Video observations, atmospheric path, orbit and fragmentation record of the fall of the Peekskill meteorite

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Abstract. Large Near-Earth-Asteroids have played a role in modifying the character of the surface geology of the Earth over long time scales through impacts. Recent modeling of the disruption of large meteoroids during atmospheric flight has emphasized the dramatic effects that smaller objects may also have on the Earth's surface. However, comparison of these models with observations has not been possible until now. Peekskill is only the fourth meteorite to have been recovered for which detailed and precise data exist on the meteoroid atmospheric trajectory and orbit. Consequently, there are few constraints on the position of meteorites in the solar system before impact on Earth. In this paper, the preliminary analysis based on 4 from all 15 video recordings of the fireball of October 9, 1992 which resulted in the fall of a 12.4 kg ordinary chondrite (H6 monomict breccia) in Peekskill, New York, will be given. Preliminary computations revealed that the Peekskill fireball was an Earth-grazing event, the third such case with precise data available. The body with an initial mass of the order of 10^4 kg was in a pre-collision orbit with $a = 1.5$ AU, an aphelion of slightly over 2 AU and an inclination of 5°. The no-atmosphere geocentric trajectory would have lead to a perigee of 22 km above the Earth's surface, but the body never reached this point due to tremendous fragmentation and other forms of ablation. The dark flight of the recovered meteorite started from a height of 30 km, when the velocity dropped below 3 km/s, and the body continued 50 km more without ablation, until it hit a parked car in Peekskill, New York with a velocity of about 80 m/s. Our observations are the first video records of a bright fireball and the first motion pictures of a fireball with an associated meteorite fall.

Key words: meteorite fall, fireball, Earth-grazing, video-records, trajectory, orbit, Peekskill

1 Introduction

In 1992 on October 9 at $23^{\mathrm{h}}48^{\mathrm{m}}$ UT, many eyewitnesses on the east-cost of the U.S. saw a fireball brighter than the full moon. It lasted more than 40 seconds.

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This happened to be early evening local time when many people, particularly fans of football games, were outdoors. At least 15 video recordings of this event were made from different locations. As well, two high resolution photographs showing extreme fragmentation of the body were made. At least 70 individual fragments separated by more than 20 km distance are visible on these photographs. Almost 4 minutes after the last light from the fireball extinguished, one of the fragments weighing 12.4 kg struck a parked car at Peekskill, New York (Wlotzka 1993). It turned out to be an ordinary chondrite, H6 monomict breccia. This is only the fourth meteorite to have been recovered for which detailed and precise data exist on the meteoroid atmospheric trajectory and thus also on orbit (Brown et al., 1994). We present preliminary results based on video recordings of this fireball from 5 stations.

2 Reductional procedures

The toughest part of computing the atmospheric trajectory for this fireball was the first step; namely computing azimuths and elevation angles to the body from individual video frames. Relative timing is, of course, perfect in this case, but the position of any object depends on the direction and focal distance of the camera. Moving and zooming cameras following the fireball flight are not only a good recording device, but also quite a problem for absolute calibration of the direction of any vision line. Photometry is an even worse problem, because the automatic focus and gain controls on camcorders inhibit collection of precise photometric data. Calibration of measured directions was mostly done by using terrestrial objects recorded together with the fireball. Some of the terrestrial objects were related to star images taken from exactly the same location later on. For each station, the individual video frames were digitized, measured and calibrated. One of the 5 stations showed too much systematic deviations with respect to the other 4 stations: thus we were forced to exclude this station from the preliminary analysis. The following preliminary data are based on measurements of 254 individual directions from 4 stations.

3 Atmospheric trajectory and orbit

The classical method of computation of a fireball trajectory uses the intersections of planes, where each plane is defined by the position of the station and all directions from this station to the fireball trajectory. But this method failed completely in the case of the Peekskill fireball. It was obvious that a curved fireball trajectory upon an even more curved Earth's surface were the reason for this failure of the classical approach usually used for much shorter and steeper trajectories. It soon became clear that the Peekskill fireball was an Earth-grazing event, actually the third ever such event with precise data available. We used a method and the software developed by J. Borovička (1990) for locating a curved trajectory as

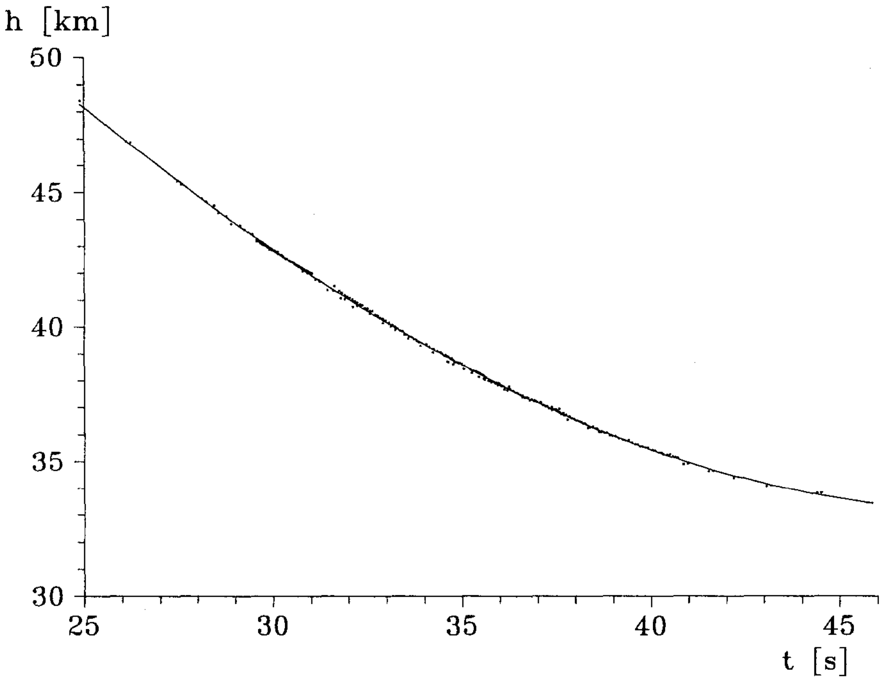

Fig. 1. Height as function of time: points correspond to individual observed values, the curve is the average change of height with time.

close as possible to all 254 lines of vision. After application of this procedure, the standard deviation for one line of vision turned to be ±0.9 km. This is about 20× to 50× less precise than is typical for multistation photographs of fireballs, but it is compensated by the extremely long trajectory. From the total luminous trajectory of almost 800 km, 250 km were video recorded.

Fig. 1 presents the change of height with time for the observed part of the Peekskill trajectory. The individual points belong to the individual values as measured from the video recordings, while the smooth curve is the model average. Our model was a circle of 12250 km over the curved Earth's surface, which corresponds to height changes due to gravity during a known time interval. It can also be viewed as an osculating circle of the hyperbolic Earth-bound orbit close to the perigee. Very good precision is evident from Fig.1.

Because of the precise relative timing of individual frames, we were also able to compute the velocity with very high precision. In Fig. 2 the velocity is plotted against time. Especially the early part of the trajectory which showed very little change of velocity (due to the large size of the initial body) resulted in an accurate initial velocity with a high precision of $v_\infty = 14.72 \pm 0.05$ km/s. Thus, also the orbit (Table II) is quite well determined. The velocity was computed using a model of ablation and fragmentation along a curved trajectory (Ceplecha et al., 1993).

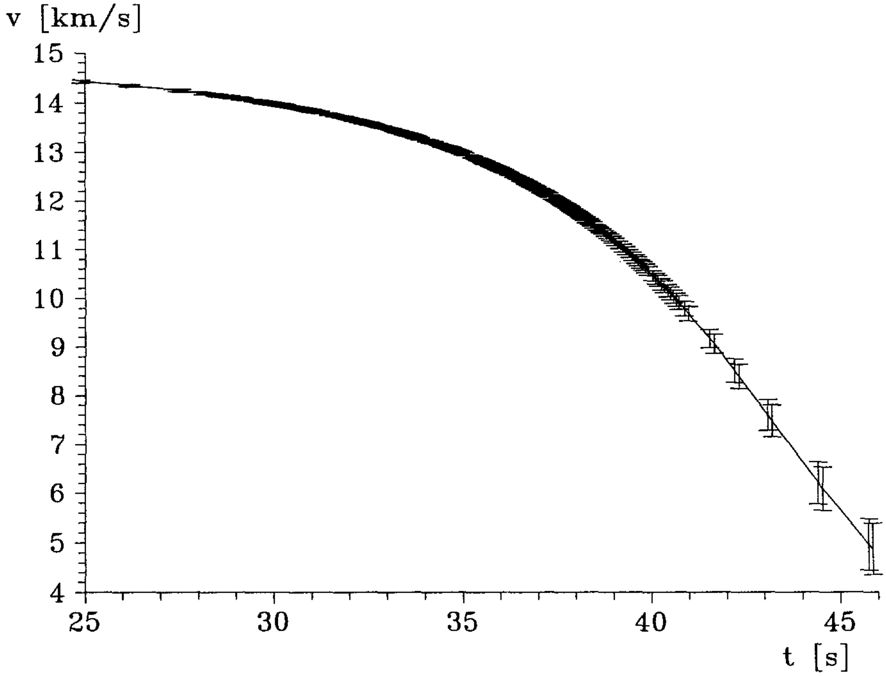

Fig. 2. Velocity with its standard deviations as function of time.

The orbit was computed by a method usual for precise meteor data as described in details by Ceplecha (1987, p. 229) including also the nomenclature customary in meteor branch. Especially, v_∞ is the initial (or no-atmosphere) velocity, i.e. the velocity the body would have had at the point, where it is measured, but without the atmosphere. v_G is then the geocentric velocity, i.e. the initial velocity corrected for the Earth's rotation and gravity. In our case we corrected the observed velocity $v = 14.45 \pm 0.03$ km/s and the observed right ascension and declination of the radiant, $\alpha_R = 226.7^\circ \pm 0.4^\circ$ and $\delta_R = -16.2^\circ \pm 0.2^\circ$, at a point of longitude $\lambda = 281.794^\circ$ E, latitude $\varphi = 39.806^\circ$ N , height $h = 46.41$ km; $(v \rightarrow v_\infty \rightarrow v_G)$.

The standard deviation for one distance measured along the fireball trajectory resulted in ± 1.0 km, almost the same value as in the direction perpendicular to the trajectory. The computed terminal velocity is in general agreement with the position of the meteorite fall at Peekskill. The vertical projection of the trajectory is represented in Fig. 3 using the usual frame of geographic coordinates. The Peekskill meteorite position lies only 9 kilometers away from the prolongated trajectory.

The Earth-grazing trajectory is evident on a schematic representation of all three Earth-grazing fireballs which have precise data available (Fig. 4). If there had been no atmosphere, the Peekskill body would have continued to a perigee of 22 km above the Earth's surface and then again skipped back into space. But due to atmospheric ablation, fragmentation and deceleration, the Peekskill meteoroid did

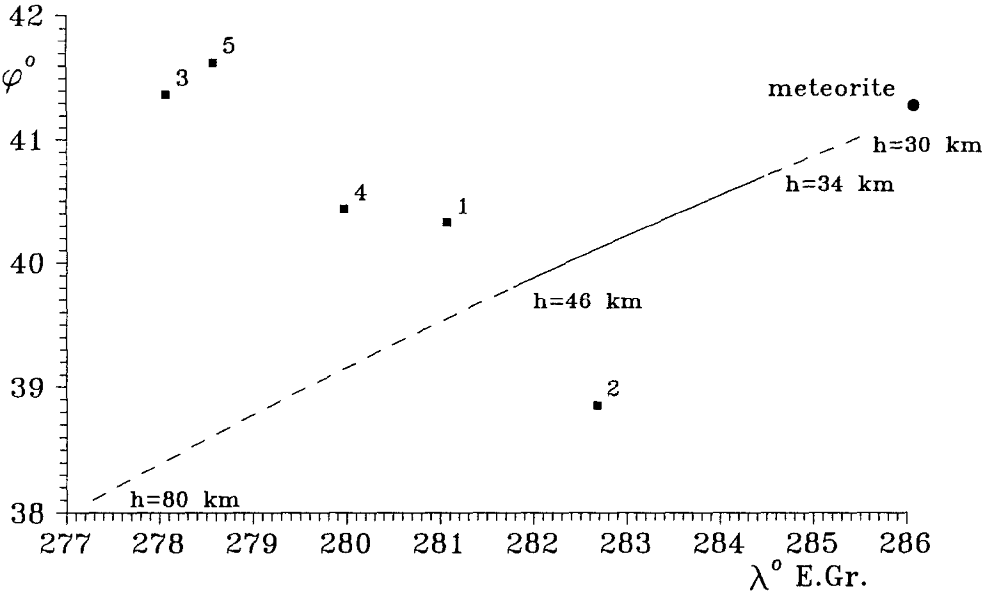

Fig. 3. Vertical projection of the Peekskill fireball trajectory in the frame of geographic longitude λ and latitude φ. Trajectory computed from video records is given by the full line, while the dashed parts correspond to the extrapolated trajectory combined with the visual sightings of the fireball. Heights, h, are given at four points along the trajectory. Location of the meteorite is denoted by a small full circle. Small full squares with numbers 1 to 5 denote positions of the stations we used in our preliminary analysis.

TABLE I

Summary of data on trajectory.

number of measured directions	254
standard deviation for one case	
perpendicular to the trajectory	±0.9 km
along the trajectory	±1.0 km
length of the measured trajectory	253 km
height of perigee	22 km
terminal height	30 km
initial mass	1.3×10^4 kg
initial size	$\approx 1.7 \times 1.7 \times 1$ m
ablation coefficient	0.090 ± 0.003 s^2/km^2
terminal (meteorite) mass	12.4 kg
impact velocity	80 m/s

TABLE II

Radiant and orbit (2000.0)

α_R	deg	226.7	±0.4
δ_R	deg	−16.2	±0.2
v_∞	km/s	14.72	±0.05
α_G	deg	209.0	±0.6
δ_G	deg	−29.3	±0.2
v_G	km/s	10.1	±0.1
a	AU	1.49	±0.03
e		0.41	±0.01
q	AU	0.886	±0.004
Q	AU	2.10	±0.05
ω	deg	308	±1
Ω	deg	17.030	±0.001
i	deg	4.9	±0.2

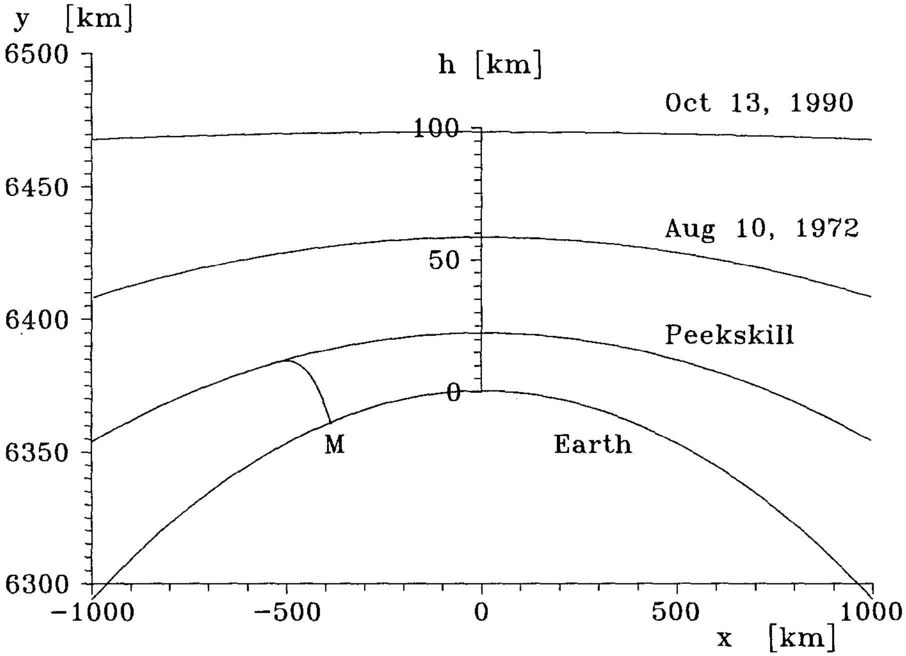

Fig. 4. Schematic representation of the Peekskill Earth-grazing trajectory in comparison to the other two Earth grazing fireballs which have precise data on their trajectories available. All trajectories are put to the same apsidal line. x is the distance from the Earth center parallel to the flight at perigee, y is the distance from the Earth center in the direction to perigee (very much enlarged relative to the x distances), h is the height at perigee, M is the location of the Peekskill meteorite.

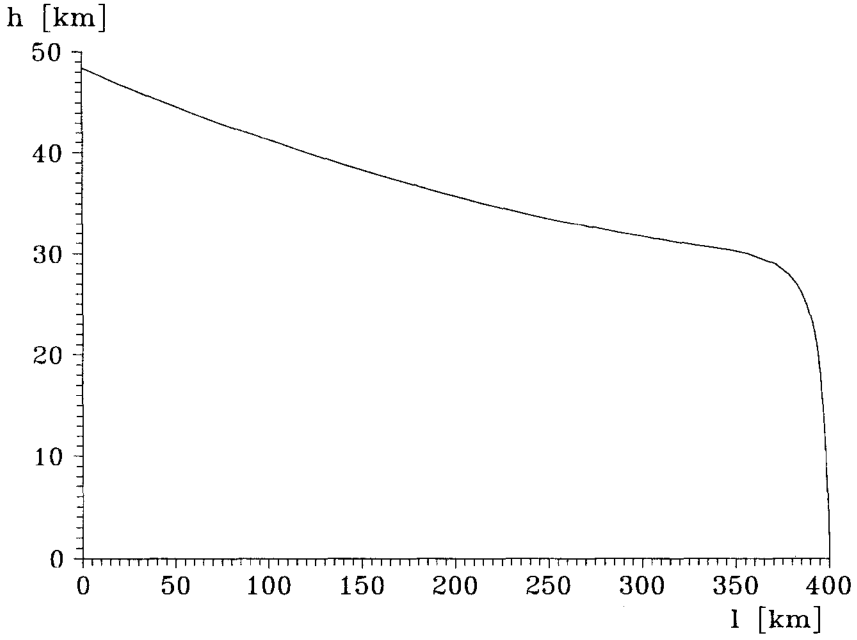

Fig. 5. Height h as function of horizontal distance l including the dark flight.

not reach the perigee point, started its dark flight trajectory at a height of 30 km and landed 460 km before the perigee. The other two Earth grazing fireballs in Fig. 4 both went through perigee and continued again on changed orbit around the Sun. The upper one of Oct 13, 1990 lost only 1% of its mass. The famous daylight fireball of Aug 10, 1972 – also over the U.S. – lost 90% of its mass (Borovička and Ceplecha 1992, Ceplecha 1979, 1994). Thus meteoroids with fusion crust produced through interaction with the Earth's atmosphere exist also in interplanetary space.

Fig. 5 represents heights as function of horizontal distance determined for the whole trajectory, i.e. including also the dark-flight computed using the actual wind field below 30 km as given by meteorological measurements. Fig. 6 demonstrates a narrow interval of heights close to 30 km, where most of the slow-down took place. Two points of gross fragmentation are also included in these model computations.

Dynamic pressure as function of height is given in Fig. 7. The Peekskill body during its flight through the atmosphere underwent severe fragmentation under dynamic pressures between 7 and 10 Mdyn/cm^2 at heights of 41 km and lower, while the meteorite has an estimated strength somewhere close to 300 Mdyn/cm^2, more than one order of magnitude higher. A mechanism other than only the dynamical pressure acting on the recovered meteorite material must be responsible for this. (*Referee's note: The parent meteoroid was likely partially fragmented from previous collisions so that the stress necessary to break it into smaller pieces*

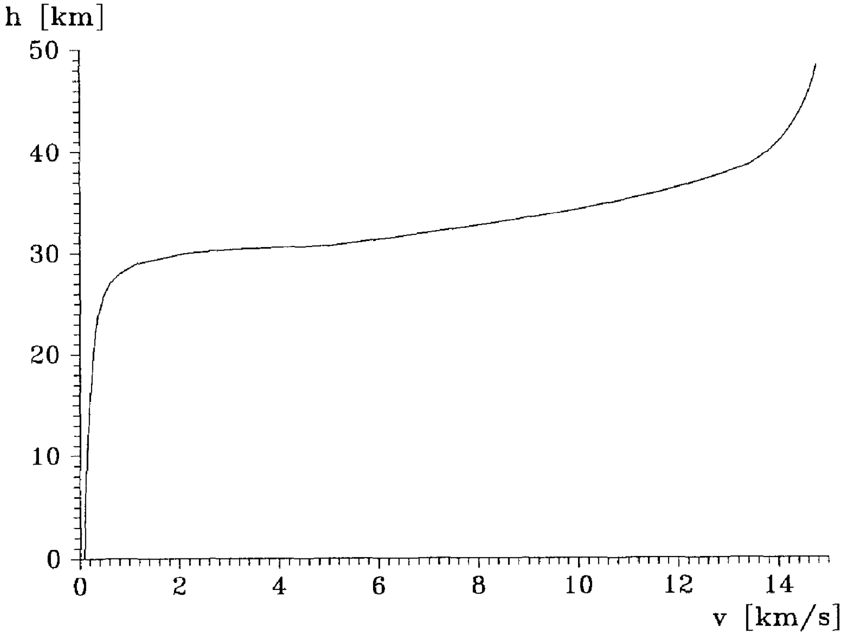

Fig. 6. Height *h* as function of velocity *v* including the dark flight.

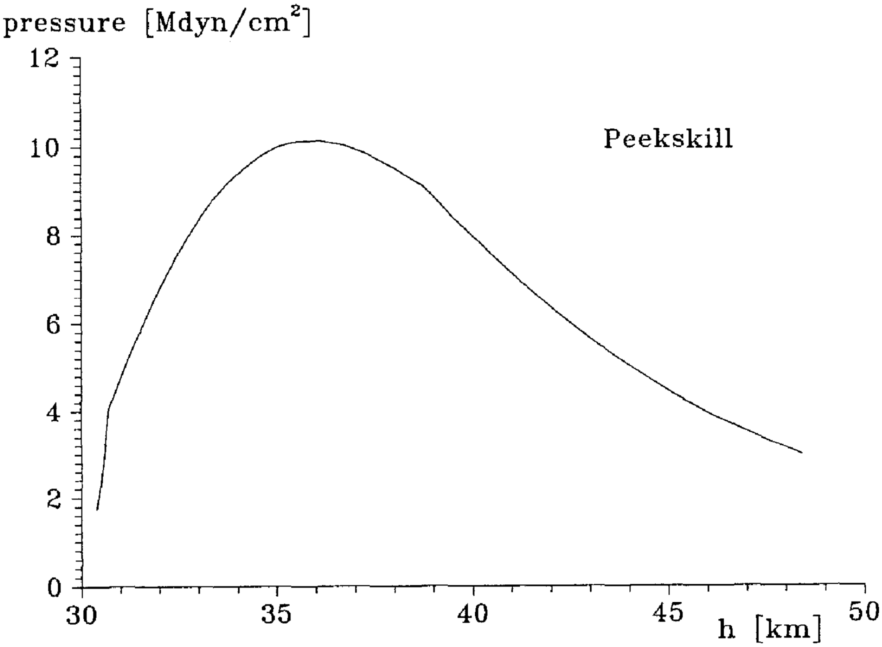

Fig. 7. Dynamic pressure as function of height *h*.

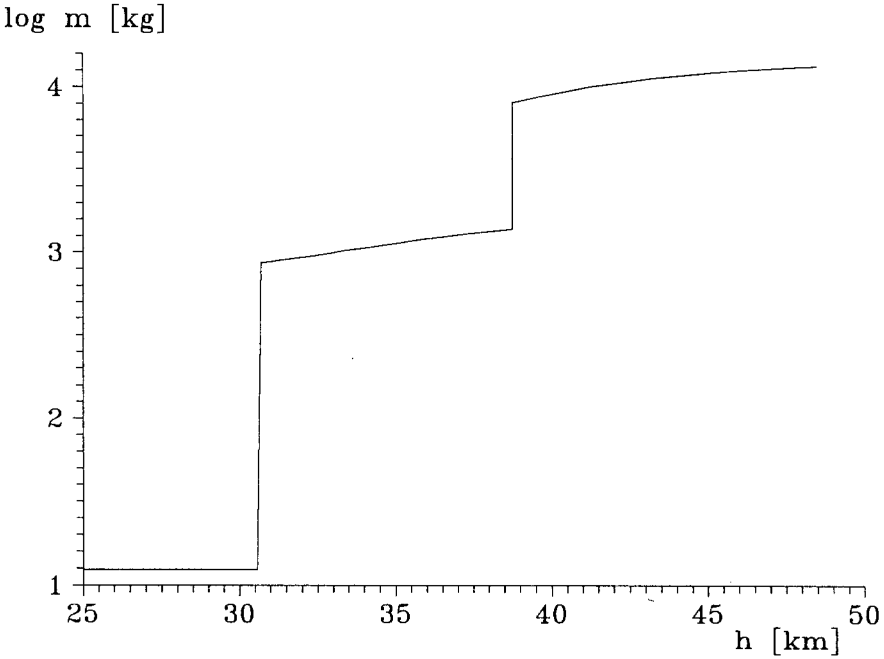

Fig. 8. Mass m as function of height h. This is just a model computation based on the preliminary computations and demonstrating two large fragmentation events important for the Peekskill meteorite fall.

was much less than the strength of the surviving, very well consolidated, fragments.) The dark-flight of the recovered meteorite started from a height of 30 km, when the velocity dropped below 3 km/s, and the body continued an additional horizontal distance of 50 km without ablation, until it hit a parked car with a vertical velocity of about 80 m/s.

Fig. 8 represents the change of mass of the precursor body of the Peekskill meteorite with height. Computation of mass is very sensitive to the measured deceleration. The low deceleration values at the beginning of the trajectory are the most model dependent from all the data we determined. In any case, to get the body from the recorded trajectory to the location, where the meteorite was recovered, at least 10^4 kg of its initial mass is needed. The best model of the initial Peekskill body is represented by a meteoroid with a 40% flattened shape with dimensions of 1.7 × 1.7 × 1 m. This is in good agreement with independent computations of the initial size of the parent meteoroid from measurements of radionuclides, noble gases and cosmic-ray tracks (Graf et al., 1994).

Summary of the principal data on trajectory and orbit as derived from the video recordings are given in Table I and Table II. The high value of the ablation coefficient 0.090 s^2/km^2, compared to average value for stony meteorites of 0.014 s^2/km^2, is due to severe continuous fragmentation. We used the dynamic model to follow only the main precursor of the Peekskill meteorite and we cannot thus distinguish different types of ablation: fragmentation is just one of the ablation forms. Quite a detailed study of motions of individual fragments is possible using the video records and we intend to perform and publish more sophisticated analyses in the near future.

We continue our work on further refinement of the atmospheric trajectory and the orbit of the Peekskill fireball and meteorite. We anticipate improvements through measurements from additional digitized video frames, more reliable positional measurements of reference objects, incorporation of data from additional stations, and better modeling of motion, ablation and fragmentation. We intent to publish our final results in Meteoritics.

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