter" of Interplanetary Dust Book (Ceplecha et al., 1997).

6. Prospects

It should be stressed once more that luminous efficiencies are not well known values and that we understand meteor radiation substantially less than we understand its motion and ablation. The same may be said about ionization processes in meteor phenomenon. There are several ways how to improve the situation and how to solve the problem: a) purely theoretically, b) from motion and ablation of another well documented fireball with a meteorite fall, c) from good and detailed spectral records, d) from simultaneous observations by optical means including spectrographs and radar equipments. In any case I feel that a priority should be now posed on studying meteor radiation, and on relating the radiation efficiency to relevant parameters.

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