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Earth-grazing fireball of October 13, 1990

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Abstract. A fireball of −6 absolute magnitude, which left the atmosphere again after appearing at heights of around 100 km above Czechoslovakia and Poland was photographed at two Czech stations of the European Fireball Network. The body travelled a 409-km luminous trajectory in 9.8 seconds with initial velocity of 41.7 km/s. The type I fireball was produced by a meteoroid mass of 44 kg, from which only 0.35 kg were ablated. The meteoroid left the Earth in a changed orbit and with solidified fusion crust on its surface. Detailed data on the fireball trajectory and both the encounter and outcast orbits are given. A special method for long trajectory determination of nearly horizontal motion was invented. This method is based on angular velocity measurements from the excellent record of one station combined with one direction derived from the not-so-good record of the other station and computes pericenter position of Keplerian motion from observations very close to this point.

Key words: meteors

1. Introduction

The entry of a meteoroid into the Earth's atmosphere usually terminates by complete ablation of the body well above the Earth's surface. Large bodies can, under suitable circumstances, reach the Earth's surface as meteorites (even bigger bodies are destroyed by explosive impacts). But there is another possibility for a meteoroid survival. If it enters the atmosphere almost tangentially, then, after appearing as a meteor and losing a part of its mass, it can leave the atmosphere again and return to a modified heliocentric orbit.

The first scientifically observed event of this type was the famous daylight fireball of August 10, 1972 above the United States and Canada (see Jacchia, 1974 for the description of the event and Ceplecha, 1979 for the correct trajectory, mass and orbits based on the original observational data of Rawcliffe et al., published with three numerical mistakes in Nature, 1974: do not use the data from Nature, they are completely misleading). The 1972 fireball reached the minimal height 58 km above the Earth's surface, its observed trajectory was 1500 km long and its geocentric velocity decreased from 15.0 to 14.2 km/s during the atmospheric flight. The estimated mass of the meteoroid was 10^5 to 10^6 kg.

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We report here the second Earth-grazing fireball, photographed by two Czech stations of the European Fireball Network on Oct 13, 1990. Because the standard methods of reduction of meteor photographs proved to be inadequate in this case, the special method for determining meteor trajectory was developed (see Sect. 3).

2. Observations and basic reductions

2.1. Visual observations

Visual observations were reported by three independent comet observers in Czechoslovakia (P. Pravec, P. Klásek and L. Buličková). These observations provided the time of the event: $03^h27^m16^s \pm 3^s$ UT (for the beginning), and the unambiguous *direction* of meteor flight, from the south to the north. A 10 s train was also visible.

Note that the radio reflection of this fireball was obtained by Kristensen (1991) in Havdrup, Denmark at $03^h27^m24^s \pm 6^s$ UT. The duration of the reflection was 78 seconds.

2.2. Photographic observations

Photographic observations came from two stations of the European Fireball Network, station no. 14, *Červená hora* ($\lambda = 17°32'38''$, $\varphi = 49°46'40''$, $h = 750$ m), and station no. 9, *Svratouch* ($\lambda = 16°02'09''$, $\varphi = 49°44'08''$, $h = 744$ m). Both photographs were taken by stationary cameras equipped with all-sky fish-eye objectives (f = 30 mm, 1:3.5). The cameras were provided by a rotating shutter breaking the image 12.5 times per second. This enables velocity determinations.

The meteor image from station no. 14 is very favourable. The visible trajectory is 110° long, starting 51° above the south horizon, passing the zenit 1° westwards only, and disappearing 19° above the north horizon. Unfortunately the shutter breaks are unresolved on last 4° of the trajectory due to very small angular velocity of the meteor in this extreme region.

The photograph from station no. 9 is less convienient. The meteor is projected 30° above the northeast horizon and it is relatively faint and only 15° long.

2.3. Preliminary trajectory

Photographic observations from two different stations (or more) make possible to determine meteor trajectory in the atmosphere by means of a pure geometric way. Two methods are commonly used at the Ondřejov Observatory, the method of planes (Ceplecha 1987), and the straight least-squares method (Borovička

1990). Both methods assume that the meteor trajectory is a straight line, which is fully sufficient assumption for normal meteors with shorter trajectories not too much exceeding 100 km.

For the meteor in this paper these standard methods could be used only as a first step of approximation . They revealed that the meteor moved almost exactly in the south-north direction at a height of about 100 km above the Earth's surface. The observed trajectory was 400 km long and the point of minimum height (further called "perigee") occured within the photographed trajectory. At the end this meteor already moved from the Earth away.

This preliminary computation yielded the average meteor velocity 42 km/s, but an apparent gradual increase of velocity by 2 km/s along the observed trail was revealed. This physically unrealistic effect was due to simple geometry, which went into systematicly wrong results: the straight line assumption was inadequate and, moreover, the slope of the straight line was fully determined by means of the unfavourable observation from station no. 9, because station no. 14 lay almost under the meteor trajectory. The effect of increasing velocity could not be removed within the framework of standard methods, which indicated that especially the computed position of perigee was unrealible. An entirely different method, described in Sect. 3, was then used for computing the final trajectory.

The preliminary results were published in GVN Bulletin (Ceplecha et. al. 1991).

2.4. Physical characteristics

The brightness of the meteor was almost constant. Knowing the brightness, velocity and height, we can estimate the meteoroid mass and deceleration. We used Eq. (11) from Ceplecha's paper (1975). Then

$$m = \left(\frac{2I}{\tau \sigma K \varrho_a v^5} \right)^{3/2} , \tag{1}$$

where I is the light intensity ($M = -2.5 \log I$ being the absolute magnitude), τ is the luminous efficiency, σ the ablation coefficient, $K = \Gamma A \varrho_m^{-2/3}$ is the shape-density coefficient, ϱ_a the air density, v the velocity of the meteoroid, Γ the drag coefficient, A the geometrical shape factor and ϱ_m the meteoroid density. Assuming the values of ϱ_m and σ from Ceplecha (1988) for different fireball types, assuming $K = 0.5$ for type I fireball and using $\tau = 8.5 \times 10^{-13}$ (c.g.s. units combined with I in 0 magnitude units: $M = -2.5 \log I$) for $v = 42$ km/s, the mass for type I fireball from Eq. (1) resulted in 44 kg at the perigee point, where the smooth value of the absolute magnitude was -6.25. The mass for type II fireball would be 4.6 kg, for type IIIA 0.6 kg and for type IIIB 0.07 kg.

Using the luminous equation (Eq. (10) in Ceplecha 1975), we can find

$$\Delta m = \frac{2}{\tau v^2} \int I \, \mathrm{d}t , \tag{2}$$

where Δm is the total ablated mass. With $\int I \, \mathrm{d}t = 2600$ (t in seconds and I in 0 magnitude units) for this fireball, Eq. (2) yields $\Delta m = 0.35$ kg. This value is the same for all fireball types, because it is independent of σK. But this clearly eliminates the fireball types IIIA and IIIB.

The change of brightness of this fireball is very small during the entire photographed trajectory (see Fig. 4). Directly measured values of brightness: beginning point $M = -5.57 \pm 0.21$, terminal point $M = -6.15 \pm 0.21$, maximum $M = -6.45$. If we omit the beginning and terminal point, the smooth values are: maximum -6.25 and minimum -5.96; standard deviations of individual measured points are all inside the interval of ± 0.13 to ± 0.18. The average absolute magnitude is -6.11 ± 0.02 for 88 measured points along the photographed trajectory (± 0.18, if expressed for one measured point assuming constant brightness). Thus the change of brightness is at the limit of the precision of our measurements and is constant within ± 0.2 magnitude.

The change of velocity is also small. The double-station directly-derived value is not precise enough, but we were able to fit the 88 observed time marks inside the time interval of 6.9 seconds with a constant velocity of $v = 41.74 \pm 0.08$ km/s (see Sect. 3.6). There is no systematic change of residuals in favour of some significant deceleration close to the terminal point (see Fig. 2). Thus the body kept its velocity almost certainly within the 3 standard deviation : 41.74 ± 0.24 km/s.

The air drag deceleration at the perigee point can be determined from Eq. (1) of Ceplecha's paper (1975). For type I fireball we have $\frac{dv}{dt} = -1.7$ m/s^2, which corresponds to total change of velocity $\Delta v = 0.012$ km/s over the 6.9 seconds of photographed trajectory, where the velocity could be measured. The same quantities for type II fireball are $\frac{dv}{dt} = -53$ m/s^2, and $\Delta v = 0.37$ km/s. Thus also type II fireball can be excluded.

The far most probable situation with this fireball corresponds to type I body (meteorite-dropping fireball) with mass of 44 kg, from which about 0.4 kg was ablated. The meteoroid left the Earth in a changed orbit and with solidified fusion crust on its surface, which made it a body similar to meteorites, but traveling in space again.

3. Detailed trajectory calculation

3.1. Statement of the problem

For type I fireball, the motion can be treated as a purely Keplerian motion in the Earth's gravity field, because the atmospheric deceleration was negligible (see Sect. 2.4). We assume type I fireball in our computations and would consider this assumption to be confirmed, if no systematic change of residuals were present in the results. The gravity field near the Earth is considered as belonging to a mass point located at the Earth's center and of total mass of the Earth and the Moon (designated M). Unfortunately the trajectory cannot be constructed geometrically because only a small part of the trajectory (1/4) was recorded from both the stations. The physical relation between velocity and orbital parameters (pericenter distance and eccentricity) have to be used. Thus the observed angular velocity from station no. 14 provides additional information for trajectory determination. Note that the solution of the August 1972 fireball (Ceplecha 1979) represented a different problem, because in that case the velocity was directly measured by an infrared satellite and the deceleration was quite considerable.

3.2. Orbital plane

The meteor orbital plane, i.e. the plane containing meteor trajectory and the Earth's center, was taken from the solution of the straight least-squares method (Borovička 1990). Although this method assumes the trajectory to be linear, the computed plane containing the trajectory is considered to be correct and the curved trajectory is located in this plane. This is justified

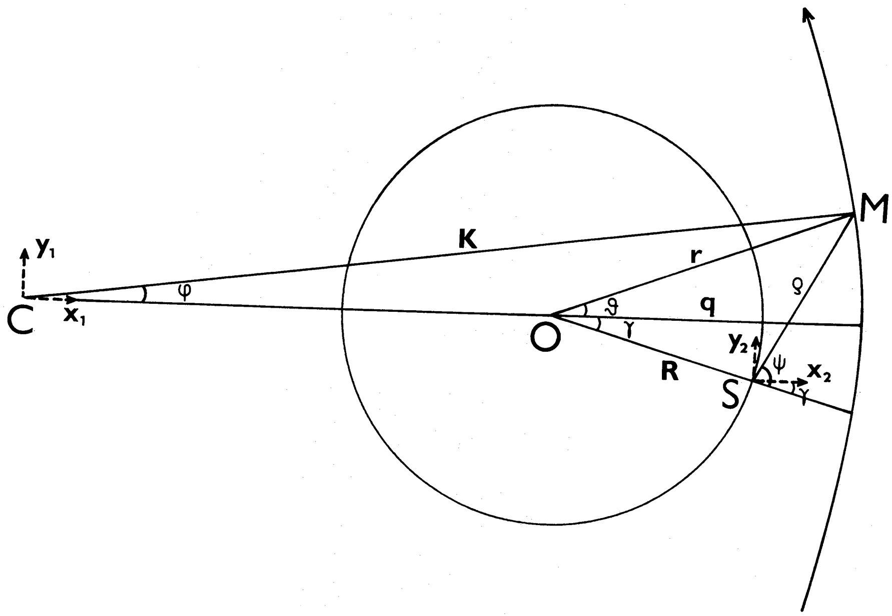

Fig. 1. Meteoroid trajectory in circular approximation

by the fact that the solution of the plane was dependent almost completely on the observation of station no. 14, which lay very close to the orbital plane and the trajectory curvature was unobservable from this station.

The calculations were performed in the coordinate system which does not rotate together with the Earth. This avoided the Corriolis force, which would cause an observable effect (≈ 140 m deviation) in the co-rotating coordinate system. The coordinates of stations were thus time-dependent.

3.3. Circular approximation

The real meteor trajectory is a hyperbole in the orbital plane described by the equation

$$r = \frac{q\,(e+1)}{1 + e\cos\vartheta}\,, \tag{3}$$

where r is the radial distance from the center of gravity, ϑ the true anomaly, e the eccentricity, and q the pericenter distance (perigee is used in another meaning here, see Sect. 2.3). The orbital velocity v is given by

$$v = \left[GM\left(\frac{2}{r} - \frac{1}{a}\right)\right]^{1/2}, \tag{4}$$

where G is the gravitational constant, M is the total mass of the Earth and the Moon, and $a = q/(1-e)$ is the semimajor axis. The velocity in infinity ($r \to \infty$) is

$$v_\infty = \left[\frac{GM}{q}(e-1)\right]^{1/2}, \tag{5}$$

and the velocity at pericenter is

$$v_q = \left[\frac{GM}{q}(e+1)\right]^{1/2}. \tag{6}$$

Combining Eqs. (3) and (4) we can express the velocity as a function of the true anomaly:

$$v = \left\{\frac{GM}{q}\left[e + 1 - \frac{2e\,(1-\cos\vartheta)}{e+1}\right]\right\}^{1/2} \tag{7}$$

The approximate values are known from preliminary calculations: $v_q \approx 40$ km/s, $q \approx 6460$ km. From Eq. (6) follows $e \approx 25$. The meteor was certainly not observed in a larger distance from pericenter than $l = 500$ km. Thus the maximal true anomaly was $\vartheta_{\max} \approx l/q \approx 0.077 = 4\overset{\circ}{.}4$. Substituting $\vartheta_{\max}$ into Eq. (7) we find that the ratio $v_{\vartheta=\vartheta_{\max}}/v_q$ is 0.99989 so that the velocity at the edge of observed meteor path differ from the velocity at pericenter by 4 m/s only. This is well below the accuracy of our observations. The meteor velocity can be therefore considered constant along the whole observed trajectory.

Further we can replace the hyperbole with an osculating circle at the point of pericenter. The radius of the circle will be

$$K = q\,(e+1)\,. \tag{8}$$

The radial distance (derived from the triangle COM in Fig. 1) in this approximation is:

$$r = q\,(\sqrt{1 + 2e + e^2\cos^2\vartheta} - e\cos\vartheta)\,. \tag{9}$$

The difference between r computed from (3) and r computed from (9) for $\vartheta = \vartheta_{\max}$ is less than 1 meter.

In the next sections we consider the meteoroid as if it moved along a circular orbit with a constant velocity during all the photographed trajectory. This is an entirely sufficient approximation holding for this part of the trajectory.

3.4. Determination of circular trajectory from the angular velocity

The geometrical situation in the orbital plane is displayed in Fig. 1. The circle represents the Earth and the circular arc represents a part of the meteoroid orbit. At start, let us assume that station no. 14 (point S) lies exactly in the orbital plane at the distance R from the Earth's center. The position of pericenter relatively to the station is described by the angle γ. The instantaneous position of the meteor (point M) is described by the angle φ at the center of the osculating circle. The distance between the station and the meteor is ϱ and the position of meteor as seen from the station is described by the angle ψ (a "geocentrical zenith distance").

The observed quantity is the angle ψ. Its time dependence is given by the time marks (breaks) on the meteor image. In order to determine orbital parameters we have to find the theoretical change of ψ as a function of the parameters.

As the meteoroid velocity v is constant, the angle φ is directly proportional to time:

$$\varphi = \varphi_0 + \frac{v}{K} t , \tag{10}$$

where φ_0 depends on the zero-time point. To derive the relation between ψ and φ , we set two auxiliary rectangular coordinate systems in the orbital plane (see Fig. 1), the first at the center of the orbital circle (x_1, y_1-system) and the second at the station position (x_2, y_2-system). The relation between these two systems is

$$\begin{aligned} x_2 &= x_1 - (K - q) - R\cos\gamma \\ y_2 &= y_1 + R\sin\gamma. \end{aligned} \tag{11}$$

The position of the meteoroid in the first system is

$$\begin{aligned} x_1 &= K\cos\varphi \\ y_1 &= K\sin\varphi \end{aligned} \tag{12}$$

and in the second system

$$\begin{aligned} x_2 &= \varrho\cos(\psi - \gamma) \\ y_2 &= \varrho\sin(\psi - \gamma). \end{aligned} \tag{13}$$

Excluding x_1, y_1, x_2, y_2 from the Eqs. (11) – (13) we obtain following relations:

$$\psi = \gamma + \arctan\left(\frac{K\sin\varphi + R\sin\gamma}{q - K(1 - \cos\varphi) - R\cos\gamma}\right) \tag{14}$$

$$\begin{aligned} \varrho = \; &\{R^2 + q^2 - 2Rq\cos\gamma + 2K(1 - \cos\varphi)(K - q) + \\ &+ 2KR[\cos\gamma - \cos(\varphi + \gamma)]\}^{1/2} \end{aligned} \tag{15}$$

By means of Eq. (14) φ can be transformed into ψ. The inverse relation is also useful. It can be obtained directly from Eq. (14):

$$\sin\varphi = -P\cos(\psi - \gamma) + \sin(\psi - \gamma)\sqrt{1 - P^2}, \tag{16}$$

where

$$P = \frac{1}{K}[R\sin\psi + (K - q)\sin(\psi - \gamma)].$$

We set time to zero at the moment when the meteor passes geocentrical zenith of the station. The angle φ_0 in Eq. (10) can be then computed from Eq. (16) for $\psi = 0$. The velocity v in Eq. (10) is given by Eqs. (6) and (8):

$$v = \frac{\sqrt{GMK}}{q} \tag{17}$$

The theoretical value of ψ, depending on three unknown parameters K, q, and γ, which define the meteor trajectory in the orbital plane, can be now computed from Eqs. (10) and (14) for each time t corresponding to a time mark on the observed meteor trajectory. Having n time marks, we have n conditions for the three unknown parameters, and the best values of K, q, and, γ can be found by the non-linear method of least squares (linearizing for parameter increments and using approximation steps by changing parameters and adding these increments each step to get new values of parameters).

In fact we do not observe directly the angle ψ because the station does not lie exactly in the orbital plane. Moreover the station moves as the Earth rotate. But the distance D of the station from the orbital plane is known for each time. The station moved almost perpendicularly to the orbital plane, because it was situated very close to it (in fact the station just crossed the orbital plane when the meteor appeared) and the orbital plane was orientated in the south-north direction. The point S in Fig. 1 represents now the projection of the station into the orbital plane and the angle γ is considered to be constant. The station lies in the distance D from the point S perpendicular to the plane.

The angle ψ computed from Eq. (14) can be transformed into the true geocentric zenith distance z according to the formula

$$\cos z = \frac{R\varrho\cos\psi - D^2}{R_c\sqrt{\varrho^2 + D^2}} , \tag{18}$$

where ϱ is given by Eq. (15) and R_c is the geocentrical radius of the station, while R is the distance of point S from the Earth's center now:

$$R = \sqrt{R_c^2 - D^2}. \tag{19}$$

Thus the method of least squares can be applied to the angle z instead of ψ as well.

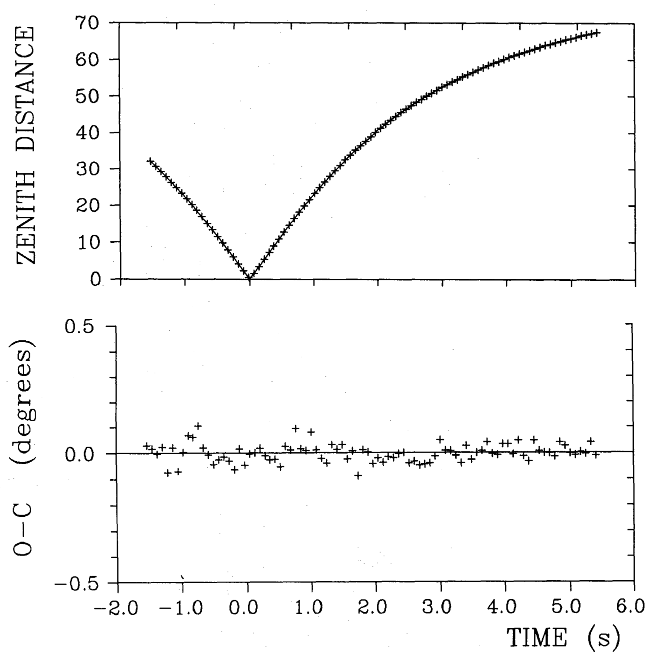

Fig. 2. Observed and computed geocentric zenith distances of the fireball at station no. 14

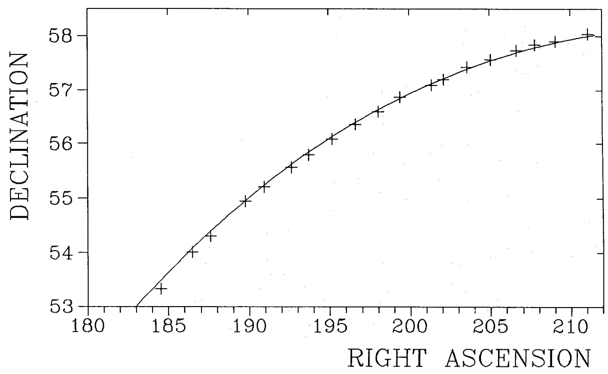

Fig. 3. Observed (crosses) and computed (line) fireball path in equatorial coordinates at station no. 9

3.5. Adding distance scale

The method described in previous paragraph was used for the data from station no. 14. This was only partially successful. While the position of pericentrum (angle γ) was determined unambiguously, the other two parameters remained uncertain. But this is not surprising. As we have used angular velocities only, the method can hardly decide, whether the meteor moves in a small distance with a small velocity or in larger distance and faster. Extremely precise observation were needed to derive distances from angular velocity change only.

To bring in the distance scale we have to turn to the observation from the second station (no. 9.) again. A point on the average meteor path as observed from station no. 9 is used as a crucial point. The direction corresponding to this point defines a point in the orbital plane, the orbit must pass close to. The distance ϱ_R from the projected station S to this supporting point and the corresponding angle ψ_R are computed and an additional condition that $\varrho(\psi_R)$ must be as near as possible to ϱ_R is built in the method of least squares. The function $\varrho(\psi)$ is not available but ϱ can be computed from ψ by means of φ using the formulae (16) and (15) successively.

The system of conditions for the method of least squares becomes "heterogeneous" now, because the zenith distances and the distance ϱ_R are measured in different units (radians and kilometers respectively). The weight of the last condition must be generally different from 1. In fact we can influence the "strength" of the last condition by changing its weight. The value 10^{-4} seems to be reasonable and it proved to be rather strong.

Note that the introduction of the additional condition does not restrict the possible values of pericenter position and the trajectory curvature. They are still determined by the angular velocities. But only one supporting point is allowed. More points would predetermine the trajectory shape.

We know that the slope of the observed meteor trail from station no. 9 is not absolutely correct. This fact resulted in the apparent velocity increase when the standard methods were used. But just one point should be correct. Therefore we tried different points along the average path as the crucial points and then we compared the resulting trajectories, as they should be visible from station no. 9, with the individual measured points. The best conforming trajectory has been chosen as the final solution. 18 measured points lie within the error of measurement ($\pm 0\overset{\circ}{.}03$) from the final trail and only 2 points have larger deviation ($0\overset{\circ}{.}1$). Both bad points are located at the beginning of the observed path, where the meteor trail is faint and their deviations are undoubtedly due to the errors of measurements.

Consequently we have found the solution of expected character (constant velocity, circular trajectory) which is consistent with the observations from both stations. This is demonstrated in Figs. 2 and 3. Figure 2 compares the observed and computed course of zenith distance from station no. 14. Figure 3 shows the positional measurements on station no. 9 compared to the final trajectory as seen from this station.

3.6. Final orbits

The least-squares solution yielded the parameters K, q, and γ ($K = 180\,400$ km, $q = 6463.8$ km, $\gamma = 1\overset{\circ}{.}766$). The orbital-plane solution (see Sect. 3.2) defined the inclination of the geocentrical orbit i and the right ascension of the ascending node Ω. Velocity was computed according to Eq. (17) and eccentricity from (8). The argument of pericenter ω was obtained from the position of station no. 14 and the angle γ. The resulting geocentric orbital parameters are summarized in Table 1.

Table 1. Geocentric orbit

pericenter distance	q	6463.8 ± 0.2 km
eccentricity	e	26.9 ± 0.1
argument of pericenter	ω	$51\overset{\circ}{.}469 \pm 0\overset{\circ}{.}001$
RA of ascending node	Ω	$94\overset{\circ}{.}74 \pm 0\overset{\circ}{.}01$
inclination	i	$93\overset{\circ}{.}347 \pm 0\overset{\circ}{.}004$
pericenter passage	T	1990 Oct 13; $03^h27^m22^s \pm 4^s$
velocity at pericenter	v_q	41.74 ± 0.08 km/s

The geographic coordinates of some important points on the observed part of the trajectory are given in Table 2. In addition, the absolute magnitudes versus time are given in Fig. 4 for each measured point. The time can be converted into height by means of the fitting formula $h = 98.672 + 0.12958 \cdot (t - 4.258)^2$ with intrinsic precision of 10 m below 120 km of height.

The photographed part of the trajectory stretches from Zlín in Czechoslovakia to Poznań in Poland. We suppose that the fireball could be still visible over south Baltic Sea at the height of 110 km.

Table 2. Relative time, geographical coordinates and absolute magnitudes of important points on the observed part of the trajectory

	t [s]	λ	φ	h [km]	mag
beginning	(−1.9)	17°39′	49°03′	103.7	(−5.6)
first velocity-point	−1.5	17 37	49 13	103.0	−6.1
station no. 14[a)]	0.00	17 32	49 47	101.0	−6.2
perigee	4.26	17 18	51 21	98.67	−6.2
pericenter	4.77	17 16	51 32	98.70	−6.0
last velocity-point	5.4	17 14	51 46	98.84	−6.1
end	(7.9)	17 04	52 41	100.4	(−6.1)

a) the point closest to the zenith at station no. 14

The heliocentric orbits before and after the encounter with the Earth were also computed. The asymptotes of the geocentric hyperbole define the direction of the meteoroid flight at the Earth's position relative to the Earth when the Earth's influence is removed. The asymptotic true anomaly is given by

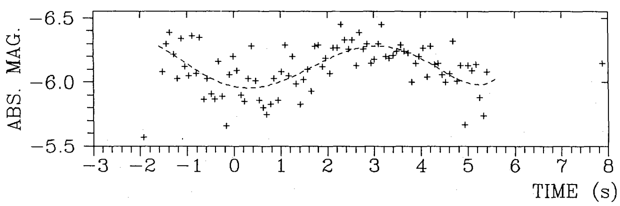

Fig. 4. Measured absolute magnitude as a function of time. A minor smooth variation is indicated, but it is insignificant.

$$\cos \vartheta_\infty = -\frac{1}{e} \qquad (20)$$

(see Eq. (3)). The equatorial coordinates of the radiant or antiradiant α, δ (i.e. the directions of the asymptotes) are given by

$$\sin \delta = \sin i \, \sin(\omega \mp \vartheta_\infty) \qquad (21)$$
$$\sin(\alpha - \Omega) = \tan \delta \, \cot i$$

where the upper sign is valid for radiant. (Eqs. (21) should be slightly transformed, if $\omega \mp \vartheta_\infty$ were greater than π). The α and δ together with the velocity v_∞ computed from (5) are equivalent to the quantities α_G, δ_G, and v_G (geocentric radiant and velocity) respectively from the paper of Ceplecha (1987). The heliocentric orbits have been computed according to the same paper. The results are given in Table 3. The semimajor axis decreased after the encounter and the inclination, which had been rather large already, slightly increased.

Table 3. Heliocentric orbits (1950.0)

	before encounter	after encounter
α_G	97°.27 ± 0°.01	96°.84 ± 0°.01
δ_G	−40°.55 ± 0°.01	−36°.31 ± 0°.01
v_G	40.22 ± 0.17 km/s	40.22 ± 0.17 km/s
a	2.72 ± 0.08 A.U.	1.87 ± 0.03 A.U.
P	4.5 ± 0.2 yr	2.56 ± 0.06 yr
e	0.64 ± 0.01	0.473 ± 0.009
q	0.9923 ± 0.0001 A.U.	0.9844 ± 0.0002 A.U.
Q	4.45 ± 0.15 A.U.	2.76 ± 0.07 A.U.
ω	9°.6 ± 0°.1	16°.6 ± 0°.2
Ω	18°.973	18°.973
i	71°.4 ± 0°.2	74°.4 ± 0°.2

4. Conclusions

We present here complete data on the 1990 October 13 fireball. This is the first Earth-grazing fireball with available double-station photographs. Its mass was about 44 kg and it was only slightly altered by the atmospheric ablation. The meteoroid left the Earth in a changed orbit losing only 0.35 kg of its mass and having formed a solidified fusion crust like meteorites.

The Earth-grazing meteors should not be especially rare. About 0.7% of meteoroids entering the Earth's atmosphere have trajectory with the perigee in heights between 70 km and 120 km above the surface. The chance for surviving an Earth's encounter then depends on meteoroid mass, compactness and velocity. But this kind of meteoroids will be always faint because they move in less dense layers of the atmosphere. For example the fireball presented here would reach almost −15 absolute magnitude, if it flew vertically to the Earth surface (−14.6 magnitude at a height of 41 km and terminating at a height of 29 km with mass below 1 gram). The 1972 August 10 fireball was, of course, a quite exceptional case.

The method developed for the determination of the trajectory of the present fireball could have a wider use. In its basic form it allows to compute pericenter position from angular velocity measurements for a Keplerian motion.

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