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The Morávka meteorite fall: 1. Description of the events and determination of the fireball trajectory and orbit from video records

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Abstract–The Morávka (Czech Republic) meteorite fall occurred on May 6, 2000, 11:52 UT, during the daytime. Six H5–6 ordinary chondrites with a total mass of 1.4 kg were recovered. The corresponding fireball was witnessed by thousands of people and also videotaped by 3 casual witnesses. Sonic booms were recorded by 16 seismic stations in the Czech Republic and Poland and by one infrasonic station in Germany. A total of 2.5% of the fireball eyewitnesses reported electrophonic sounds. Satellites in Earth orbit detected part of the fireball light curve.

In this first paper from a series of 4 papers devoted to the Morávka meteorite fall, we describe the circumstances of the fall and determine the fireball trajectory and orbit from calibrated video records. Morávka becomes one of only 6 meteorites with a known orbit. The slope of the trajectory was 20.4° to the horizontal, the initial velocity was 22.5 km/s, and the terminal height of the fireball was 21 km. The semimajor axis of the orbit was 1.85 AU, the perihelion distance was 0.982 AU, and the inclination was 32.2°. The fireball reached an absolute visual magnitude of –20 at a height of 33 km.

INTRODUCTION

More than 800 meteorite falls have been witnessed and documented to the present time. Only in 5 cases was the fireball preceding the fall able to be imaged instrumentally from at least 2 sites and the fireball atmospheric trajectory and velocity reliably determined by triangulation. Three of the fireballs were recorded by dedicated photographic programs, namely Pribram in Czechoslovakia in 1959 (Ceplecha 1961), Lost City, USA in 1970 (McCrosky et al. 1971), and Innisfree, Canada in 1977 (Halliday et al. 1981). The fourth was Peekskill, USA, recorded by a number of video cameras of casual eyewitnesses in 1992 (Brown et al. 1994). All 4 of these meteorites are ordinary chondrites. More recently, an enstatite chondrite from a photographed fall was recovered in Germany (Spurný et al. 2002, 2003). Trajectories and velocities of some other meteorite falls were determined with varying degrees of reliability, ranging from good data based on photos and videos of the dust trail combined with satellite fireball light curve for the unique Tagish Lake carbonaceous chondrite (Brown et al. 2000) to the satellite/visual data for the St. Robert meteorite fall (Brown et al. 1996) to trajectories based purely on visual observations (Jenniskens et al. 1992).

The importance of good fireball data is obvious. From the trajectory and velocity, the heliocentric orbit of the meteoroid can be computed. The backward numerical integration of the orbit provides information about the type of evolutional path of the meteoroid in the solar system (Jopek et al. 1995). Attempts have even been made to link the meteorites directly to their parent asteroids on the basis of the orbits (Farinella et al. 1994; Drummond 2000). Studying the behavior of the meteoroid in the atmosphere is also important. The known properties of the meteorite (density, mass, shape, etc.) can enable calibration of the fireball data, so that other fireballs without recovered meteorites can provide information on the physical properties of respective meteoroids. Ceplecha and McCrosky (1976), for example, used the Lost City fall to establish a diagnostic of meteoritic material based on the fireball end heights. The Innisfree and Lost City falls were used to derive luminous efficiency of fireballs (Halliday et al. 1981; Ceplecha 1996).

Here, we report another meteorite fall which occurred in the Czech Republic during the daytime on May 6, 2000. The fireball was, fortunately, recorded on videotape by 3 casual witnesses. One meteorite was recovered immediately after the fall and 5 other meteorites were found later. The total recovered mass was 1.399 kg. The meteorites were classified as H5–6 ordinary chondrites. A good trajectory and orbit has been derived, though the precision is less than in the photographic cases. The video, on the other hand, was very useful for following individual fragments of the fireball and enabled us to derive data for a number of fragmentation events. Sonic booms produced by the fireball were detected on 16 seismic stations located conveniently in the vicinity of the trajectory, and a number of fragmentation events could be identified in the seismic records. One infrasonic record of the fireball containing 3 different types of signals was also obtained. Satellites in Earth orbit also detected the fireball.

This paper is the first paper of a series of 4 papers devoted to the detailed analysis of all available data. First, we describe the events of May 6, 2000, i.e., the fireball observations, data records, and the meteorite recovery. The video records are then used to compute fireball trajectory and heliocentric orbit. Finally, the satellite light curve is presented. The second paper (Brown et al. 2003), is devoted to the detailed interpretation of rich infrasonic and seismic data. In the third paper (Borovička et al. 2003), various methods are used to determine meteoroid pre-atmospheric size and the recent history of the meteoroid in the solar system is studied. The composition and structure of the meteorites is also described. Finally, in the fourth paper (Borovička and Kalenda 2003), the behavior of the meteoroid during the atmospheric entry, in particular its extensive fragmentation, is studied in detail.

DESCRIPTION OF THE EVENTS

Visual Sightings

May 6, 2000 was a sunny Saturday in central Europe and was unseasonably warm. Many people were spending their time outside when the fireball appeared at 13:52 local daylight savings time (11:52 UT). Consequently, the fireball had thousands of witnesses. Professional and public observatories and planetariums in the Czech Republic received more than 500 reports in the following days. The fireball was described as a bright object dominating the sky even during broad daylight (one hour after noon) and even from sites more than 400 km from the fireball trajectory. At closer sites, some people reported recognizable additional illumination beyond natural sunlight on ground objects by the fireball light. We estimated the maximal absolute (100 km distance) brightness of the fireball to be −20 stellar magnitude using the visual reports. The people who saw the whole fireball described 3 main phases. At the beginning, the fireball was nearly point-like, resembling a distant airplane in sunlight. The object then became larger and developed a tail. In the last third of the trajectory, the fireball disrupted into a number of fragments that disappeared successively. The fragmentation was, of course, more conspicuous from close sites where the terminal part was described as resembling fireworks. The fireball left a white train which, however, was visible only for a short time (seconds to tens of seconds).

Since we soon learned that video records of the fireball existed, we did not pursue collection/analysis of visual data. However, plotting the geographical distribution of the sightings is interesting (Fig. 1). The reporting of the fireball in the media, as well as the data collection, was quite uniform in the Czech Republic. The skies were clear over most of central Europe, except for some scattered cumulus clouds in the mountainous regions (Fig. 2). So, the received distribution of sightings across the Czech Republic reflects accurately the probability of seeing the fireball. The sightings are distributed nearly equally except for the western and southwestern part of the country, where they are less numerous. Here, the fireball was less than 5 degrees above the ideal horizon. It was still bright enough to be easily visible as some reports confirm, but it was hidden behind the terrain objects for most people. The situation progressively worsened further away due to the earth's curvature. The most distant observations from the Czech Republic and Poland are from about 400 km.

The coverage with respect to Poland is less uniform since most data we have at our disposal were collected at Wrocław Observatory. This is the reason for the excess of sightings in this city. However, other parts of Poland are covered as well, and a remarkable lack of sightings exists in central southern Poland, close to the fireball trajectory. We believe that the reason is that the fireball was high in the sky and close to the sun here and could, therefore, be missed easily. The sun was at an elevation of 54° and azimuth of 29° (SSW). The fireball was also seen in Slovakia and probably in parts of Austria and Hungary as well, but we received no reports from the last 2 countries.

Sounds Associated with the Fireball

Two types of sounds are commonly reported in connection with bright fireballs. Electrophonic sounds are hissing sounds heard simultaneously with the fireball. They are explained as being caused by a very low frequency radio emission generated by plasma turbulence in the fireball wake and transformed to audible form by a suitable object located close to the observer (Keay 1992). Normal sonic booms are heard more than 1 min after the fireball and are generated by the hypersonic flight of the meteoroid in the atmosphere and, in some cases, also by meteoroid fragmentation. Both types of sounds were reported for the Morávka fireball. Their geographic distribution is shown in Fig. 3.

Electrophonic sounds were infrequent. In fact, many people were surprised by the silence of such a conspicuous event. We register 14 reports of electrophonic sounds scattered up to 250 km from the fireball. This means that about 2.5% of witnesses heard electrophonic sounds, which is less than the average value of 5% found by Keay and Ceplecha (1994) for nighttime fireballs. The observation of

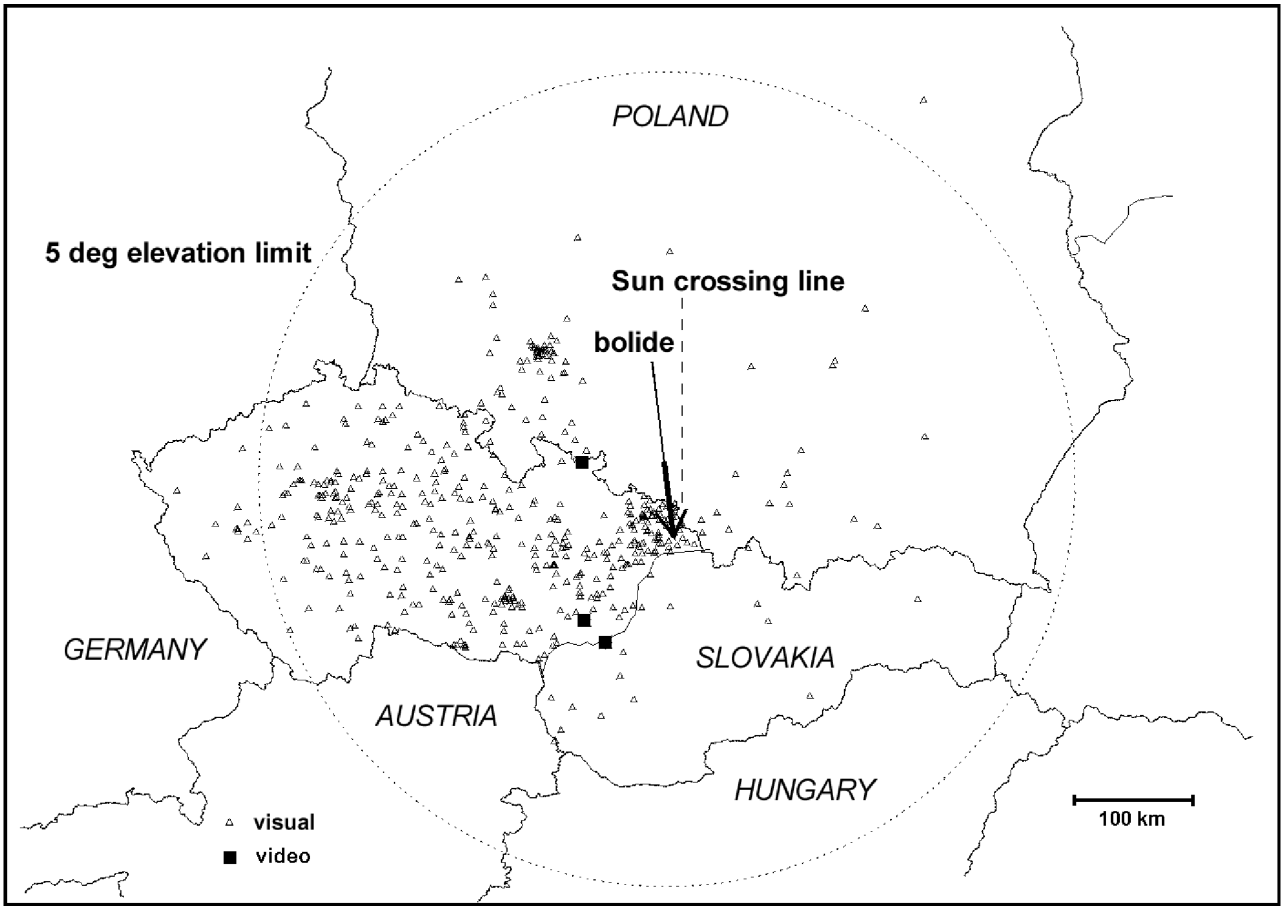

Fig. 1. Geographical distribution of the received reports of fireball sightings. The locations where videorecords were taken are also shown. The arrow represents the ground projection of the fireball trajectory; the thick part is the section covered by videorecords. The sun crossing line designates the locations where the fireball crossed the sun when observed from the ground. The big circle designates points where the fireball's brightest part was visible 5° above ideal horizon.

the Morávka fireball in a noisier environment during the daytime can easily explain this difference. The maximal range of 250 km somewhat expands the maximum value of 200 km for electrophonic sounds found by Keay and Ceplecha (1994).

Sonic booms were heard up to about 100 km from the fireball. They were very strong in the area of about 50 km around the terminal part of the fireball, where they were heard by almost everybody. The sounds were described as prolonged thunder, as airplane booms, or as distant cannonade and were followed by several minutes of rumble. The arrival time of the booms at the locations close to the ground projection of the fireball trajectory was mostly reported to be 1–2 min after the fireball passage. However, several seemingly reliable reports were received claiming the arrival times to be only 3–20 sec, which would require supersonic propagation of the booms. These reports resemble the testimonies obtained on the 1996 Honduran fireball (Borovička et al. 1999). Nevertheless, seismic waves, which represent transformed sonic booms, were recorded 60 sec and more after the fireball, and nothing was registered earlier. We, therefore, consider the reported early booms as doubtful.

Instrumental Data

The Morávka fireball and meteorite fall is significant by virtue of the existence of a variety of instrumental data that enabled us to study the event in considerable detail. The daytime nature of the fall prevented the photographic cameras of the European Fireball Network to capture the fireball (see Spurný [1997] for the characteristics of the Network and associated data). Fortunately, 3 casual witnesses were alert enough to capture part of the fireball trajectory with video cameras. In all cases, the cameras were not running when the fireball appeared but were in stand-by mode, and the operators started recording after they saw the fireball. Jiri Fabig was trying his new camera by taking pictures of butterflies in the garden of his weekend house in Janov. He captured the middle part of the fireball trajectory before the fireball disappeared behind the roof of his house. Josef Mišák was filming a small airplane in which his wife was flying with a highly zoomed camera on the Kunovice airport. He was able to take the final part of the fireball. Numerous fragments are seen on his pictures. Jiri Gurnák was descending from Velká

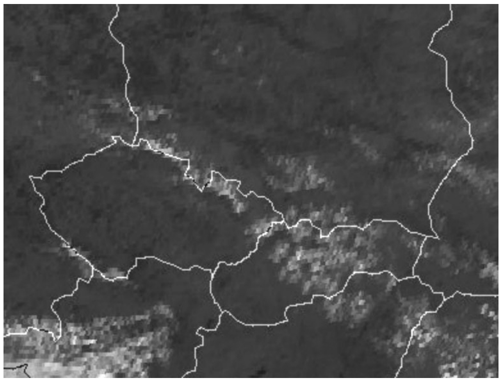

Fig. 2. METEOSAT weather satellite image of central Europe taken in visual passband on May 6, 2000, 12 UT. Image courtesy of Czech Hydrometeorological Institute and Eumetsat.

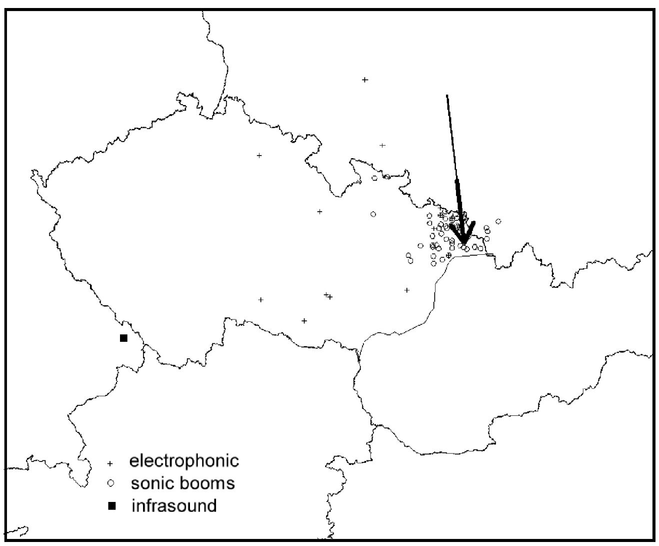

Fig. 3. Geographical distribution of the received reports of fireball electrophonic sounds and sonic booms. The location of the infrasonic array in Freyung is also shown.

Javorina mountain and captured wide field pictures of the final part of the trajectory after his attention was drawn to the fireball by other people. We obtained the copies of the video records from the videographers and digitized them. We also interviewed the videographers at the places where the pictures were taken, determined the exact position of the cameramen, and performed measurements of the terrestrial objects for image calibration. The procedures are described in more detail below.

The northeastern edge of the Czech Republic and the neighboring Polish territories contain numerous deep coalmines. For this reason, a dense network of seismic stations is located there. The fireball crossed the middle of this area in the second half of its trajectory. Seismic waves induced by the fireball generated sonic booms that were recorded on 10 seismic stations operated by DPB Paskov, 9 of them lying within 7 km of the ground projection of the fireball trajectory! This includes 3 stations located in considerable depth under the surface, 350 to 717 m. Seismic signals were also recorded at 4 stations operated by the Masaryk University in Brno and 2 seismic stations operated by the Polish Academy of Science. Other seismic networks in Poland probably recorded the fireball as well, but we contacted the operators too late, and the data were already deleted.

Infrasonic signals associated with the fireball were captured in Freyung, Germany by station IS26 of the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty (CTBT) at a distance of 360 km from the fireball endpoint.

Finally, the fireball was also detected by 2 satellite systems in Earth orbit, namely infrared sensors aboard satellites operated by the US Department of Defense and visible sensors operated by the US Department of Energy (Tagliaferri et al. 1994). The visible sensors provided a light curve of the brightest part of the fireball and measured the total radiated energy.

Meteorite Recoveries

A party with 12 people was held in the garden of a weekend house near the village of Morávka, Northern Moravia, Czech Republic on May 6, 2000. As tall trees cover most of the garden and its surroundings, the people did not see the fireball, however, they heard a thunder-like sound for about 5 sec shortly before 2 p.m. Another 5 sec later, a whistling noise was heard. A small meteorite hit a spruce tree, broke one thin branch, and landed only a meter from 2 girls standing below the tree, forming a pit 4 cm deep in relatively hard soil. The meteorite was collected immediately, reportedly being slightly warm. The recovery was reported to the Observatory and Planetarium of the Technical University in Ostrava by the house owner, J. Manoušek. After some negotiation, the meteorite was kindly lent for scientific research and was taken to the Astronomical Institute of the Academy of Sciences in Ondrejov on May 10. The mass of the meteorite was 214.2 g. The surface of the 6.5 × 4 × 4 cm meteorite was 90% covered by a dark brown fusion crust up to 1 mm thick. The original mass possibly was somewhat larger, and a small part of it was separated and kept by the finder.

The meteorite fall was described in national and local media. People were also informed by posters displayed in all settlements in the suspected fall area. On May 25, the recovery of the second meteorite was reported to the Ostrava Observatory by J. Vlcek. The meteorite was found on May 13 in the middle of a grass road near another weekend house in Morávka. The site lies 3 km north of the site of the first meteorite. The meteorite fall was actually heard on May 6, but a brief search was not successful; a more careful search one week later yielded a flat 8 × 6.5 × 3 cm, 329.5 g meteorite. One side of the stone was rather pointed, and the meteorite was partly buried in the soft soil on this side to the depth of about 3 cm. The fusion crust covers only two thirds of the surface.

The third meteorite was reported on June 23. It was recovered by M. Vihnár at the end of May during the grass harvest in the village of Horní Tošanovice, 11 km north of the first meteorite. This is a small meteorite, 4.5 × 3.5 × 2.5 cm in size and 90.6 g in mass, with 70% crust cover. All 3 meteorites were purchased by the Astronomical Institute in September 2000. According to the agreement reached with the finders, the meteorites have been exhibited in the National Museum in Prague since March 2003. The photograph of the meteorites is in Fig. 4.

Additional inspection of the fall area, including interviewing many local people, was performed by Kalenda in May and June 2001. This activity yielded the discovery of the fourth meteorite, which was found by a local family on a dusty road near the Morávka village on May 13, 2000 but was not reported. The meteorite is 5 × 4 × 4 cm in size, has a mass of 235.1 g, and is 80% covered by fusion crust. The meteorite was purchased by Kalenda.

In August 2002, we learned that another meteorite was recovered by an anonymous finder during a dedicated 5-day search performed in the summer of 2001. The 229 g specimen was found in woods only 200 m from the site of the first meteorite and was confirmed to be a true Morávka specimen by the University of Cologne (Heinlein D. 2002, private communication). One side of the flat 7.5 × 5.5 × 2 cm stone was without fusion crust. Under suspicion that the meteorite broke after hitting a tree, a careful search for a second fragment was performed in the vicinity without success.

In April 2003, following the coverage of Morávka in the media connected with the exhibition of the first 3 meteorites in Prague, we were contacted by a family who had kept a meteorite at home silently for almost 3 years. We visited them and confirmed that they really had a fragment of Morávka. The 300.8 g meteorite was found only 6 days after the fall. It was plainly visible in fresh soil within a small potato field only 70 m from the site of meteorite #4. As with all previous cases, this meteorite was only partly covered by fusion crust (about 60%).

The coordinates of the impact points of the 6 meteorites as measured by a GPS device in the WGS84 coordinate system are given in Table 1. The positions are also shown on the map in Fig. 5. The area is generally very unfavorable for meteorite searches. Except for the northernmost part, where the smallest meteorite was found and which is flat and mostly cultivated, the majority of the region is mountainous and heavily forested. The altitudes range from 350 to 1200 m above sea level. Morávka is the only larger village in the southern area, where larger meteorites can be expected. Other small settlements, individual houses, and cottages are scattered in the mountains, but most of the region is rarely visited. The fact that 5 meteorites were found quite close to houses indicates that the total number of fallen fragments is large. Four additional reports were obtained of the characteristic whistling sound accompanying the meteorite fall. The searches in the vicinity of these sites (also indicated in Fig. 5), however, did not yield any finds. One of the sites lies close to the first meteorite and, the sound may belong to the recovered meteorite.

Fig. 4. Photograph of 3 Morávka meteorites of masses of 214 g (left), 330 g (right), and 91 g (bottom).

Table 1. Coordinates of the recovered meteorites from the Morávka fall.

#	Date of recovery	Mass [g]	Longitude East	Latitude North	Altitude [m]
1	May 6, 2000	214.2	18°32′26.6″	49°35′02.8″	561
2	May 13, 2000	329.5	18°32′00.4″	49°36′40.5″	642
3	end of May 2000	90.6	18°30′14.9″	49°40′39.8″	385
4	May 13, 2000	235.1	18°32′17.4″	49°35′25.9″	538
5	July 31, 2001	229.1	18°32′16.6″	49°35′00.8″	545
6	May 12, 2000	300.8	18°32′18.6″	49°35′28.2″	544

Meteorite Analyses

The meteorite was classified as ordinary chondrite H5–6 by the Faculty of Science of Charles University, Prague (Borovička et al. 2000, 2003). Cosmogenic radionuclides in the first 2 specimens were measured in the Laboratori Nazionali del Gran Sasso, Italy. The measurements of the first meteorite started on May 15, 2000 and activities of 12 cosmogenic and 3 primordial radionuclides were obtained (Neder et al. 2001). Chemical composition was measured by instrumental and radiochemical neutron activation analyses and instrumental photon activation analysis in the Nuclear Physics Institute, Rez near Prague (Randa et al. 2003; Borovička et al. 2003). Other INAA measurements were done in the Institute of Inorganic Chemistry in Prague. Noble gases were measured in the Max-Plank-Institut für Chemie in Mainz, Germany (Borovička et al. 2003). Accelerator mass spectrometry of several isotopes was done at the University of Cologne, Germany (to be published). Mineral analyses, reflectance spectroscopy, studies of the fusion crust, and studies of the meteorite structure were performed at the

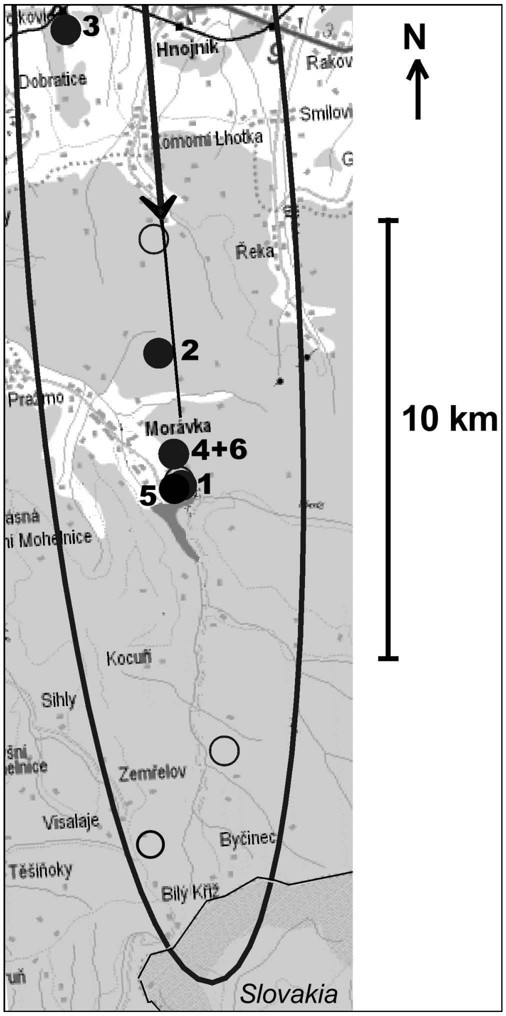

Fig. 5. Positions of the recovered meteorites (full circles) and the sites where the characteristic sound of a falling meteorite was heard but no meteorite was found (empty circles). The arrow represents the ground projection of the fireball luminous trajectory as seen on video. The thinner line represents possible continuation of the luminous trajectory as indicated by eyewitness reports from close sites. The semi-elliptical curve marks the meteorite fall area as estimated from fireball trajectory and dark flight computation. The gray areas in the background map are forests. The dark gray streak to the south of the Morávka village is a freshwater reservoir.

Faculty of Science, Prague and are reported in part in Borovička et al. (2003).

FIREBALL TRAJECTORY

The 3 video records were the primary sources for determining the fireball atmospheric trajectory. After a careful and laborious calibration (described below), each video frame provided celestial coordinates (azimuth and zenith distance) of the fireball as seen from the spot at the given instant. The video records also provide relative timing. All videos were taken in the PAL system; the individual frames are, therefore, separated by 0.04 sec. We were able to use half-frames (consisting of even or odd rows) for 2 videos, improving the time resolution to 0.02 sec. The timing enables us to determine fireball velocity and deceleration, which is necessary for computing heliocentric orbit and for other studies.

We will first describe the video records and their calibration in more detail. Table 2 contains the coordinates of the sites, the fields of view of the cameras during filming, the time spans between the first and the last frame, the total number of individual calibrated positions extracted from the record, the video formats, and the authors' names.

Video Janov

Four frames of the Janov video record are shown in Fig. 6. The fireball appears as a nearly circular object with rays due to saturation of the camera and with a long tail. The movie shows the fireball flying over a roof, shortly being hidden behind the chimney, and finally disappearing behind the roof. The position of the center of the circular head was measured on each half-frame. Seven positions were obtained before the chimney crossing and 18 positions after that. The time interval between the first and the last measurement is 0.74 sec. The chimney gap represents 0.24 sec. Another 0.24 sec passed when the tail was still visible after the head disappeared behind the roof.

To obtain absolute coordinates of the measured positions, we took calibration nighttime photographs showing the roof and stars at precisely known times (Fig. 7). The roof, however, was located only about 8 m from the observer. For reliable calibration, the position of the video camera at the time of the fireball had to be known with cm precision. This, of course, was not the case in the horizontal direction (the vertical position was well constrained by the height of the observer). To solve the problem, calibration pictures were taken from 6 locations in a 60 × 40 cm grid. Using the coordinate system defined by the stars, azimuths and elevations of about 50 reference points on the roof and the chimney were measured on each picture. Three-dimensional coordinates of the reference points in the space were computed from these data. A consistent solution was found for 27 reference points. The actual position of the video camera was found by comparing the overlap of the chimney and the roof edge (which constrained well the forth/back direction) and the overlap of the 2 roofs on the right (which constrained the left/right direction) of the video and on the calibration photographs. Then, the azimuths and elevations of the reference points as seen from the camera position were computed.

Each half-frame of the video record was calibrated separately using the reference points seen on it. A simplified gnomonic projection was assumed for the video pictures. The center of the projection was set in the center of the frame and 4 free parameters were searched for by the least-squares method: the azimuth and elevation of the center of vision, the angle between the vertical direction and the y-axis, and the

Table 2. Basic data on the video records.

Site	Longitude	Latitude	Altitude [m]	Field of view	Record length	No. of positions	Format	Author
Janov	17.47553	50.24275	422	8 × 11°	1 sec	25	Hi-8	J. Fabig
Kunovice	17.43967	49.03219	175	1.6 × 2.1°	3.1 sec	43	Hi-8	J. Mišák
Javorina	17.67950	48.85789	952	35 × 45°	0.8 sec	20	VHS	J. Gurnák

Fig. 6. Four individual half-frames from the Janov video record. The video was deinterlaced by replacing the odd rows by the even ones or vice versa.

camera focal length in pixels. Finally, a small correction for the movement of the camera during fireball filming proved to be necessary. This was estimated as 0.01 degree coordinate correction per degree of the change of the center of vision in each direction.

Video Kunovice

The Kunovice video was taken with the maximal optical zoom of the camera. This technique has some advantages and some disadvantages. The record covers the late phase of the fireball flight, when the object was clearly separated into a large number of fragments. The high zoom enables us to see the fragments in considerable detail. However, most of the frames are blurred due to the shaking of the hand held camera and combined with the fireball proper motion. Four frames from the video are shown in Fig. 8. The blurred images, nevertheless, proved to be usable. By measuring the edges of the bars, we extracted positional information with only slightly degraded precision.

Another problem of the high zoom is the lack of terrestrial reference objects on the video. Fortunately, this problem could be overcome. The swarm of the fragments passed behind a cloud, and the largest fragment disappeared just before reaching another cloud. The cameraman by chance took an overview picture 30 sec after the fireball's passage (Fig. 9). The clouds could be identified on this picture and they were used as intermediate reference objects. We assumed that the ≈10 km distant clouds did not move significantly during the 30 sec. Common features on the cloud shapes were

Fig. 7. One of the calibration pictures for the Janov video containing stars from constellations of Aql, Her, Lyr, and Cyg.

found on both the overview picture and the fireball pictures, though the quite different scale posed problems. The positions of the landmarks seen on the overview picture were measured by a theodolite and by GPS and were used to calibrate the overview picture and to determine the positions of the cloud features. Stellar calibration was not necessary here because all ground objects were far enough from the observer. The positions of the cloud features were further improved by constructing a composite image of both respective clouds from the fireball frames and applying the least squares method to the positions.

The fireball measuring was done frame by frame. Only the frames where parts of the clouds were in the field of view could be used. Since the number of reference points was generally low, only 3 parameters were computed. The focal length derived from the composite images was kept constant. The positions of the main fireball fragment were measured. Fourteen positions were obtained before the cloud crossing, 15 positions after the cloud crossing, and 14 positions when approaching the second cloud. The time interval between the first and the last measurement was 3.02 sec; the gap when the fireball was hidden behind the first cloud was 0.16 sec, while the second gap due to no reference points between the clouds was 1.92 sec. After the calibration was done and the trajectory determined, the positions of individual fragments relative to the main fragment were measured on each available frame.

Video Javorina

The Javorina video was taken with a wide-field adjusted camera. Its record covers the final part of the fireball. The fireball is seen as a mere point (Fig. 10), partly hidden behind a ski lift wire on some frames. In contrast to the previous videos, the positions measured on individual half-frames were not taken individually, but a mean was computed to obtain one position per frame and reduce the scatter of the points. In total, 20 positions covering an 0.8 sec interval were obtained. The calibration was done using distant terrestrial objects seen on the video and was measured by a theodolite. The clouds were used as secondary reference objects to ensure frame-to-frame consistency. The wires were useless.

The Trajectory

The fireball positions extracted from videos were corrected for standard astronomical refraction before use. The correction amounted maximally 0.08° at the end of the Kunovice and Javorina videos. The fireball trajectory was assumed to be straight. This assumption is justified because any curvature caused by Earth's gravity during the 5 sec flight over the distance of the 70 km covered by the videos is indistinguishable from a straight line within the precision of the data. Therefore, the straight least squares method (Borovička 1990) was used to determine the trajectory. Two videos from different sites, even if they do not cover the same segment of the trajectory, would be sufficient for this task. With 3 videos, the results are likely to be more accurate.

The 3 videos gave quite consistent results. This is demonstrated in Fig. 11, where the deviations of the individual lines of sights from the computed trajectory are plotted. These maximal deviations are 40 m, 110 m, and 210 m for Janov, Kunovice, and Javorina, respectively. The deviations correspond to the scatter of the data; no significant systematic trends exist. This confirms that no large errors exist in the video calibration.

The radiant of the trajectory lies at astronomical azimuth 175.5° ± 0.4° and elevation 20.4° ± 0.2°. The fireball flew almost from the north to the south with a slope of 20.4° to the horizontal, valid at the end of the trajectory (the slope slightly changes due to the earth's curvature). See Fig. 1 for the map. Geographical coordinates and heights (above sea level) of some points along the trajectory, namely the beginnings and ends of the video records, are given in Table 3. The relative length along the trajectory, the distance from the video station to the fireball, and the observed astronomical azimuth and elevation are also given. Note that these last values do not represent exact directions to the fireball but the measured values influenced by the measurement errors and are uncorrected for refraction.

The precision of the trajectory determination is about 300 m in the east-west direction and about 100 m in height. The standard deviations for the first and the last video point are given in Table 3. We quote standard deviations 3 times larger than the formal results from the mathematical method, a technique chosen because the formal errors reflect only the scatter of the points and do not account for possible small systematic errors of video calibrations. Note that the trajectory was also independently determined from the seismic data. The seismic trajectory is given and compared with the video trajectory in Borovička and Kalenda (2003).

As video records do not cover the whole fireball trajectory, we used reliable visual observations of

Table 3. Fireball atmospheric trajectory as determined from video records.

Point	Longitude °	Latitude °	Height (km)	Length (km)	Range (km)	Observed azimuth	Observed elevation
Visual beginning	18.36	51.00	80	–94	–	–	–
Janov first image	18.463	50.219	45.7	0.0	84	271.78	32.31
	±0.003	±0.001	±0.1	–	–	–	–
Janov last	18.480	50.086	40.0	16.0	84	283.27	27.82
Kunovice first	18.507	49.865	30.6	42.5	125	219.46	13.58
Javorina first	18.523	49.732	25.0	58.4	118	211.93	11.34
Javorina last	18.530	49.677	22.7	64.9	112	213.89	10.83
Kunovice last	18.534	49.641	21.2	69.3	107	229.24	11.02
	±0.004	±0.001	±0.1	–	–	–	–
Visual end	18.539	49.60	19.5	74	–	–	–

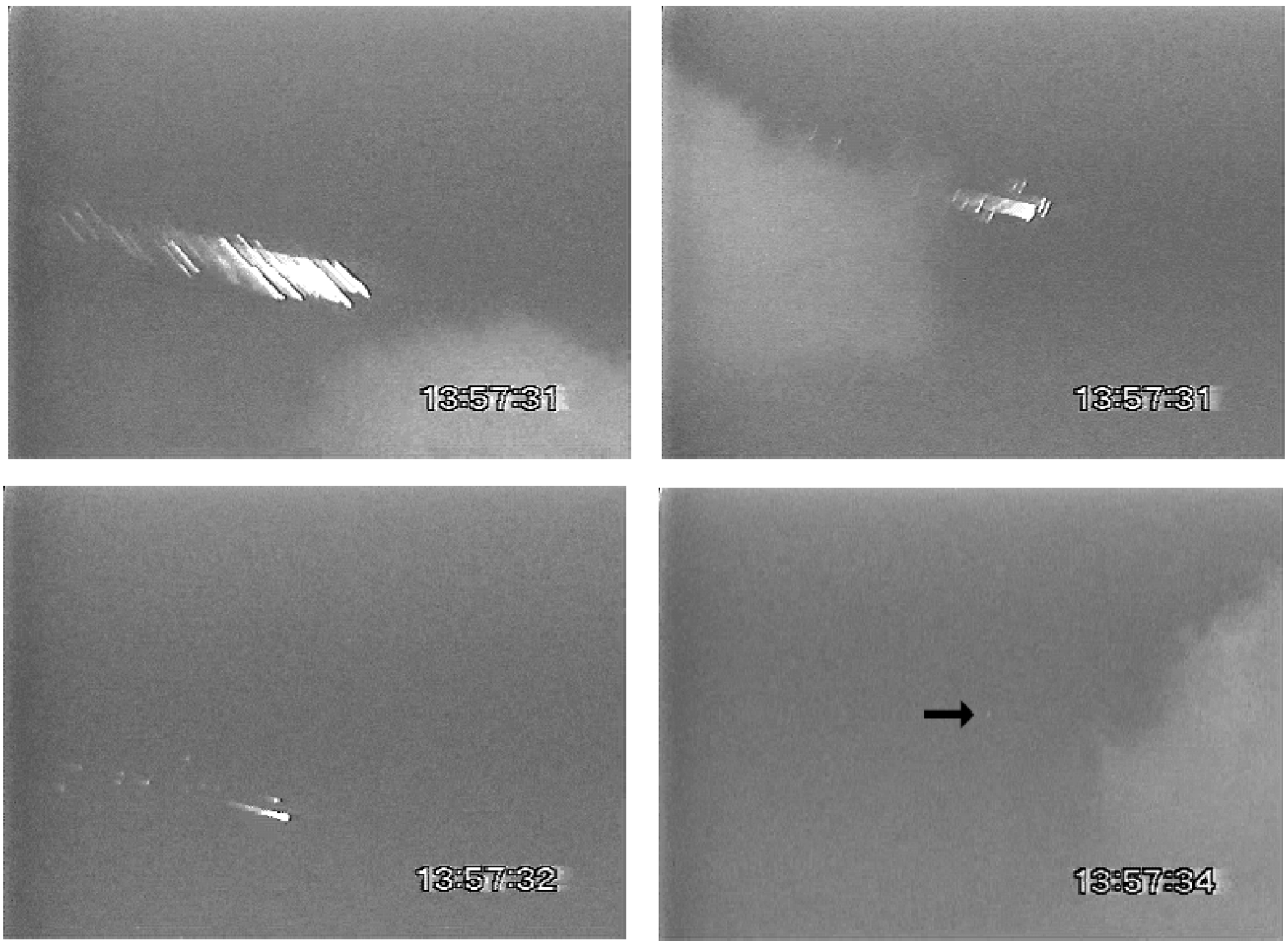

Fig. 8. Four representative individual half-frames from the Kunovice video record. The upper pictures are blurred due to camera shaking. Contrast was enhanced here relative to the original. See Borovička and Kalenda (2003) for additional frames from this video. The time of the camera was not set correctly.

interviewed people to estimate the beginning and the end of the luminous trajectory, i.e., the points on the extrapolated video trajectory where the fireball started and ceased to be visible. Approximate coordinates of these points are given in Table 3. Visual observers seem to have first noticed the fireball at the altitude of about 80 km, much earlier than the videos start. The Kunovice video, on the other hand, shows the fireball almost to the end, to the height of 21.2 km. Only people in the immediate vicinity of the trajectory saw the fireball continue further south, probably reaching a height just below 20 km. This height is quite typical for a meteorite-dropping fireball.

Fig. 9. An overview picture (average of several video frames) taken from the Kunovice video site 30 seconds after the fireball passage. The arrows show the two possible fireball paths between the clouds. A closer inspection revealed that the upper path is correct.

Fig. 10. The first half-frame from the Javorina video record.

Figure 11 and Table 3 also show gaps in video data coverage. Most importantly, 26 km of fireball length is not covered between the end of the Janov video and the beginning of the Kunovice video. Evidently, the main fragmentation occurred within this interval, which spans the heights between 40.0 and 30.6 km.

INITIAL VELOCITY, TIME, AND ORBIT

To compute the heliocentric orbit of the meteoroid before the Earth encounter, we need to know the fireball pre-atmospheric velocity. The Janov video provides good velocity information, but it starts at a relatively low height of 45.7 km. By fitting the Janov data, we determined the velocity at this height to be 21.9 ± 0.1 km/s. Simple computation suggests that a meteoroid of Morávka size should not be decelerated more than by 0.4 km/s at this height. However, the deceleration observed on the Janov video is larger than that which would follow from this model. This fact led to the conclusion of meteoroid early fragmentation as is discussed in Borovička and Kalenda (2003). Strictly speaking, we do not know exactly what happened above 45 km. Nevertheless, all realistic possibilities lead to the initial velocity of 22.5 ± 0.3 km/s. This velocity change down to 45 km is also consistent with the behavior of well-observed fireballs of similar brightness and velocity, namely Pribram (Ceplecha 1961) and Benešov (Borovička et al. 1998).

Though not so critical for orbit calculation, the exact time of fireball passage is also important. In particular, the correlation of data from different instruments depends on the knowledge of time. Unfortunately, visual data provide precision only to within a minute. The best information comes from the DoD satellites, which registered the maximum light at 11:51:52.545 UT. However, at which part of the trajectory the maximum light was reached is unclear. Of the 3 video records, only Kunovice had the time inserted, and this time stamp was wrong by more than 5 min. By measuring the camera time difference several times in the following days and weeks, we found that the Kunovice record began at 11:51:53 UT ± 0.5 sec. This is in perfect agreement with satellite data and suggests that the maximum brightness occurred at the height of 33 ± 4 km. The fireball began to be visible about 6 sec earlier.

The heliocentric orbit was computed by the standard procedure described in Ceplecha (1987). Table 4 gives the apparent and geocentric radiant. The orbital elements are given in Table 5. The orbit is plotted in Fig. 12 together with the orbits of other meteorites. Morávka encountered the earth in the descending node on the way to perihelion, which was to be reached 19.5 ± 1 days after the collision. Though the impact occurred on the day side of the earth, the meteoroid did not come from the direction of the sun—the geocentric radiant lies 105° from the sun.

In Table 6, we provide the orbital elements of other meteorites with well or relatively well-known orbits for comparison with Morávka. Note that the recently recovered Neuschwanstein EL6 chondrite fallen on April 6, 2002 in Germany and having a photographically determined orbit almost identical to the orbit of the Pribram meteorite (see Spurný et al. 2002, 2003) is not included. The most unusual element of the Morávka orbit is the inclination of 32°, by far the highest value among the 6 meteorite orbits. However, this is not so exceptional because about 10% of known Apollo asteroids have inclinations larger than Morávka. Other elements of Morávka are quite normal. The aphelion lies in the asteroid belt, and the perihelion is just below 1 AU. This is typical for meteorite-producing fireballs because objects on such orbits have the highest probability of collision with the earth (Wetherill and ReVelle 1981). The different local time of the fall of Morávka did not mean substantially different orbit in comparison with other meteorites.

Table 4. Radiant and initial velocity of Morávka (J2000.0).

	Apparent	Geocentric	Heliocentric
Azimuth	175.5° ± 0.4°	–	–
Elevation	20.4° ± 0.2°	–	–
Right ascension	249.75° ± 0.8°	250.1° ± 0.7°	–
Declination	60.58° ± 0.16°	54.96° ± 0.24°	–
Velocity [km/s]	22.5 ± 0.3 km/s	19.6 ± 0.4 km/s	35.75 ± 0.3 km/s
Ecliptical longitude	–	–	145.0° ± 0.3°
Ecliptical latitude	–	–	31.9° ± 0.5°

Table 5. Heliocentric orbit of Morávka (J2000.0).

Semimajor axis	*a*	1.85 ± 0.07 AU
Eccentricity	*e*	0.47 ± 0.02
Perihelion distance	*q*	0.9823 ± 0.0009 AU
Aphelion distance	*Q*	2.71 ± 0.13 AU
Argument of perihelion	*ω*	203.5° ± 0.6°
Longitude of ascending node	*Ω*	46.2580°
Inclination	*i*	32.2° ± 0.5°
Orbital period	*P*	2.51 ± 0.14 years
Last perihelion passage	*T*	Nov 21, 1997 ± 49 days

Table 6. Known orbits of meteorites. The date (UT) and local time of the fall and the classification are also given for each meteorite.

	Morávka 2000–05–06 1 p.m. H5–6 (J2000.0)	Pribram 1959–04–07 8 p.m. H5 (1950.0)	Lost City 1970–01–04 8 p.m. H5 (1950.0)	Innisfree 1977–02–06 7 p.m. LL5–6 (1950.0)	Peekskill 1992–10–09 7 p.m. H6 (J2000.0)	Tagish Lake 2000–01–18 8 a.m. C (J2000.0)
a	1.85	2.401	1.66	1.872	1.49	2.1
e	0.47	0.6712	0.417	0.4732	0.41	0.57
q	0.9823	0.7894	0.967	0.986	0.886	0.891
Q	2.71	4.012	2.35	2.758	2.10	3.3
ω	203.5	241.75	161.0	177.97	308.	222.
Ω	46.258	17.110	283.0	316.80	17.030	297.900
i	32.2	10.481	12.0	12.27	4.9	1.4
Ref.	This paper	Ceplecha (1977)	McCrosky et al. (1971)	Halliday et al. (1978)	Brown et al. (1994)	Brown et al. (2000)

FIREBALL LIGHT CURVE

The visible sensors onboard the DoE military satellites are the only source of data on the fireball radiation. The attempt to perform photometry on video records was unsuccessful because the 2 main videos have the fireball image saturated and have different scale. The satellite detector was able to detect only the brightest part of the fireball. The instruments are described in Tagliaferri et al. (1994). The light curve is rather noisy and is displayed in Fig. 13. The fireball exhibited a double or triple maximum of duration of 0.1 sec and about threefold signal increase. In other words, a flare of amplitude of about 1 magnitude exists. The clear signal begins 0.4 sec before the maximum, although an indication of signal level increase exists starting 1.0 sec before the maximum. Similarly, the clear signal continues for 0.3 sec after the maximum with a possible extent up to 1.0 sec. The background zero level is somewhat less after the fireball than before it.

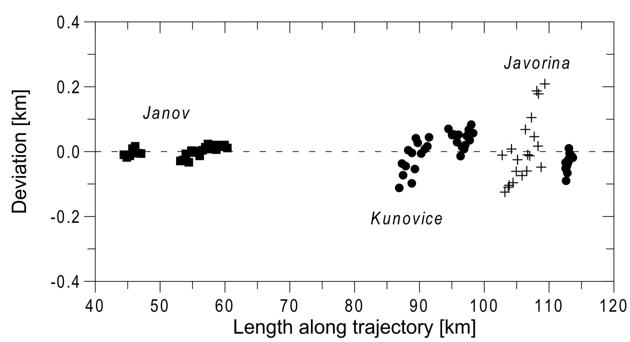

Fig. 11. The deviations of individual positions measured on video records of the computed fireball trajectory.

The satellite data were calibrated, and the absolute radiative output was inferred. The peak intensity was determined to be 1.05×10^{10} W/ster (taking into account the changing background level). This value was computed to include radiation at all wavelengths using a 6000 K blackbody

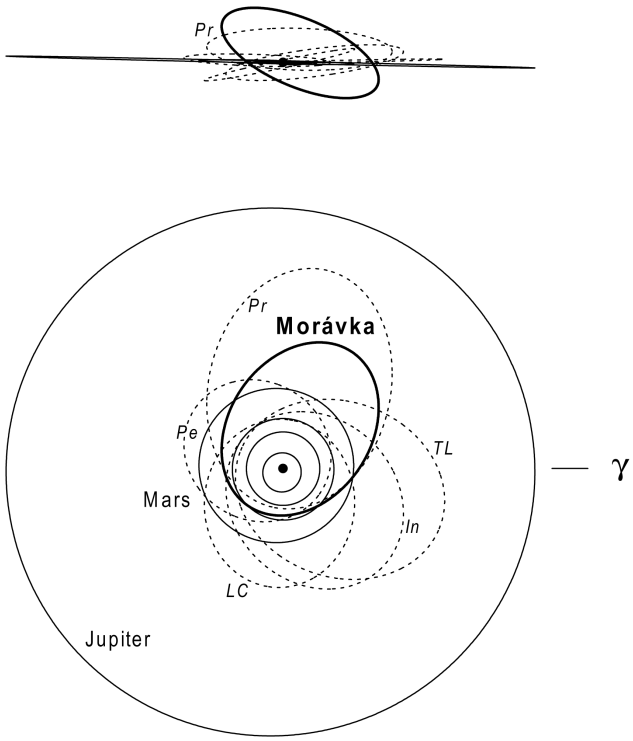

Fig. 12. Orbit of Morávka in the inner solar system. The projection into the plane of the ecliptic (lower part) and into the plane perpendicular to the ecliptic (upper part). The orbits of other meteorites are drawn as dashed lines.

model. Using the conversion factor of Ceplecha et al. (1998, page 365), the value can be expressed equivalently as −20.2 visual magnitude. This corresponds well with the rough estimate from eyewitness reports. The integrated radiated energy as measured by the satellites was 2.5×10^{10} J. We will use this value in Borovička et al. (2003) to estimate the meteoroid initial mass.

CONCLUSIONS

The Morávka meteorite fall is one of the best-documented meteorite falls in history. In this paper, we first summarized all available data and then used the 3 video records to derive the atmospheric trajectory of the fireball and the pre-atmospheric orbit. The fireball was described as a bright object dominating the sky even during broad daylight and even from sites more than 400 km distant. A total of 2.5% of fireball eyewitnesses reported electrophonic sounds. The video records, after careful calibration, enabled us to determine the fireball trajectory with the precision of 300 m. The slope of the trajectory was 20.4° ± 0.2° to the horizontal, and the fireball radiated down to the height of 21 km (or somewhat less, if visual reports are believed). The maximum brightness of −20 absolute magnitude was reached at the height of 33 ± 4 km. The knowledge of the trajectory will be used in Brown et al. (2003) for the interpretation of the infrasonic and seismic data. The video records and the knowledge of the trajectory will be exploited further in Borovička and Kalenda (2003), where the dynamics and fragmentation of the meteoroid in the atmosphere will be studied.

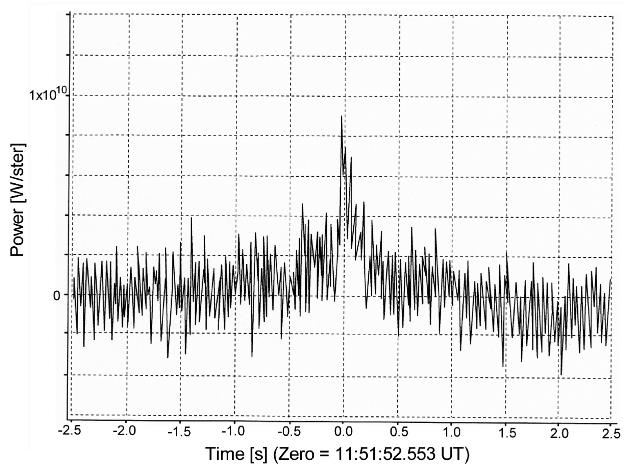

Fig.13. The visible-wavelength signal of the Morávka fireball as detected by a DoE satellite on the earth's orbit.

The initial velocity of 22.5 ± 0.3 km/s was rather high for a meteorite-dropping fireball. Nevertheless, despite this high velocity and the daytime occurrence of the fall, the heliocentric orbit was rather normal with the perihelion distance just inside of the Earth's orbit (0.9823 ± 0.0009 AU) and aphelion distance in the main belt of asteroids (2.7 ± 0.1 AU). Only the inclination of 32.2° ± 0.5° was rather high. The heliocentric orbit will be integrated backwards in Borovička et al. (2003) to study the possible history of the meteoroid in the solar system.

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