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The multiple meteorite fall of Neuschwanstein: Circumstances of the event and meteorite search campaigns

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Abstract–A large meteorite fall in southern Germany on April 6, 2002 was captured by camera stations of the European Fireball Network (EN) which routinely monitors the night sky over central Europe. From analysis of the images, a prediction on the geographic location of the meteorite strewn field could be made. Following systematic ground searches in difficult high-mountain terrain, three fragments of a rare EL6 enstatite chondrite were recovered during search campaigns in the summers of 2002 and 2003. "Neuschwanstein" is the fourth meteorite fall in history that has been photographed by fireball networks and the fragments of which have been found subsequently. It is the first time since the beginning of the EN operation in the early sixties that the photographic observations have made a meteorite recovery possible.

INTRODUCTION

The spectacular circumstances of any meteorite fall are of great interest to laymen and planetary scientists alike. Although meteorite falls worldwide occur on a regular basis, the successful observations of a fall with scientific instrumentation, such as high precision cameras, at any given place require considerable endurance and patience. While photographic observations, in general, yield valuable data on the dynamic properties of any object entering Earth's atmosphere, photographic data may be especially important when meteorite dropping events are observed and directions for a meteorite search are needed.

We report on a meteorite fall, which occurred on April 6, 2002, within an area that is routinely monitored by all-sky cameras of the European Fireball Network (EN). On the basis of the photographic data, the meteor trajectory could be fully determined, and a prediction on the geographic location of the meteorite strewn field could be made. Meteorite search campaigns resulted in the recovery of three meteoritic fragments by the time of this writing.

While aspects of this well-documented meteorite event, such as the trajectory and its unusual orbit, have been described previously (Spurný et al. 2002, 2003; Oberst et al. 2003), this paper fully describes the circumstances of the meteorite fall and the recovery efforts that followed. Two companion papers will describe results from the laboratory analysis of the meteorite (Hochleitner et al. 2004) and the results from analysis of seismic and infrasound data that were collected (ReVelle et al. 2004).

FALL CIRCUMSTANCES

Eyewitnesses

The meteoroid entered the Earth's atmosphere on April 6, 2002 at 22:20 (local time) over Innsbruck, Austria and passed over Mittenwald and Garmisch-Partenkirchen, southern Germany within approximately 5 sec (Fig. 1). The brightest flare of the fireball, which accompanied this meteorite fall, occurred at $20^h20^m17.7^s$ UTC (Spurný et al. 2002).

The event had large numbers of casual witnesses. Owing to clear sky and good observing conditions for the comet Ikeya-Zhang, a good number of amateur astronomers were outdoors and were able to give "educated" eyewitness reports. Detailed descriptions, including celestial coordinate information and estimates of the meteor's apparent brightness, came from the private observatory Meyer/Obermair at Davidschlag near Linz, Austria.

The bolide was described as showing a deep blue or greenish head and a yellow-to-orange tail. Reddish-blue pulsation was observed. From a distance of less than 100 km, the bolide appeared brighter than the full Moon and produced extreme cast shadows, "similar to the headlights of a car." Reports of a sudden bright flare suggest that the fireball broke into fragments near the end of its trajectory. Observers

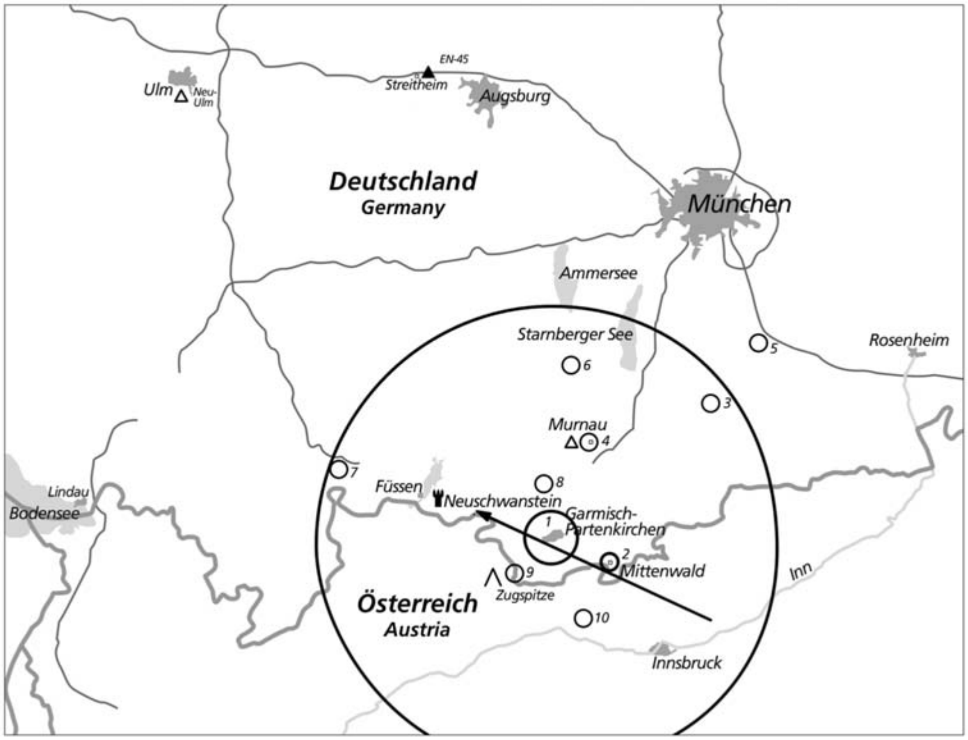


Fig. 1. Map showing the fireball trajectory, the locations of confirmed audio-witnesses (small circles), the location of the Streitheim EN station (marked by a filled triangle), as well as the location from where the Murnau and Ulm videos were obtained (marked by open triangles). The large circle has a radius of approximately 50 km and marks the general area in which sound from the meteor could be perceived. Sound from the event was described by various audio witnesses as follows (numbers refer to the small numbered circles): 1) Garmisch-Partenkirchen: "sizzling noise, windows rattling, floor shaking;" 2) Mittenwald: "house shaking; explosion like a bomb;" 3) Bad Tölz: "windows rattling; then a 'bang' like from thunder, approximately 4 min after the fireball;" 4) Murnau: "rolling thunder, approximately 2 min after the event;" 5) Holzkirchen: "bang like from a cannonball after 3 min;" 6) Weilheim: "bang and rolling thunder;" 7) Oy-Mittelberg: "noise like that from drums;" 8) Oberammergau: "long rolling thunder, approximately 2 min after the event;" 9) Zugspitze: "sharp bang, approximately 2 min after the event;" 10) Seefeld/Tirol: "bang and rolling thunder."

reported seeing "detached pieces forming a line like pearls on a string," "one main piece, followed by two others, smaller ones," "3–4 pieces," or "several pieces." R. and N. Schmidts, who were approximately 190 km north of the event were able to supply a drawing (Fig. 2). None of the observers reported afterglow or smoke.

The meteor was well-visible from the Oberpfaffenhofen facility of the German Aerospace Center. Guards who were on duty that night could give accounts of the event to TV stations the next day. The event was also visible from the flight tower of the Munich international airport (MUC). Though, as it turned out later, the event was far from Munich, the airport runway was examined for possible debris or damage. The event was also observed from the visitor platform of the Zugspitze, Germany's highest mountain. In fact, it was right above the Zugspitze that the fireball reached its maximum brightness.

The fireball was visible over wide areas of central Europe, up to distances of approximately 550 km, for example, as far away as Hannover. Reports on this spectacular meteor event were picked up by the German national news the next day.

Sound

The bolide was accompanied by a variety of acoustic effects. In the cities of Garmisch-Partenkirchen (80 km south of Munich; Fig. 1), Mittenwald, and Bad Tölz, located below the projectiles trajectory, the fireball's sonic boom left windows rattling and the ground shaking.

Audio witnesses in the surrounding areas (Fig. 1) reported hearing sharp explosions; those at larger distances from the event reported noise like that from drums or rolling thunder, often many minutes after the fireball event. There were no acoustic reports by observers from areas located toward the far south, though potential audio witnesses were available, and the event was clearly visible from there. Perhaps, propagation of sound was facilitated by the prevalent wind direction.

Video Observations

The event circumstances were fortuitously recorded by two surveillance video cameras located at Murnau, 22 km north of the fireball, and Ulm, 100 km north-northwest of the

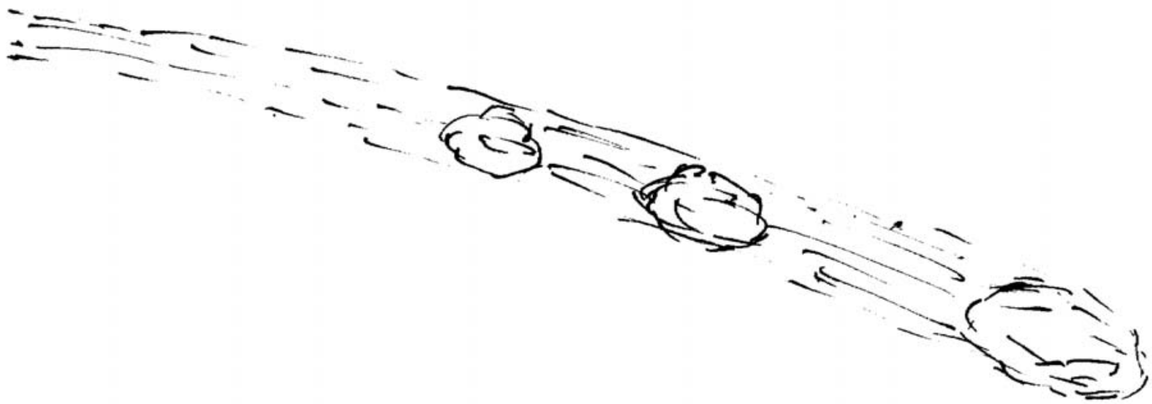


Fig. 2. Drawing by R. and N. Schmidts, who were eyewitnesses of the event, of the visual appearance of the meteoroid fragments in flight.

Fig. 3. Two still images from the Murnau video obtained during the meteor event. The automatic video camera, located 20 km north of Garmisch-Partenkirchen, was observing an animal feeding place.

event (see Fig. 1). The recordings from Murnau, where the camera had been deployed to observe an animal feeding place, show pronounced cast shadows of surrounding trees move over the ground (Fig. 3). The recordings also included surprisingly clear sound from the event: a roaring thunder, exactly 119 sec after the fireball had terminated, consistent with the distance from the event. From the observations, the apparent light curve of the meteor could be obtained, confirming the unaided eyewitness reports that the meteor ended in a powerful flash (Fig. 4).

Radiometers

More systematic observational means included high-speed sky photometers located at two EN stations in the Czech Republic. Though the photometers were at larger distances from the event, the recordings provided well-calibrated data on the absolute brightness and the timing of the event, which are important for the determination of the meteorite's heliocentric orbit and for the seismic and infrasound analyses (Spurný et al. 2002; ReVelle et al. 2004).

Infrasound and Seismic Data

CTBT (Comprehensive Test Ban Treaty) microbarograph arrays located at Freyung, Germany, near the Czech border (range: 250 km from the event), in the Netherlands, and as far away as Sweden recorded infrasound from the bolide's atmospheric entry. The recordings are in good agreement with the timing and the location of the event. In addition, seismic data from several seismic stations in Germany, Switzerland, and Austria from ranges between 24–164 km were obtained (ReVelle et al. 2004).

EUROPEAN FIREBALL NETWORK OBSERVATIONS

Network Status

Cameras of the European Fireball Network (EN), which routinely monitor the night sky over central Europe, obtained the most important among all the observational records. The history of this network goes back to the double-station small camera program, initiated at the Ondrejov Observatory in 1951.

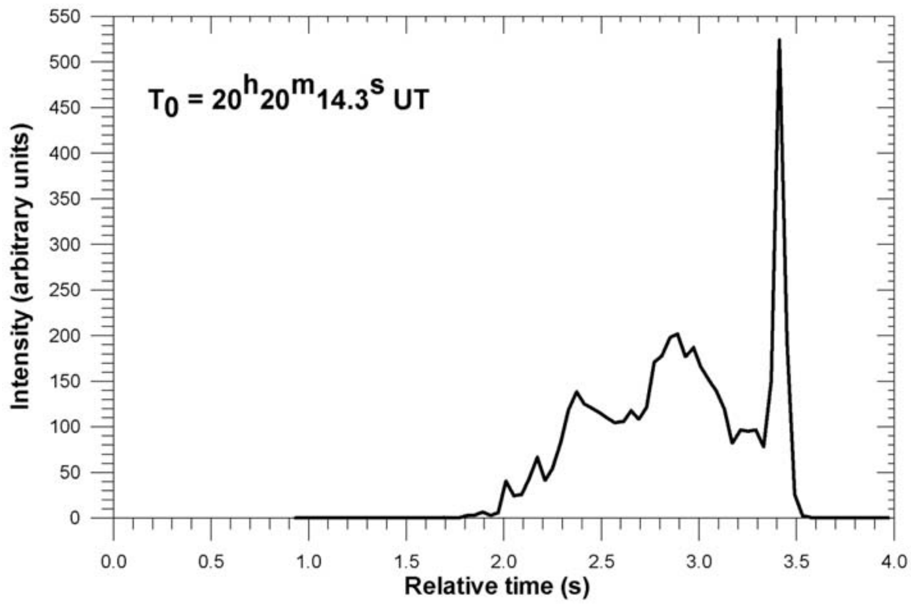


Fig. 4. Observed light curve of the meteor, digitized from the Murnau video (see Fig. 1 for location). Note the sharp peak in brightness (flare) at the end of the light curve, marking the break-up of the meteorite.

Observations of the Pribram meteorite fall on April 7, 1959 (Ceplecha 1957, 1961) motivated the beginning of regular observations in 1963 (Ceplecha and Rajchl 1965). In 1968, the network was expanded to cover wider areas of central Europe (see Oberst et al. [1997] and Spurný [1997] for recent status reports). At the time of the Neuschwanstein meteorite fall, the network comprised 10 camera stations in the Czech Republic, two in the Slovak Republic, and 16 camera stations in Germany, Austria, Belgium, and Luxemburg (see Fig. 5). The camera operation is coordinated by the Astronomical Institute of the Czech Academy of Sciences of the Czech Republic at the Ondrejov Observatory and the DLR (German Aerospace Center) Institute of Planetary Research, respectively.

The basic equipment of the DLR stations consists of Leitz cameras with images being recorded on regular black-and-white film. Coverage of the complete sky is achieved by obtaining photographs of a convex-shaped all-sky mirror. The Czech and Slovak stations are equipped with the cameras using large fish-eye lenses (Zeiss-Distagon 3.5/30 mm, diameter of image: 80 mm) and large-format film, which give much better positional accuracy. The cameras take one single image exposure per night through rotating (12.5 Hz) shutters. Thus, fast moving objects result in interrupted trails on the film from which the angular velocity of moving objects in the sky can be determined. If observations from several stations are available, a meteor's atmospheric trajectory can be reconstructed. To obtain the exact time of a fireball passage for all photographed fireballs, there are additional fish-eye cameras at the Ondrejov Observatory, Churanov station (both in the Czech Republic), and Modra Observatory (Slovakia), which are operated in a driven regime simultaneously with the fixed cameras placed at all stations of the EN.

The cameras are deployed at approximately 100 km spacing and cover a total area of about 10^6 km^2 (Fig. 5). Typically, there is one exposure of the sky each night from each of the cameras. Time information to open and close the aperture is computed individually for each camera depending on the camera location, the local time of sunrise and sunset, and lunar ephemeris. The exact exposure interval is defined by nautical twilight. For the EN combined, this procedure results in approximately 10,000 image exposures, with a total exposure time of 55,000 hours per year. However, due to weather, clear sky observations are achieved for only 3–3.5 hr per day on average.

Photographic Data

The meteor of April 6, 2002 was recorded by 10 of the EN camera stations from ranges between 100 and 480 km: 45 Streitheim (Fig. 6, top), 85 Tuifstädt, 43 Öhringen, 68 Losaurach (Fig. 6, bottom), 87 Gernsbach, 69 Magdlos, 73 Daun, 75 Benterode (all German), 11 Primda (Czech), and 74 Gahberg (Austrian) (Fig. 5). Station 45 Streitheim was located 163 km from the beginning and 100 km from the end of the trajectory and, therefore, was closest to the event (Fig. 1; Fig. 6, top). This important camera station had shown a malfunction in March 2002, but the camera body was repaired and put back into operation just a few days before the April 6 event. The recordings from 69 Magdlos, 73 Daun, and 75 Benterode, beyond a distance of 300 km from the event, were not used in the analysis.

As the event was unusually bright and very close to the horizon at all stations (because of the meteoroid's high penetration depth), image smear masked the shutter breaks

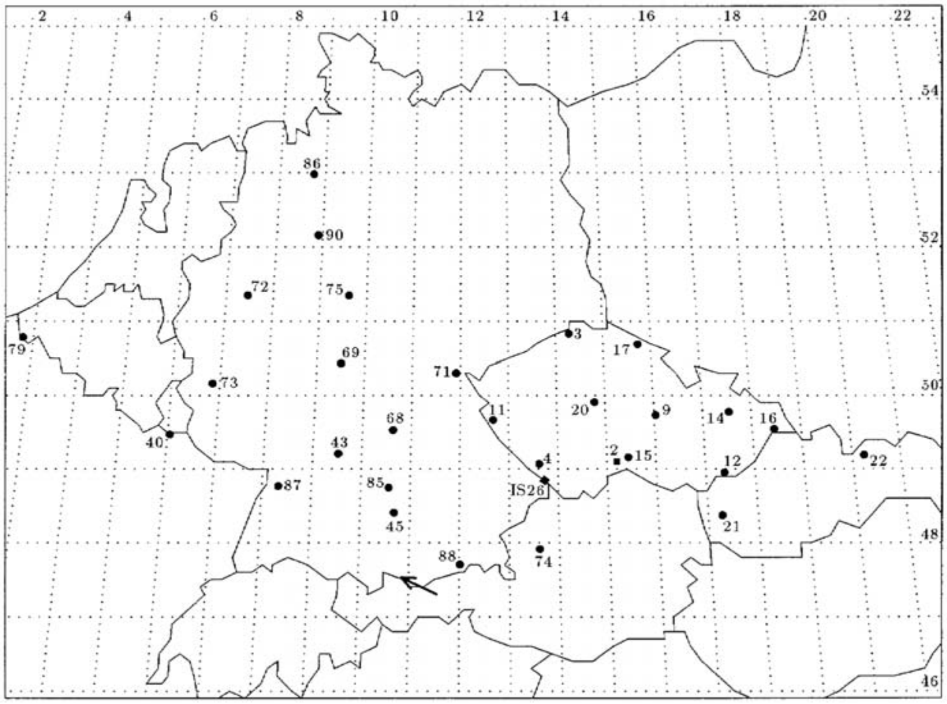


Fig. 5. Map showing all EN camera stations (circles), photometer stations (squares), and the Freyung Infrasound station (rhomb) at the time of the April 6, 2002 Neuschwanstein fireball.

(needed for velocity analysis) on most of the images. Fortunately, the fireball was also recorded by one of the Czech stations. The image from 11 Primda has a geometric resolution three times better than the images from the nine remaining stations, even though the fireball was photographed only five degrees above ideal horizon. Regrettably, we did not obtain an image from the German station 88 Wendelstein, located at high elevation with prime viewing conditions (Oberst et al. 1997), which would have given us the best data, especially from the beginning part of the luminous trajectory. Due to reconstruction of the observing platform, the camera was temporarily not operating in the spring of 2002.

Following the event, a new set of GPS measurements of all station coordinates in Germany and Austria were made, replacing the previously used coordinates taken from topographic maps. These maps were based on the different coordinate frames used in the different countries of the EN (Germany, Austria, and Czech Republic). With GPS measurements, a consistent reference frame for all observations was established (Table 1). All coordinates are in the WGS84 coordinate system.

Wind Data

The dark flight of a meteorite is significantly affected by atmospheric conditions, notably wind. Wind velocity information for different atmospheric heights were derived from weather balloon ascents, as they are carried out by the Deutscher Wetter Dienst (DWD) on a routine schedule. The DWD stations at Munich Oberschleissheim and Stuttgart were closest to the meteorite event, with balloon ascents taking place through the week of the meteorite fall at noon, 6 p.m., and midnight for both stations. In addition, there were 6 a.m. data from Munich. The wind, from north to northwest, was strongest between the altitudes of 13–4 km, with speeds between 10 m/s and 21 m/s (Fig. 7). Only data from Munich (April 6, 18:00, and April 7, 0:00) were used in the analysis.

SEARCH CAMPAIGNS

Early Meteorite Hunt

The meteorite fall received much attention in the public. In the days following the event, there were numerous reports on putative meteorite finds. A suspected "meteorite" find near Zolling (east of Munich) received broad press coverage. The finder reported to have recovered a glowing fragment right from the fireball landing in the backyard of his house. However, the rock sample soon turned out to be of terrestrial origin: in this particular case, it was a piece of bitumen from the roadside. We have many similar reports, in which interpretations of the visual impressions, such as estimates of the meteor distance, were completely in error.

Predictions of the Impact Locations

While exposed films from the camera stations are normally returned once a month during regular EN operation,

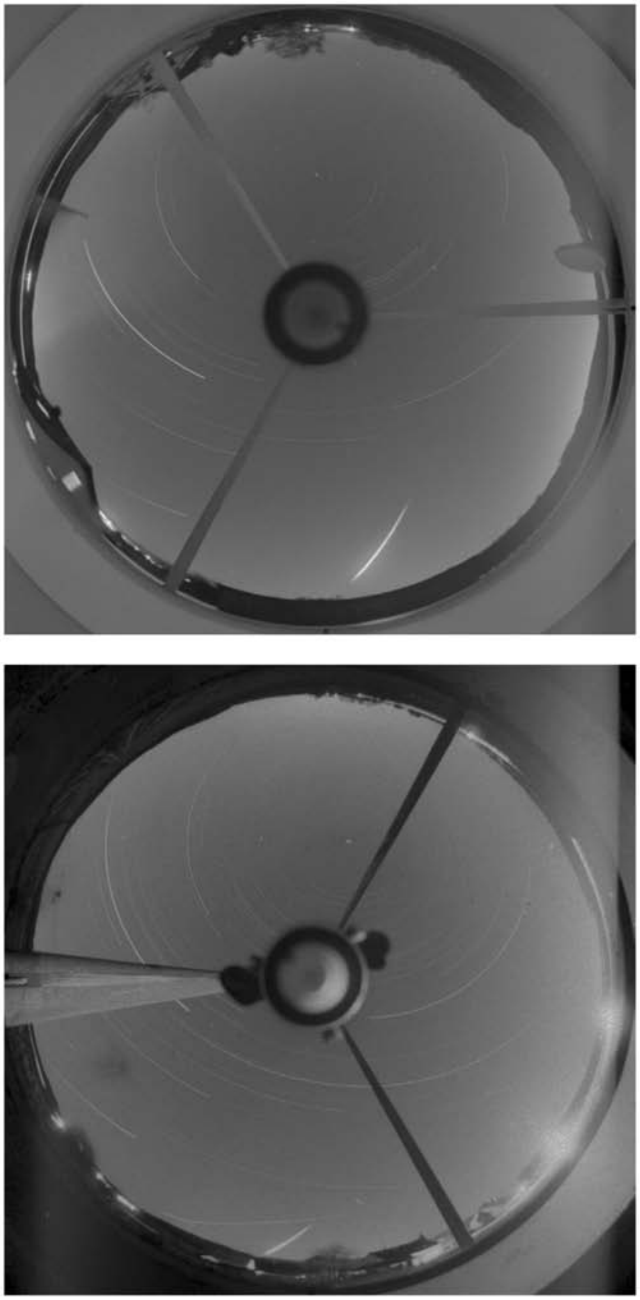


Fig. 6. EN images of the Neuschwanstein bolide obtained by station 45 Streitheim (top) closest to the event and by station 68 Losaurach (bottom). As the images of this very bright fireball are overexposed, shutter breaks are not visible on these copies. (On the original Streitheim image, breaks are visible.)

two films were personally picked up by the Network Coordinator (D. Heinlein) on the morning following the event; other films were immediately recalled from the station representatives to initiate a rapid analysis.

A first visual inspection of the photographic data, indeed, revealed indeed that the light and sound phenomena had been caused by a meteoroid penetrating deep into the atmosphere (not by space debris, as was suggested by some) and that, possibly, meteorites had been dropped. The final set of photographs, which had to be collected from the seven camera stations, were received on April 10 and sent by courier to the Ondrejov Observatory (near Prague) where all measurements and computations were made (Spurný et al. 2002, 2003). It was quickly determined that the meteoroid had successfully penetrated unusually deep into the atmosphere to an end-height near 17–20 km and that, very likely, the fireball had deposited meteorites of considerable mass, estimated to have a mass of approximately 20 kg, on the ground. The general impact area was predicted to be located between Garmisch-Partenkirchen and Füssen.

From the eyewitness reports, it was clear that the meteorite had broken into several fragments. Owing to the limited spatial resolution of the mirror cameras, only the main fragment could be tracked for some short time after the break-up. Hence, a direct prediction of its fall point was possible. Early estimates of the main fragment mass were 5–15 kg (later these estimates were revised to moderate upper limits). These estimates suffered from large uncertainties, as only one shutter break after the fragmentation flare was usable for velocity analysis. As the masses, shapes, and dispersion vectors of the other fragments after the break-up were not known at all, only estimates of fall coordinates for assumed fragment masses and standard shapes (and assuming one single break-up point for the meteorite) could be made (see Fig. 8). We expected the various fragments to be spread over quite a large strewn field, with smaller fragments (because of the large ratio of cross section to mass) to be found uptrack of the meteor path to first order.

On the morning of April 18, wind information from weather balloon ascents in Stuttgart and Munich from the night of the fall arrived (Fig. 7; see above). The first prediction for the location of the strewn field was available on the same evening. It was estimated that the main fragment had drifted approximately 700 m transverse to its nominal flight path (i.e., approximately south) during its dark flight. In contrast, for smaller fragments of 100 g (and longer flight times), this transverse drift could have been up to 1800 m (Spurný et al. 2002). Initially, there was some concern that the atmospheric situation in the (high mountain) meteorite fall area could differ from the Munich wind data. Yet, it was estimated that the main mass (assumed mass: 15 kg) had impacted southeast of Hohenschwangau, within an ellipse that could be specified to within 0.7×1 km^2 (1σ error across and along the flight path, respectively). Finally, ground coordinates for a targeted meteorite search were in hand.

Inspection of aerial photographs (Fig. 9a) revealed that the target area was far from perfect for a systematic meteorite search, implying that there would be little hope to recover the precious extraterrestrial sample(s). In the meantime, i.e., long before the first meteorite search campaign took place, it was

Table 1. GPS coordinates of EN stations.[a]

EN#	Location	Longitude (E)	Latitude (N)	Elevation
3	Ruzova	14°17′11.5″	50°50′02.8″	349 m
4	Churanov	13°36′53.8″	49°04′06.3″	1119 m
9	Svratouch	16°02′03.2″	49°44′06.8″	745 m
11	Primda	12°40′40.4″	49°40′09.7″	745 m
12	Veseli nad Moravou	17°22′10.6″	48°57′14.8″	176 m
14	Cervena Hora	17°32′31.1″	49°46′38.1″	750 m
15	Kostelni Myslova	15°26′18.3″	49°09′32.9″	576 m
16	Lysa Hora	18°26′51.5″	49°32′47.1″	1324 m
17	Pec pod Snezkou	15°43′45.4″	50°41′31.7″	823 m
20	Ondrejov	14°46′48.1″	49°54′36.5″	525 m
21	Modra	17°16′34.0″	48°22′23.0″	531 m
22	Skalnate Pleso	20°14′02.2″	49°11′21.9″	1787 m
40	Tetingen	6°02′52.9″	49°28′15.8″	317 m
43	Öhringen	9°31′03.1″	49°12′25.4″	285 m
45	Streitheim	10°41′01.7″	48°24′37.0″	504 m
68	Losaurach	10°37′33.9″	49°31′47.7″	390 m
69	Magdlos	9°30′10.9″	50°25′54.9″	420 m
71	Hof	11°54′51.7″	50°18′03.7″	524 m
72	Hagen	7°27′22.9″	51°20′44.8″	290 m
73	Daun	6°50′52.4″	50°09′44.3″	549 m
74	Gahberg	13°36′27.5″	47°54′45.4″	866 m
75	Benterode	9°36′59.4″	51°20′43.0″	280 m
79	Westouter	2°46′11.2″	50°47′14.1″	98 m
85	Tuifstädt	10°33′42.3″	48°44′44.1″	510 m
86	Seckenhausen	8°44′51.4″	52°58′28.5″	23 m
87	Gernsbach	8°19′41.0″	48°45′59.0″	220 m
88	Wendelstein	12°00′44.3″	47°42′12.7″	1838 m
90	Kalldorf	8°54′30.0″	52°09′20.5″	145 m

[a]Coordinates refer to the WGS84 datum.

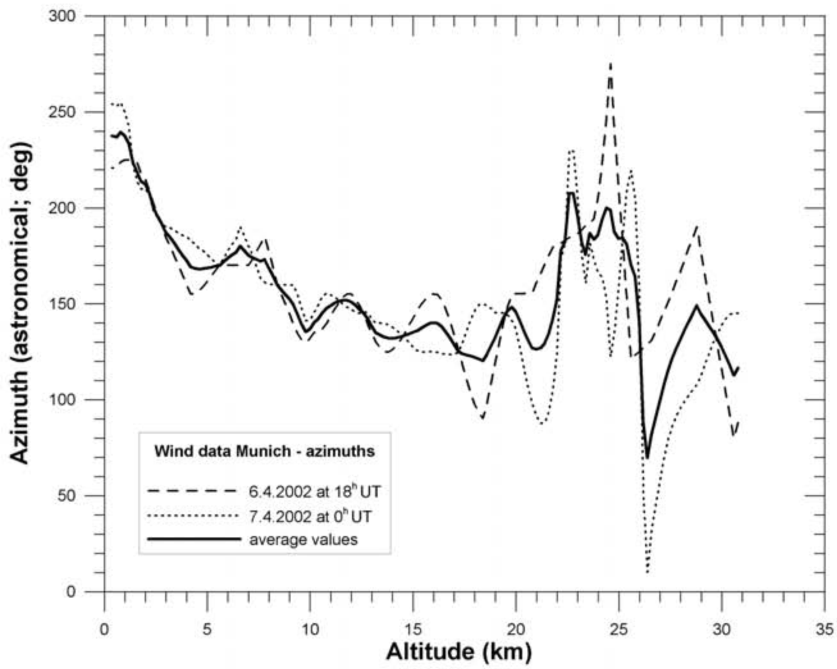
discovered that the orbit of the April 6 bolide matched the orbit of the Pribram chondrite (E-mail from P. Spurný to D. Heinlein and J. Oberst of April 17; Spurný et al. 2002, 2003), raising the speculations that any meteorite sample, if ever found, would be an ordinary H5 chondrite, perfectly identical to Pribram.

During May and June 2002, a set of GPS-measured camera station coordinates (cf. Spurný et al. 2002, 2003; Table 1) in Germany and Austria were obtained for use in the final trajectory calculation. The full set of coordinates was available on July 10. With the updated coordinates, the target ellipse moved south by approximately 300 m. The estimate of the impact point of the main fragment at that time was 10°47′43″ E, 47°32′12″ N, assuming a main fragment of 15 kg mass (Spurný et al. 2002). More recent estimates using an updated dynamic model (Spurný et al. 2003) suggest that the main mass is more likely near 6.9 kg, with an impact location near 10°48′19.3″ E, 47°31′48.9″ N (Fig. 8). The size and shape information from the first three recovered fragments and estimates of the meteorites preatmospheric mass from cosmic ray studies (Bischoff and Zipfel 2003; Zipfel et al. 2003) are in agreement with this improved estimate.

Terrain Characteristics

The final leg of Neuschwanstein's journey took place over the so called Northern "Kalkalpen," the northernmost mountain chain of the Alps forming a fold belt predominantly built by carbonate rocks, stretching from Lake Constance in the west far into Austria in the east. The fall itself took place in a mountain chain named the "Ammergebirge," roughly limited by the Neuschwanstein castle in the west, by the Plansee, Ammerwald, and Ettal in the south, by Oberammergau in the east, and by a ridge of mountains in the north: Tegelberg—Hoher Straußberg—Hochplatte—Große Klammspitz (with heights between 1,800–2,100 m above sea level).

The final part of the ground track of the main meteorite fragment can be described by a straight line from the Kreuzjöchl saddle, southeast of the Ammerwald, with an azimuth of 60° toward the northwest to a point south of Hoher Straußberg (see topographic map 1:25,000 sheets; Bayerisches Landesvermessungsamt 1992, 1993; sketch map in Fig. 8). The fall areas of the smaller fragments is defined by a zone of 2.0–2.2 km in width extending north and south of the hypothetical flight path of the main mass. The principal geographical features in this "corridor" are the broad southern



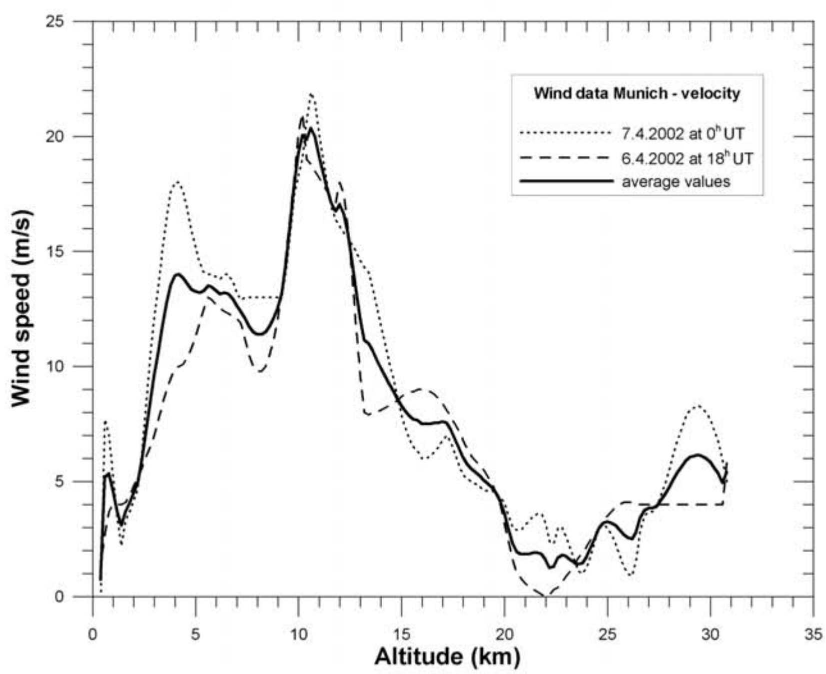


Fig. 7. Munich wind direction and speed data for the evening of the meteorite fall.

flank of the Hoher Straußberg (Figs. 9a and 9b), reaching from the summit at 1933 m down to the steeply cut-in Pöllat creek at 1300 m, and on the opposite (south) side of the Pöllat, a smaller mountain ridge with three prominent summits, namely, Ochsenälpeleskopf (1905 m; Fig. 9c), Kreuzkopf (1909 m; Fig. 9c), and Altenberg (1718 m), respectively. In the east, the potential search area is limited by the Ammerwald valley (see Fig. 8) and the Torsäulenbach. At the time of the meteorite fall, the entire area had been under complete and thick (approximately 1 m) snow cover; the ground had been frozen.

May 1 Search Campaign

An ambitious search campaign was launched on May 1, 2002. The search team of 29 involved DLR personnel, associated meteorite scientists, amateur astronomers, and a mountain rescue crew (Fig. 9e). The remote area near the

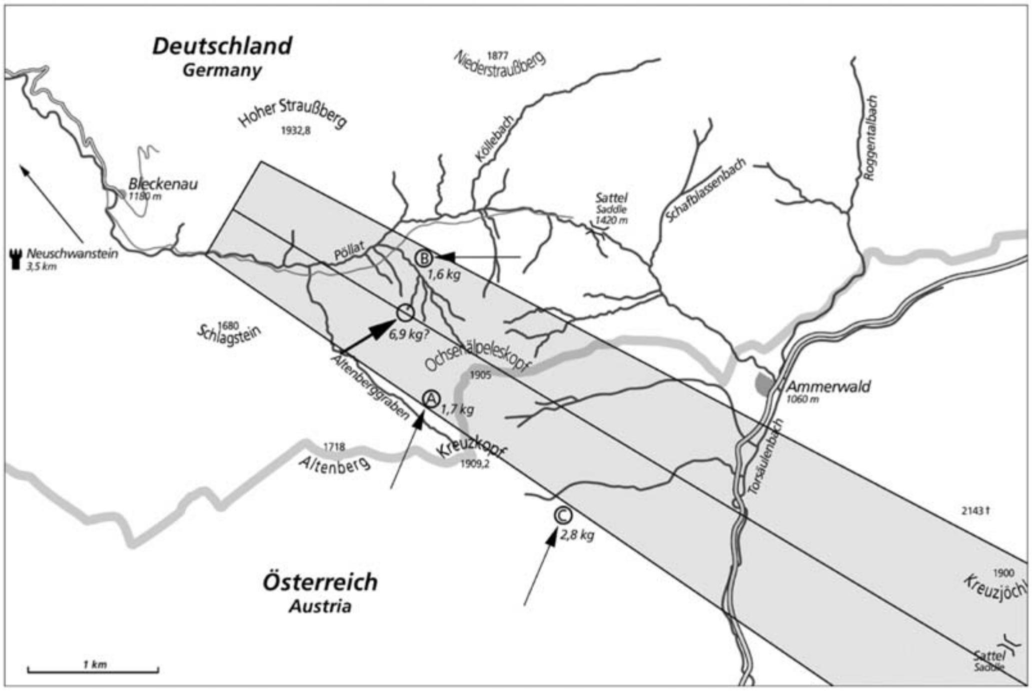


Fig. 8. Map showing the predicted strewn field of the Neuschwanstein meteorites within the Ammergebirge and locations of the first, second, and third (A, B, C) meteorite recoveries. Also, the calculated impact point of the meteorite main fragment is shown, assuming the main fragment had a mass of 6.9 kg, according to current best estimate. The May 1 meteorite search took place on the southern flank of the Hoher Straußberg, near the lower end of the predicted strewn field. West of the area, a steep cliff ("Hintere Bena") made searches impossible (compare also with Figs. 9a and 9b). Munich is approximately 90 km northeast.

Austrian border required long (and costly) travel, including a train or car ride, a 4WD vehicle transfer, and finally, 1.5 hr of uphill hiking to reach the main search area.

Steep slopes of 20°–35° inclination, rock outcrops, and deeply cut-in creeks, with vertical elevation differences of several hundred meters characterized the typical alpine environment. The ground was solid, if not rocky, though along the creeks, some swampy patches existed. Forest vegetation (mountain pines) covered about two thirds of the potential search area, including many collapsed trees hit by a severe winter storm a few years earlier (Fig. 9c). In higher altitudes, an almost inaccessible macchia-type dense brushwork (named "Latschen" by locals) marked the upper limit of the tree line. Only a small stretch in the Pöllat valley consisted of open, easy accessible mountain meadow terrain. There were some remaining scattered snow fields in the area.

Though several fragments were known to have dropped, the search fully concentrated on the main fragment, as finding a single large meteoritic fragment within some confined area appeared more promising than looking for smaller fragments scattered along the meteor ground track. We expected that a meteorite, consisting usually of dark material, would be easily recognized on the surface among the brighter limestone rocks of the "Kalkalpen."

All in all, the area was searched for approximately 6 hr without success. We estimate that 30% of the 1σ and 20% of the 2σ ellipses, respectively, were covered by the search. Hence, if our search efficiency had been perfect, we would have had a 25% chance of finding the meteorite. However, owing to the difficult character of the terrain, a systematic search (e.g., by combing the area with search lines) proved not to be effective. Therefore, it could not be ruled out that the meteorite main fragment is still to be found within the area that was covered.

In the west, 150 m from the estimated mean impact point, the effective search area was confined by a north-south cutting rock face of the Hoher Straußberg, ending at the Bleckenau mountain lodge at the bottom, called the "Hintere Bena." Here, any search activities by large groups was practically impossible (Fig. 9b).

Sporadic search campaigns by smaller teams consisting of amateur astronomers, adventurers, or professional meteorite hunters followed thereafter. When possible, the search efforts were coordinated, and search teams were directed to specific places. With the approaching summer season, fresh vegetation began to cover the area, and searching became more difficult.

METEORITE RECOVERIES

Neuschwanstein I

Two young amateur astronomers from Berlin were lucky to find the first meteorite fragment, 99 days after its fall, on

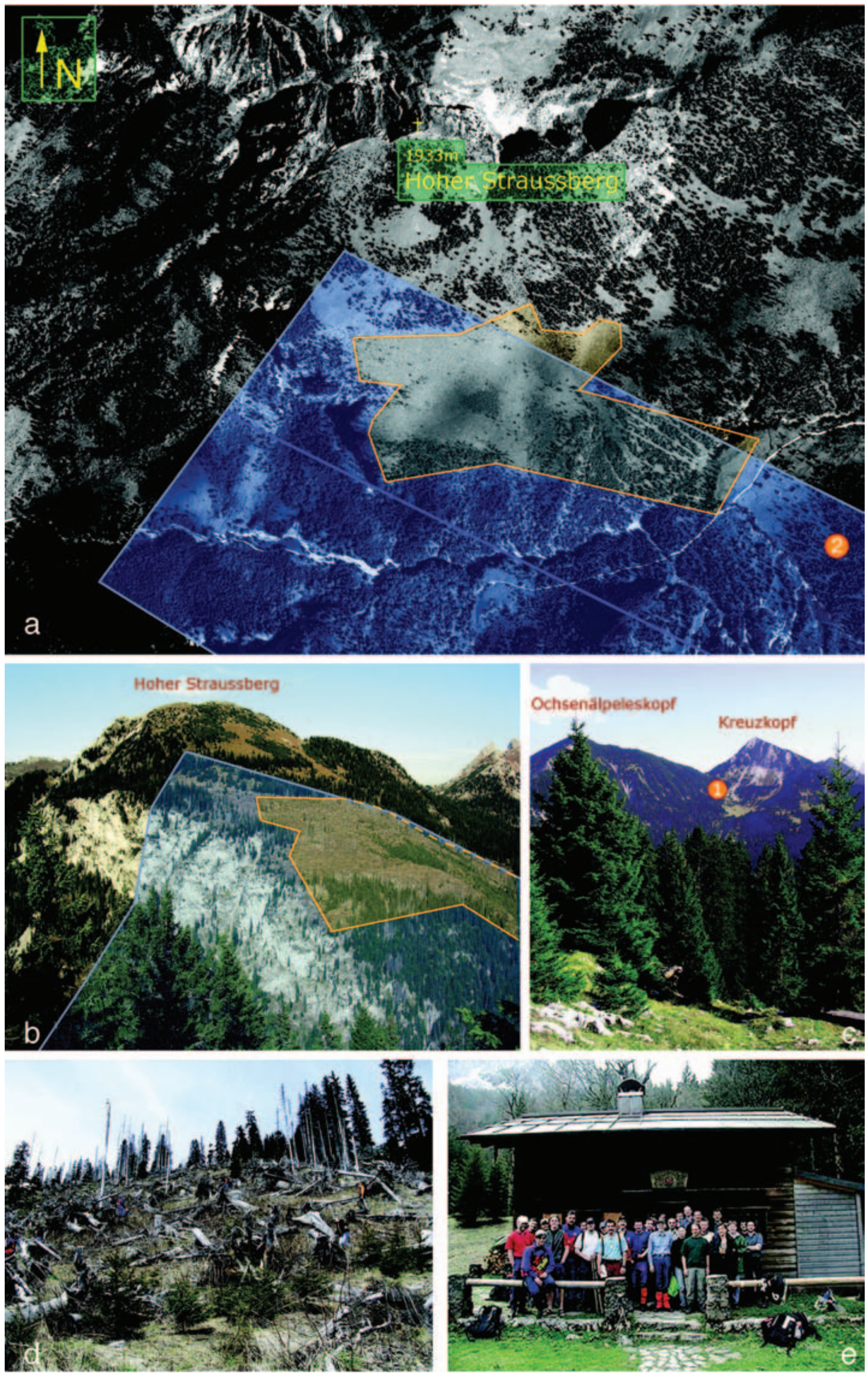


Fig. 9. a) Aerial photo taken by DLR's HRSC (High Resolution Stereo Camera) in a summer flight campaign the year before the Neuschwanstein fall. The image has a spatial resolution of 15 cm. The dark blue line marks the estimated central line of the strewn field (and in lighter blue, its error) of the meteorite fragments. The search area covered during the May 1 campaign is outlined in orange. The location of the second meteorite (Neuschwanstein II) is marked with an encircled "2;" b) view at Straussberg (see Fig. 8 for reference), again with the flight "corridor" outlined in blue and the search area marked in orange, as in the aerial view (a), respectively. Note the steep cliff to the left (west), where further searches were impossible at the time; c) view at Ochsenälpeleskopf's west face, taken from the peak of the Schlagstein (Fig. 8). The location of the first meteorite fragment find (Neuschwanstein I) is marked with an encircled "1;" d) a view at the Hoher Straußberg from the ground on the day of the May 1 search campaign, demonstrating the difficult character of the terrain; e) group picture of the May 1, 2002 search team in front of the Bleckenau lodge of the Füssen mountain rescue team, who guided the campaign.

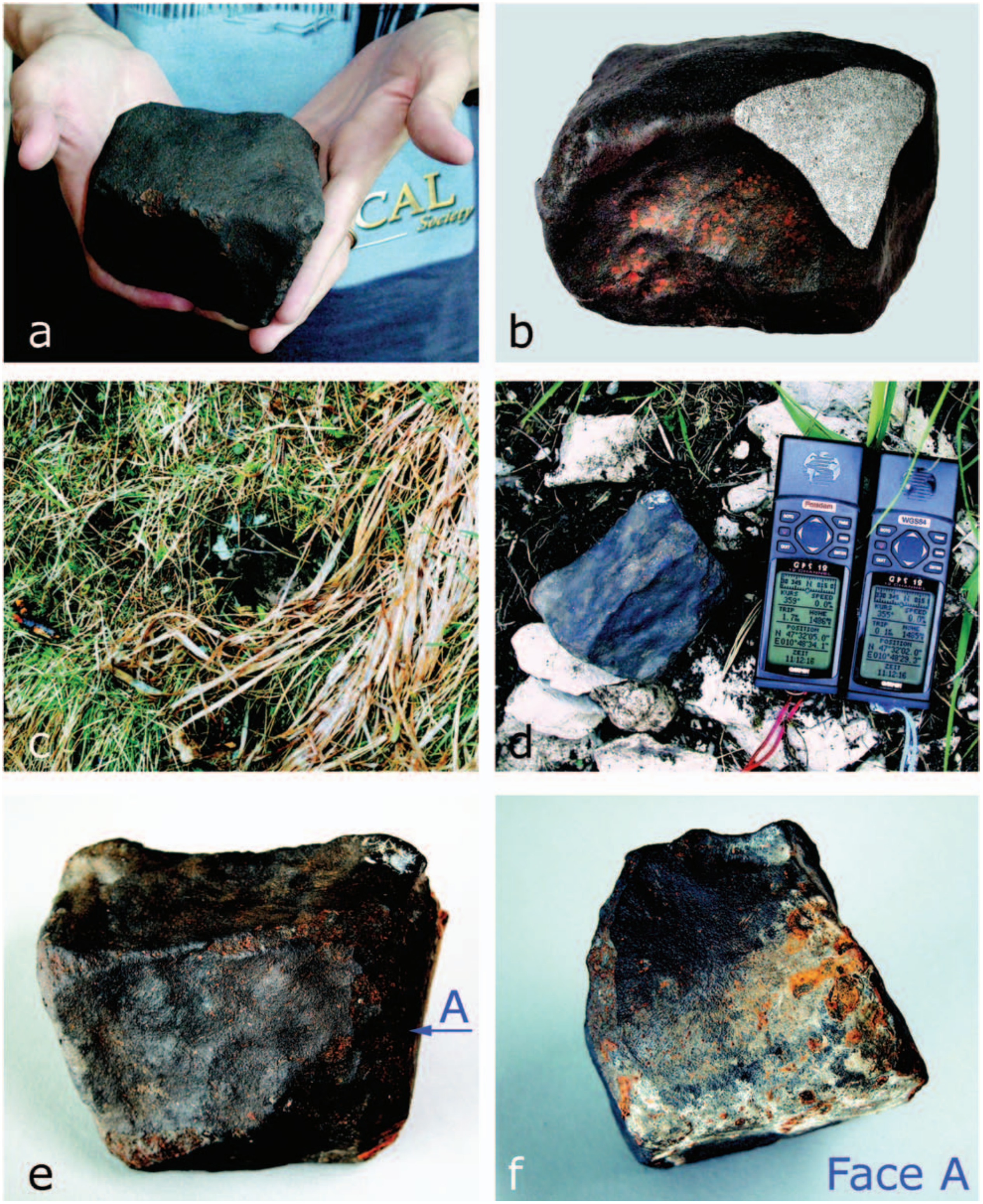


Fig. 10. a) The 1750 g Neuschwanstein I fragment, found on July 14, 2002; b) Neuschwanstein I with a polished face of a cut-off corner, as it is on display now in the Nördlingen Rieskrater Museum; c) the 1625 g Neuschwanstein II fragment, found on May 27, 2003 in its original location; d) GPS measurements at the site of Neuschwanstein II; e) Neuschwanstein II after recovery, with "A" marking the face imaged in (f) showing evidence of radial ablation flood marks, suggesting that the meteorite was oriented during portions of its flight. Both meteorites have sizes of approximately 10 cm.

July 14, 2002. They had been planning for an extended search, but spotted the specimen right on the first day of their campaign. The recovery site at 10°48′28.9″ E and 47°31′ 26.1″ N, altitude: 1650 m (WGS 84), was about 500 m south (left) from the computed trajectory and approximately 1.7 km uptrack from the estimated impact of the main mass, well within the modeling prediction for a fragment of the given mass, 1750 g (Fig. 8; Fig. 9c; Fig. 10a). Therefore, it was clear that the sample represented only a small fragment and that the main mass, possibly together with other fragments, were still at large.

The fragment, having the shape of a paving stone, was found on top of flat ground. Probably, it had not hit the ground directly but had fallen into a thick layer of snow. With the snow melting of the spring season, the fragment may have “sunk” to the position on the ground where it was found. Luckily, therefore, the meteorite piece was not damaged by the impact. The specimen was almost completely covered by a black or brownish fusion crust. On several rather sharp edges of the meteorite fragment, small patches of the fusion crust had been chipped off, presumably in the very last stages of the atmospheric flight. Not surprisingly, the residence time of several months on Earth had resulted in some surface weathering, as was indicated by several rusty spots on the surface, especially on one side of the meteorite, which was covered by a comparably thin layer of secondary fusion crust. The severe rusting suggested high content of metallic iron. From the first visual inspection, it was obvious that the sample was a chondrite.

The recovery site was approximately 5 km from the well-known Bavarian castle Neuschwanstein. Consequently, the meteorite was proposed (and later confirmed; Russell et. al. 2003) to be named “Neuschwanstein.” This meteorite discovery suddenly placed very high credibility in the analysis of the meteorite trajectory and represented a significant boost for further meteorite search efforts.

Neuschwanstein II

With snowfall of the winter season beginning as early as October 2002 in this high-altitude region, all meteorite searches came to a stop and did not resume until early May of the next season. Two young men from Bavaria, who had been searching the area for several weeks, found a second meteorite fragment on May 27, 2003. The location (10°48′29.4″ E and 47°32′01.9″ N, altitude: 1490 m) was 350 m north of the calculated central line of the meteorite fall’s strewn field, closer to this central line than the first fragment (Fig. 8; Fig. 9a).

The slightly smaller (1625 g) fragment obviously was found right where it had fallen on April 6, 2002. It was discovered within an impact cavity, approximately 5 cm deep (Figs. 10c, 10d, and 10e). Probably, the snow layer was very thin in this area, making it possible for the meteorite to reach the ground and penetrate the soil to be stopped finally by the rock basement. The meteorite was preserved in comparably good shape considering that it was exposed to the wet Alpine climate for almost 14 months. However, the bottom side of the meteorite (which was stuck in the ground and so was kept permanently wet) clearly shows more weathering than the exposed upper side of the stone (Fig. 10f).

Interestingly, this second piece is more conical in shape and shows ablation markings (Fig. 10f), suggesting that the fragment maintained some constant orientation through the final ablation portion of its flight.

Neuschwanstein III

The third and largest meteoritic fragment so far (2840 g) was recovered in the summer season of 2003 (Wimmer 2003) after extensive search activities by the finder and his wife. This specimen has a somewhat elongated shape and clearly shows more surface rust than the previously recovered pieces. The fragment, though heavier, was found uptrack from the two previous samples (Fig. 8), suggesting that the odd-shaped piece had experienced stronger atmospheric drag.

Laboratory Tour

From August 5 until August 19, 2002, the first Neuschwanstein sample was analyzed for short-lived radioisotopes in the Max-Planck Institute of Nuclear Physics in Heidelberg.

Measurements of the natural radiation of the specimen revealed the presence of short-lived isotopes, confirming beyond much doubt that the recovered meteorite had originated from a very recent fall and, therefore, was associated with the fireball on April 6, 2002 (Bischoff and Zipfel 2003; Zipfel et al. 2003).

While the meteorite was still in its pristine shape, several silicon moulds and plaster casts were manufactured: these were used for laboratory studies and, especially, for public display and education in research institutions, museums, and planetariums. The first cutting of the meteorite was carried out at the University of Münster on September 3, 2002, where thin section studies revealed that the meteorite was an enstatite (EL6) chondrite (Bischoff and Zipfel 2003; Zipfel et al. 2003) not an ordinary chondrite as we had suspected earlier. A final cut was performed within the facilities at the Max-Planck Institute for Cosmochemistry in Mainz to obtain material available for distribution to researchers as well as a 20 g reference sample, archived in Mainz. The final Neuschwanstein I piece now had a remaining mass of 1705 g (Fig. 10b).

Likewise, Neuschwanstein II and III were subjected to analysis for radioisotopes recently; their association with Neuschwanstein I and a connection with the April 6, 2002 fireball was confirmed. To what extent further analyses of these meteorites will be carried out is currently being discussed.

Meteorite Ownership

The recoveries of the Neuschwanstein meteorites initiated lively discussions on the ownership of the precious samples, a subject that also appeared to be of great interest to the "rainbow" press. According to rulings by the Bavarian state (though these rulings do not go undisputed), the meteorite finder and the owner of the land where the meteorite was found share the ownership of the specimen. Both Neuschwanstein I and II had been recovered in the Bavarian State Forest, and hence, the Bavarian state and the finders were considered to be the co-owners of the meteorites. In the particular case of Neuschwanstein I, the Bavarian state, represented by the Mineralogical Museum in Munich and supported by various sponsors, purchased the finder's portion of the meteorite. On July 19, 2003, the stone was officially awarded to the Ries Crater Museum in Nördlingen, where it is now on public display. The fate of Neuschwanstein II was less fortunate. The negotiations between the two finders and the Bavarian state ended in the decision to cut the meteorite in half, with one half being held in the collection of the Bavarian State Museum in Munich and the other half remaining with the finders, who are currently selling slices of their specimen. The destiny of Neuschwanstein III (which was found south of the Austrian boarder) is still not clear.

PUBLIC OUTREACH

The Neuschwanstein meteorite fall demonstrated that the public is very much fascinated by the idea of hunting for precious space rocks falling from the sky. Though the observations of the meteorite were achieved only with considerable technical effort, in the end, the classical virtues of patience, endurance, and the luck of young amateurs, led to the discoveries of the meteorites. The public was also struck by the fact that the meteorite fell near one of Bavaria's most important historic landmarks, the Neuschwanstein "fairy tale" castle.

Following press releases by DLR (German Aerospace Center) after the first and the second meteorite recovery, virtually all the newspapers in the country reported on the story. The authors gave numerous presentations at public observatories, planetariums, schools, or to visiting school children. A number of articles were published in popular science magazines. The authors gave radio and TV interviews; various TV shows reported on the meteorite find and on associated aspects, such as the general impact hazard. Camera teams asked to accompany our meteorite searches.

The meteorite recoveries raised the awareness for meteor events and meteorite falls in the public. The number of new meteor eyewitness reports dramatically increased following the Neuschwanstein reporting in the media. We continue to receive packages and pictures of putative meteorite finds by various enthusiasts. However, so far, all of these samples have turned out to be of terrestrial origin ("meteo-wrongs").

Two of the meteorites were presented at professional meetings: at the ACM conference, Berlin (July 29–August 2, 2002) and at the Meeting of the Meteoritical Society, Münster (July 28–August 1, 2003). The Neuschwanstein specimens were also presented at the Munich Mineral Shows in 2002 and 2003, during various public talks, and on national TV.

Several dozen plaster casts of the three meteorites were produced by one of the authors (D. Heinlein) and his wife. These Neuschwanstein look-alikes are residing in various research institutions, museums, the city hall of Hohenschwangau, at the DLR Adlershof facility, the Ondrejov Observatory and in numerous private collections.

DISCUSSION

The Neuschwanstein fall demonstrates that it can be very rewarding to monitor large areas of the sky persistently for time scales on the order of decades. The photographic observations were absolutely crucial for the recovery of the meteorite in the rough terrain. Peekskill, and Morávka (meteorites that have been observed by video techniques), on the other hand, would have been found even without the availability of observational records. Eyewitnesses were in the neighborhood of the impact points to immediately recover the sample. Clearly, the three Neuschwanstein fragments would not have been found without access to photographic data and the prediction for the location of the strewn field.

Moreover, the precise trajectory data derived from the photographs demonstrates that the meteorite orbit may hold surprising information on the origin of the extraterrestrial sample and its place in the meteoroid environment. Clearly, the association between Neuschwanstein and Pribram would not have been discovered from eyewitness accounts of the meteorite fall alone. That fragments from both meteorite falls were recovered is an important acheivement. The Canadian MORP network photographed a similar meteorite pair, Innisfree and Ridgedale, in 1977 and 1980 (Halliday 1987), respectively. However, while Innisfree (identified as an L5 chondrite) received a full laboratory analysis, the much smaller Ridgedale could not be recovered. On the basis of the orbit similarity, Halliday (1987) proposed that the two meteorites were derived from the same parent in Earth-approaching orbit. With the lack of laboratory data for Innisfree's twin, this novel idea could never be seriously challenged. In contrast, with the discovery of the diverse chemistry and cosmic ray history of Neuschwanstein and Pribram (Bischoff and Zipfel 2003; Zipfel et al. 2003), a good controversial discussion is currently under way as to whether or not the similarity of the two meteorite orbits is a coincidence.

Neuschwanstein is the most recent meteorite fall in Germany within the past 14 years (Table 2) and the first

Table 2. Meteorite falls in Germany[a] within the last one hundred years.

Meteorite	Fall date	Class	Rec. mass (kg)	Lat. (N)	Long. (E)
Treysa	1916/04/03	IIIB-AN	63	50°55′	9°11′
Simmern	1920/07/01	H5	1.222	49°59′	7°32′
Oesede	1927/12/30	H5	1.4	52°17′	8°03′
Oldenburg	1930/09/10	L6	16.57	52°57′	8°10′
Peckelsheim	1953/03/03	ADIO-P	0.1178	51°40′	9°15′
Breitscheid	1956/08/11	H5	1.5	50°40′	8°11′
Ramsdorf	1958/07/26	L6	4.682	51°53′	6°56′
Kiel	1962/04/26	L6	0.7376	54°24′	10°09′
Salzwedel[b]	1985/11/14	LL5	0.043	52°45′	11°03′
Trebbin	1988/03/01	LL6	1.25	52°13′	13°10′
Neuschwanstein	2002/04/06	EL6	6.22	47°32′	10°48′

[a]There were three more meteorite falls in Austria and five more in the area of the Czech Republic.
[b]Photographed by one EN station.

meteorite fall in Bavaria in 156 yr. Hence, in spite of the high population density of central Europe, recoveries of meteorites do not happen very often. Previous studies of the observational performance of the EN (Oberst et al. 1997), taking the meteorite flux estimates of Halliday et al. (1984) as a basis, indicate that approximately 15% of the meteorite encounters taking place in the EN area are photographically recorded and classified as "meteorite candidates." Furthermore, 1% or less of all meteoritical material deposited on central European ground is actually recovered, regardless of the availability of photographic data. Hence, the probability of capturing photographic records of a meteorite fall and recovering samples from a given meteorite event is 0.0015. Thus, a meteorite with a mass of 100 g or 1 kg would be recorded and recovered in the European Fireball Network area within 20 or 100 yr, respectively. The occurrence of the Neuschwanstein event is well within expectations.

However, the estimate does not take into account the possibility that the fireball observations actually make the recovery of the meteorite feasible, as had been hoped for when the EN was initially commissioned. Indeed, during the years of EN activity, a good number of meteorite dropping events have been observed (see list in Oberst et al. [1997], containing 23 entries). Following these events, several ground searches for meteorite fragments had been carried out, e.g., 1969 near Otterskirchen, 1974 Leutkirch, 1979 Kamyk nad Vltavou, 1983 Zdar nad Sazavou, 1984 Valec (extensive search), 1987 Janov, 1991 Benesov (extensive search), and 1995 Jindrichuv Hradec. However, none of these meteorites was recovered, demonstrating that it is not trivial to locate meteoritic fragments when only theoretical predictions for the location of a meteorite strewn field are available. On the other hand, Neuschwanstein was extraordinary in its deep penetration and its large terminal mass. The Benesov bolide, the hitherto most "promising" meteorite candidate, in comparison, had almost the same terminal height (1 km higher) but, unfortunately, a lower terminal mass than Neuschwanstein.

All the more, it is remarkable that the Neuschwanstein event marks the first time in the long history of the European Fireball Network that the camera data helped in the recovery of an extraterrestrial sample.

Acknowledgments–We wish to thank the many operators of the EN camera stations for their dedicated work over the many years. We very much appreciate the cooperation of M. Lusteck, who kindly made his (Murnau) video records of the bolide available to us for analysis. We also wish to thank the Füssen Mountain Rescue Team for their support during the May 1 meteorite search campaign, as well as the meteorite owners for revealing details on their meteorite recoveries. F. Wewel, DLR, carried out the processing of the HRSC airborne image. S. Pieth, DLR, helped in the preparation of the graphics for this paper. Our special thanks are due to Mrs. J. Keclikova, who carried out the measurements for all the photographic records. The EN is jointly sponsored by the Academy of Sciences of the Czech Republic and the German Aerospace Center (DLR).

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