The orbit and atmospheric trajectory of the Peekskill meteorite from video records

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ON 9 October 1992, a bright fireball appeared over West Virginia, travelled some 700 km in a northeasterly direction, and culminated in at least one impact: a 12.4-kg ordinary chondrite was recovered in Peekskill, New York[1]. Fortuitously, the event was captured on several video recordings, which provide a detailed record of both the fragmentation of the object and related atmospheric effects. These are the first motion pictures of a fireball from which a meteorite has been recovered. We report here the preliminary analysis of 14 video recordings of the event, from which we determine the ground path and the original orbit of the object.

Objects responsible for bright fireballs occupy the low-mass (1–10^6 kg) end of the asteroid size spectrum. Several recent studies[2,3,4] have considered the fragmentation of large meteoroids during atmospheric flight, but comparison of these models with observational data has not been possible. Up to now, only three meteorites have been recovered[5,6,7] for which detailed data exists on their atmospheric trajectory and orbit. Consequently, there are few constraints on the numerical models of meteoroid entry dynamics and the position of meteorites in the Solar System before impact on Earth.

At 23:48 UT (±1 min) on 9 October 1992, a fireball, brighter than the full moon, appeared over West Virginia. The fireball travelled in an approximately northeasterly direction with an estimated luminous flight time in excess of 40 s, covering a ground-path of >700 km (Fig. 1). During the second half of its flight, the fireball exhibited extensive fragmentation with several dozen individual fragments visible on some video frames. These fragments reached a maximum simultaneous separation of >20 km, with at least 70 pieces visible on two higher-resolution still photographs of the event. Two main pieces were visible in the last part of the trajectory. A fragment struck a parked car, at Peekskill, New York (41° 17′ N, 73° 55′ W). Many eye-witness accounts of the fireball were received and at least 14 video recordings of the event were made.

The results presented here are based on triangulation analyses using video data from four locations: Fairfax, Virginia (38° 51′ N, 77° 19′ W); Johnstown, Pennsylvania (40° 20′ N, 78° 56′ W); Pittsburgh, Pennsylvania (40° 26′ N, 80° 01′ W); and Willoughby, Ohio (41° 38′ N, 81° 26′ W). The location of these stations is indicated in Fig. 1. The most comprehensive view of the event is provided by the Johnstown video, which records ~22 s of the flight. From each station the individual video frames were digitized and measured. This analysis is based on measurement of 254 points. The multi-station analysis procedures are fully described elsewhere[8,9].

The apparent radiant (the point on the celestial sphere from which the meteor appears to originate) is $\alpha = 15\,\text{h}\;07\,\text{min} \pm 02\,\text{min}$, $\delta = -16.2° \pm 0.2°$ (epoch 2000.0). The trail is extremely shallow. At the start of the video records (a height of 46.4 km), the trail makes an angle of only 3.4° with the horizontal. The last point measured on the video records corresponds to a height of 33.6 km, although this is not the end of the luminous path. This Earth-grazing fireball would have returned to space were it not for the Earth's atmosphere. Indeed, if it were ~40 km higher at perigee it would have skipped out of the atmosphere as did the 10 August 1972 Wyoming fireball[10].

TABLE 1 Orbital parameters for the Peekskill meteorite

a	(semimajor axis)	1.49 ± 0.03 AU
e	(eccentricity)	0.41 ± 0.01
q	(perihelion distance)	0.886 ± 0.004 AU
ω	(argument of perihelion)	308° ± 1°
Ω	(longitude of ascending node)	17.030° ± 0.001°
i	(inclination)	4.9° ± 0.2°
T	(orbital period)	1.82 ± 0.05 yr
DT	(time since perihelion)	41 ± 1 d
Q	(aphelion distance)	2.10 ± 0.05 AU

These video recordings present a wealth of time-resolved dynamical detail never before recorded for a fireball-meteorite event. In Fig. 2 we show a composite of the fireball as recorded from Johnstown. In the first part of the recorded luminous trajectory there is significant wake behind the fireball, but no distinct fragments. By a height of ~41.5 km, fragmentation into individual pieces is clearly visible. Differential aerodynamically induced lag makes it possible to discern several dozen fragments of different sizes by the time the object has reached a height of 38.6 km. The detail of this fragmentation is more clearly visible in the higher-resolution still photograph (Fig. 3). As well as a maximum longitudinal fragment displacement of >20 km, there is a much smaller but significant transverse displacement. There is a significant flare at a height of 36.2 km, followed by a burst of material which rapidly decelerates relative to the main fragments. In the last part of the trajectory there are four main fragments, with only the largest two being visible eventually. This would seem to indicate that there should be at least two,

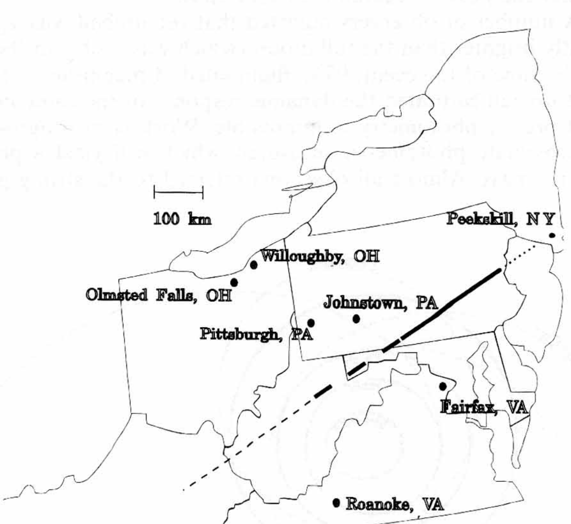

FIG. 1 Map of the northeastern United States showing the location of the stations used in the video analysis, the projection of the trajectory on the Earth's surface and the Peekskill meteorite recovery site. The ground track as actually recorded on video is the solid line; the dotted line represents the undocumented trajectory past the last recorded point; the thick dashed line is based on a compilation of visual observations for the early part of the trajectory; and the thin dashed line is a theoretical initial portion of the trajectory based upon the assumption of an 80-km height at the start of the luminous trajectory. NY, New York; OH, Ohio; PA, Pennsylvania; VA, Virginia.

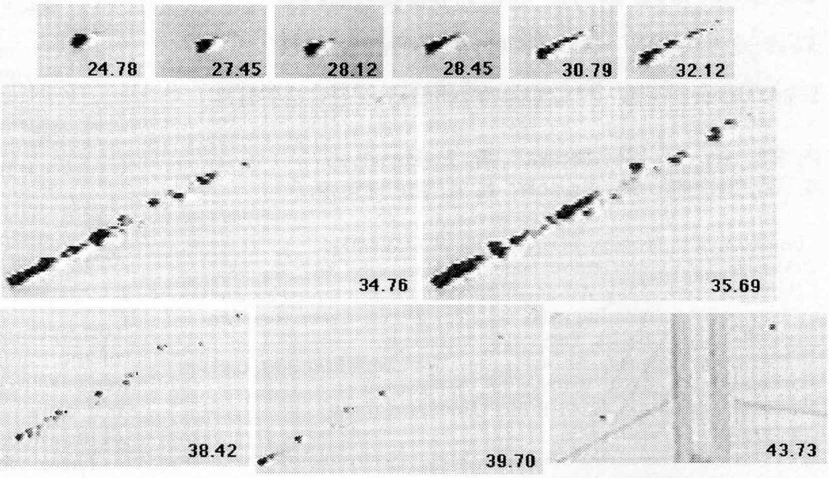

FIG. 2 Set of images showing the changing appearance of the fireball as viewed from Johnstown (see Fig. 1). The relative time (in seconds) is given on each image (the absolute value of the time marker has no significance). Early in the flight the fireball had a central luminous core and a trailing wake, probably due to spraying of liquid droplets or very fine grains (the scale in the first 6 images is ~5.7° horizontal width). The length of the combined luminous trajectory is 3.7 km in image 24.78 s (height 46.3 km) and grows to 13.8 km in image 32.12 s (height 40.5 km). As illustrated in the two central images, the distribution of fragments changed dramatically over rather short time intervals. In the latter part of the trajectory (bottom images) the fragments became more clearly distinct, until only two main pieces are visible (on either side of the double stadium pole in the image) at relative time 43.73 (height 34.1 km) (original video recording by J. Derr).

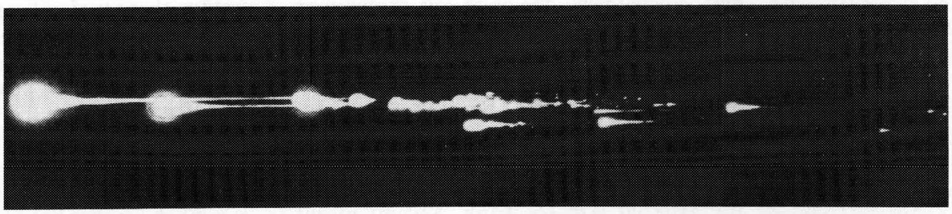

FIG. 3 Enlargement of a portion of a still photograph (by S. Eichmiller) taken from Altoona, Pennsylvania, showing extensive fragmentation. The photograph was shot on Kodak TMZ (3200) film with a 300-mm lens (shutter speed either 1/250 or 1/500 s, at an aperture of *f* 4 or *f* 2.8). The portion of the photograph reproduced here represents an angle of 3.4°. A minimum of 70 fragments are visible on the original photograph.

and possibly four or more, meteorite fragments on the ground, although only one has yet been found. The shallow trajectory makes the possible search area very large.

A number of observers reported that the fireball was significantly brighter than the full moon (which was visible in the sky at the time of the event, 97% illuminated at magnitude -12.8). The fireball saturated the dynamic response of the camcorders, and precise photometry is impossible. Work is in progress on approximate photometric measures, which will yield a photometric mass. Almost all observers referred to the strong green hue of the fireball although this colour does not appear strongly in the video recordings owing to the spectral response of the CCD (charge-coupled device) photodetectors.

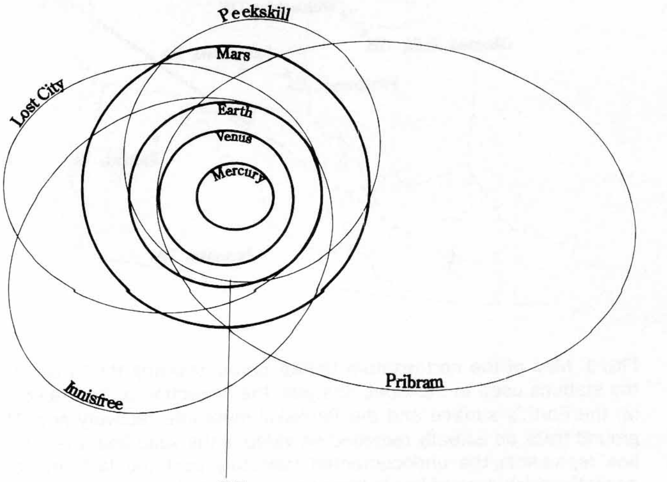

FIG. 4 The orbit of the Peekskill meteorite, along with the three previous meteorites with photographically determined orbits (Lost City, Pribram and Innisfree). The symbol γ is the Vernal Equinox.

The video record shows the distinct presence of a flickering phenomena in the fireball's pre-fragmentary (above 43 km) flight. Frame-by-frame analysis of several video segments indicates that the plasma tail, or wake, periodically disconnects from the main body of the fireball. An average disconnection frequency of 6 Hz is found. Such a phenomenon has been reported previously[11], although at higher disconnection frequencies. We suggest that the disconnection events may be driven by the rotation or aerodynamic oscillation of the pre-fragmented parent body. These mechanisms associate the disconnection events with a modulated ablation rate. The disconnection events may alternatively be associated with a hydrodynamic instability in the fluid layer of the pre-fragmented meteoroid. This mechanism, on small scales, has recently been discussed[12].

As all the images were recorded in response to the spectacular event, the initial part of the trajectory was not obtained. However, the data suggest that the meteoroid had not suffered significant deceleration before the first video recording. We assumed a frame rate of 30 frames per second (60 video fields per second). The crystal-oscillator-based timing on the camcorders used should result in an error of no more than 0.1%. The analysis yields a pre-atmospheric velocity of 14.72 ± 0.05 km s^{-1}, whereas the velocity for the last measured intervals was ~5 km s^{-1}. The spatial accuracy of individual points is inferior to photographic meteor work, but the duration of the event (10–20 times longer than typical fireballs), the use of data from four widely spaced stations, the large number of points used (254), and the excellent (1/60 s) time resolution all contributed to a rather precise pre-atmospheric velocity and apparent radiant. Nevertheless, considering that the raw data were collected by mobile non-scientific instruments, and that a celestial reference object was available only at one station, perhaps the probable error should be increased by a factor of two or more to allow for possible uncorrected systematic errors.

Following corrections to the apparent radiant and velocity, to account for the gravitational attraction of the Earth and for rotation of the Earth, one obtains a corrected radiant of $\alpha =$ 13 h 56 min ± 02 min, $\delta = -29.3^\circ \pm 0.2^\circ$ (epoch 2000.0) with a geocentric velocity of 10.1 ± 0.1 km s^{-1}. It should be noted that the shallow trajectory required sophisticated analysis procedures[10]. The orbital parameters are given in Table 1, and the orbit is plotted in Fig. 4 along with the previous three meteorite orbits. In all cases the probable errors quoted are ±1 standard deviation, subsequently multiplied by 2 to allow for possible uncorrected systematic errors. The object was encountered near perihelion, as are most meteorite-producing fireballs[13].

Work is continuing on the further refinement of the atmospheric trajectory and the orbit. We anticipate improvements through measurements from additional digitized video frames, more reliable positional measurements of reference objects, possible incorporation of data from additional stations, and better modelling of deceleration. Other researchers are currently measuring the cosmogenic radioisotopes of the one recovered fragment (an H6 monomict breccia), which will provide independent evidence relevant to the pre-atmospheric mass. In addition the rich video record should permit a detailed analysis of the fragmentation dynamics and flare phenomena. □

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