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Orbits of meteorite producing fireballs

The Glanerbrug – a case study

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Abstract. At 18:32:38 UT on April 7,1990, a breccious L-LL type chondrite fell near Glanerbrug in the Netherlands. From visual observations of the meteor by 200 occasional observers, a heliocentric orbit is derived by several independent methods, including a new method using the slope of the meteor on the sky as seen from different locations.

The orbit found has a relatively high inclination of 23 ± 5 degrees, adding weight to the high inclination tail of meteorite producing fireballs. The average value of i for this population matches that of the population of near Earth asteroids, but is significantly higher than that found for the possible meteorite producing fireballs registered in the Prairie Network (Wetherill & ReVelle 1981) and the Meteorite Observation and Recovery Project (Halliday et al. 1989).

Key words: meteors – meteorites – asteroids

1. Introduction

The orbital evidence that links meteorites with asteroids is rather scarce. as it is based on three accurate orbits determined by multistation photography of meteorite falls (Ceplecha 1961; McCrosky et al. 1971; Halliday et al. 1978) and about eleven much less accurate orbits derived from visual observations (Wylie 1948; LaPaz 1949; Fesenkov 1951: Krinov 1960; Folinsbee et al. 1961, 1969; Ballabh et al. 1978). Indirect evidence is provided by the Prairie Network (PN) and Meteorite Observation and Recovery Project (MORP) from multistation photography of meteors from which a meteorite fall is expected to have occurred, but from which the meteorite has not been recovered. Recently Wetherhill & ReVelle (1981) and Halliday et al. (1989) have published a statistical analysis of 27 and 44 such meteors respectively

On a global scale, a meteorite fall is not a rare occurrence. About fine falls are reported each year (Millard & Brown 1963). But the conditions are rarely favourable for gathering the necessary observational data to obtain a heliocentric orbit.

Here we add one case study of a well observed meteorite fall, which occurred in the Netherlands on April 7th. 1990. The meteorite, that penetrated the roof of a house, is of a rare (5-6 known) inhomogeneous kind of chondrite with dark gray and lighter grey breccias in a fine grained matrix. Both chondrules and metallic grains are present. From electron microprobe analyses (Lindner et al. 1990). the light-grey part is classified at the high Fa end of the L field, and the dark-gray part is at the high Fa-Fs end of the LL field.

The meteor appeared at 18:32:38 UT. shortly after sunset and therefore was not photographed by any of the European Netwerk fireball cameras. The sky was cloudless and very transparent for the 200 occasional observers who reported on the event The locations are nicely spread over an angle of 200 degrees around the impact point at $\lambda = 6^{\circ}57'04''$E and $\phi = 52^{\circ}\,13'05''$N. which is near the town of Glanerbrug.

We discuss several methods of dealing with the rather inaccurate observations in order to derive the atmospheric trajectory and give orbital elements and an estimate of the pre-entry mass. A more extended discussion of the circumstances of the fall is given in Jenniskens et al. (1991).

2. Observations

Information about the position of the meteor in the sky was obtained from 27 observers. chosen from the 200 reports in order to be located more or less equally spread around the point of impact. They were visited in the four weeks after the event. From the original location the observers were helped to measure the position of the meteor using a compass and height measuring device. These are referred to as the "quality A data".

The reports contained another 30 letters with specific information about the apparent direction of the trail. usually given as direction arrows on a map or obtained by the use of a simple compass. They are expected to be of low accuracy We will refer to these as the "quality B data".

As a result of 120 telephonic interviews between five and 15 days after the event, a total of 78 estimates were obtained of the angle between the meteor trail and a great circle with constant azimuth. These observers are not used to the alt-azimuth system

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Table 1. Radiant of the trajectory and the height of beginning and end points as obtained by several methods. The method of location dependent apparent slopes uses an independent dataset

Method:	Az (0)	H (0)	Hb (km)	He
gnomonic plot	241±8	37±6	-.-	-.-
intersecting planes	244±8	41±5	4 5	22±6
minimising directions	237±7	41±5	4 9	23±2
location dependent slope	236±7	46±6	4 6	22±12

and on other occasions would have been useless for obtaining directional information.

3. The trajectory of the luminous path

There are a number of methods to deal with the observations in order to derive the direction (radiant: Az,H) and position of the luminous path. Each method uses a combination of information from the location of the observer (three dimensions), the directions of beginning or ending point of the meteor (two dimensions) and the projected direction of flight (one dimension). The results, summarized in Table 1, are in good agreement and are discussed below. All azimuth directions are from south over west.

3.1. A gnomonic alt-azimuth map

If plotted on gnomonic maps, the convergence point of the quality A data (Tab. 1) is at a much lower altitude than that of quality B data (Az = 232o + 14o and H = 63o + 9o). Apparently there is a tendency for steepening of the meteor's path, i.e. underestimating the angle subtended in azimuth, or overestimating the angle subtended in altitude.

This method includes the position of the meteor and the flight direction, but does not take into account the exact location of the observer. Therefore there is no information about the location of the trajectory.

3.3 Method of intersecting planes

Each set of directions of beginning and end points of the luminous path from a given location, defines a plane. Intersecting all pairs of possible planes results in an average trajectory (Tab. 1). The program FIRBAL (Ceplecha 1987) was used. The method uses all available information from the quality A data.

After excluding the most obvious erroneous data (easily recognized in the gnomonic plots) the result is found to be only weakly dependent on the weights attached to the observations. The dependence of this result on the selection of observations is illustrated by the following subsamples. The observers who were inside a house at that moment, and are expected to have better local reference points available for direction estimates, give a result at Az=251^o H=46^o Including only the stations with more or less consistent beginning and end heights, results in a solution at Az=237^o H=39^o.

In spite of this consistency, there is a tendency of the solutions to give high end heights (in km) for the locations west-south-west of Glanerbrug and low end heights for locations to the north and South. Also the beginning and end heights reported tend to correlate: the observed bcginning height is about twice the end height. i.e. on average about 45 km. This disturbing result illustrates uncertainties in the position of the metcor trajectory in the sky and is a selection effect: the visited locations in the north and south are mostly outdoor observers with less suitable local reference points available.

The average end height is 22±6 km and varies from 8 to 35 km in individual cases. The average beginning height varies from 20 to 70 km. The position of the path is from (λ, ϕ) = (7.46, +52.44) to (7.07, +52.33). which misses the impact point in Glanerbrug (6.95, +52.22 7 km. The dev iation is due to the observational errors and not accounted for by the observed atmospheric wind directions (Kuiper 1990).

3.3. Minimizing the individual direction estimates

Instead of using planes as in Sect. 4.2. one can treat each pointed direction as independent of the others. All observations of two directions of the trajectory from one station are taken as if they were done by two different observers.This has the advantage that one of them can be rejected.

The shortest distance between a direction vector (ξ_i, ζ_i, η_i) from the location (X_i, Y_i, Z_i) of beginning or end point and the vector that describes the meteor path (ξ_m, ζ_m, η_m), in a rectangular geocentric system of coordinates starting at a chosen X_m). is minimized by a linear least squares method (Borovicka, 1990) from which the notation is adopted). This method needs the information about the location of the observer and the direction to the trail, but not that of the slope of the trail on the sky.

Data of both quality A and B were used. but up to half of the data were rejected (see Jenniskens et al. 1991). The rejection procedure was an iterative one with many different combinations attempted. Naturally the solution depends on the selection of the observations. but the final selection seems to be reasonable within the errors quoted.

The result of Table 1 was obtained by forcing the solution to align with the impact position. However without this restriction the results do not differ much: the meteor trajectory passes the vertical line at the impact position only by 3 km at an altitude of 24 km instead of 23 km. The radiant in this case is at Az=237^o and H=39^o The value of H_e given in table 1 is the height of the meteor path above the impact point. The endpoint of the luminous trajectory will be a few km higher than this. The length of the observed trajectory is about 40 km which puts the first observed point at a height of 49 km above the position $\lambda = 7.31^o E, \phi = 52.37^o N$.

3.4. The apparent slope of the meteor path

The angle between the projected meteor path on the sky and a great circle with constant azimuth (ψ) is a function of radiant position (Az,H), the azimuthal direction from the observers location to the impact point (Az,,) and the altitude of the end point (h) :

$$\tan\psi = \frac{\sin(Az_o - Az)}{\cos h_o \tan H - \sin h_o \cos(Az_o - Az)} \qquad (1)$$

We noticed that the angle ψ is more easilv estimated than altitudes and azimuths by occasional observers. The available data are plotted in Fig. 1 as a function of A_z. The meteor was seen to fall straight down (ψ = 0°) from locations west-south-west of the impact point (Az=240o). The angle of the trajectory with the Earth's surface (H), is determined by how quickly ψ changes for positions close to this head-on case. The change of ψ as a function of observer location Az, near ψ = 0o is rather shallow, favouring a steep trajectory. The requirement that ho should cover a small range, is met: most data imply that ho= 10-30 degrees. A least squares fit (Tab. 1) was made by linearizing and neglecting the ho-term and afterwards adding a small correction for ho. Az is well defined. The uncertainty in H is slightly asymmetric, favouring higher values of H.

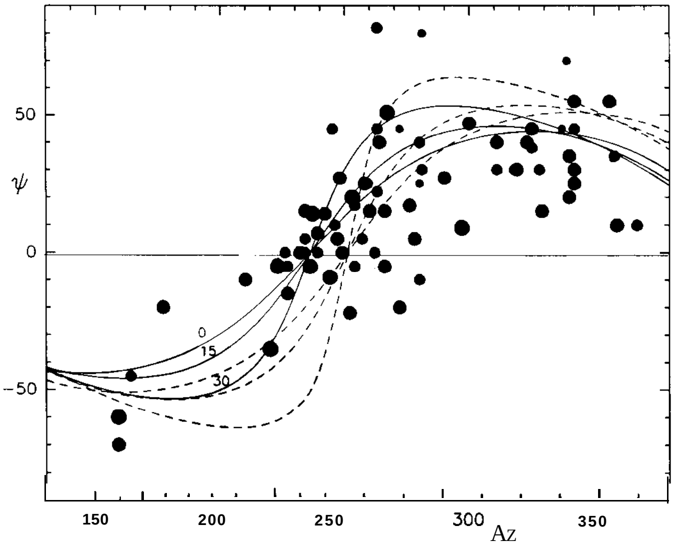

Fig. 1. The angle (ψ) between apparent meteor path and the great circle through zenith and meteor end point is plotted as a function of the location of the observer relative to the impact point (A z,). The expected behaviour from Eq. 2 is given for (Az,H) = (236,46) – thick lines – and for (Az,H) = (251,39) – dashed lines – for ho is 0, 15 and 30 degrees

Again Fig. 1 shows that the observers tend to remember the path to be steeper than it was: there are many points below the curve of best solution. This may be due to eye movements while the meteor appeared, confusing ψ and h_o, or even due to prejudices of a "falling" object.

Assuming a trajectory close to the impact point, the rough height estimates, using stretched arm and spread fingers as a measuring unit of angle on the sky, gives an average altitude of 22 ± 12km for the end point and a value of 32 ± 1 km for the trail length, in good agreement with the previous estimates.

4. Entry velocity and orbit

In the near daytime conditions of the Glanerbrug fall, only part of the meteor was conspicuous enough to be noticed. The durations were estimated by allowing the observers to recall the event and say "stop" after an initial signal. The distribution of reported durations peaks at 1.2 seconds and has a tail of longer durations up to 3.2 s. The average duration is 1.6 seconds. Combining the median values of length and duration, results in an entry velocity of V_∞ = 27 ± 15 km/s. The average values of trail length and duration give V_∞ = 20 ±10 km/s. Neither is very accurate.

One observer measured the length of the apparent trajectory and estimated the duration of the meteor several times with a stopwatch shortly after the event and found a length of 10 ±3" and a duration of 0.7 ± 0.1 seconds. This amounts to V_∞ = 22 ± 7 km/s.

The descriptions of apparent velocity are of some help. The meteor was described as "fast, but taking its time", "fast, but not as fast that it became a line", "point, moving very fast", "comparing to meteors on a scale from 1 to 4, I would say at 2", "average speed, not fast". These descriptions are consistent only with a velocity of at least V_∞ = 20 km/s.

Finally, an upper limit to the velocity is set by the calculated trajectory and the expectation that the body is from within the solar system, i.e. V_∞ < 27 km/s.

We adopt a velocity V_∞ = 23 ± 4 km/s. For the radiant direction we adopt values of Az=240o±7o and H=41o±6o (Table 1), which corresponds to a radiant position at α = 202o ± 7o and δ = +49o ± 6" (Eq. 1950.0). The resulting orbital elements are q=0.85±0.05 AU, a<1.5 AU, i=23o±5o, ω = 230" ±11" and Ω = 17.117 deg. (Eq. 1950.0).

5. The pre-entry mass

Trajectory, entry velocity and end-height allow an estimation of the preeentry mass (Halliday et al. 1989).

Those observers who saw the meteor close to the nearly full moon that evening agree with an observed apparent brightness of mv = 12.5f1.5 mag, which would correspond to m_∞ = **20-200** kg. The mass estimate depends on the adopted luminosity efficiency (7). Here we have followed Wetherhill & ReVelle (1981): 7 = **0.02** (V_∞(km/s)/40), which gives masses that are a compromise between the masses determined from photometry (factor of 10 larger) and deceleration measurements (factor of two less).

The end-height is related to the preeentry mass, but the uncertainty is too large to give a useful restriction. Theoretically the end-mass is also related to the preeentry mass. Depending on entry velocity, the preeentry mass is between 10 and 50 times the end-mass (Halliday et al. 1989). But the end-mass is not well known. The fragment that penetrated the roof collisionally fragmented with a normal distribution with δ = 1.15 ± 0.12. Its total mass may have been 1.2 ± 0.2 kg. Some of the finest dust was not recovered: in total 855 grams of material was found. More fragments must have fallen, but not too many more, because a search of 0.4 km2 around the impact point one week after the fall did not result in more fragments (Betlem 1990).

6. Discussion

Table 2 compares the resulting orbital elements with the other reasonably well determined meteorite orbits available in the literature. The Pultusk event (Krinov 1960) has not been included (see Millard & Brown 1963). Except for the photographically recorded events, these orbits have uncertainties similar or somewhat larger than those of the Glanerbrug case. The main uncertainty is in the velocity determination, and from that in the semi major axis.

The inclination of the Glanerbrug meteoroid orbit is surprisingly high, but not unusual. Halliday et al. (1989) stress the presence of a high inclination tail in the population of possible meteorite producing fireballs observed in the MORP project. Together with another recent case of a visually observed meteorite fall at Dhajala (Ballabh et al. 1978), the Glanerbrug adds weight

Table 2. A comparison of the Glanerbrug orbital elements with those from other well observed meteorite falls. The photographically recorded events are indicated by an asterisk

Name:	i ^{0})	a (AU)	q (AU)	e	Reference:
Glanerbrug	23	2.8	0.85	0.69	this work
Khmelevka	28	1.2	0.15	0.88	Krinov 1960
Dhajala	28	1.8	0.74	0.59	Ballabh et al. 1978
Paragould	19	2.5	0.93	0.63	Wylie 1948
Bruderheim	16	0.9	0.68	0.25	Folinsbee et al. 1961
Innisfree’	12.3	1.87	0.99	0.47	Halliday et al. 1978
Lost City’	12.0	1.66	0.96	0.42	McCrosky et al. 1971
Kunashak	11	1.8	1.00	0.45	Krinov 1960
Pribram’	10.4	2.42	0.79	0.67	Ceplecha 1961
Sikhote Alin	9	2.2	0.99	0.54	Fesenkov 1951
Vilna	8	1.2	0.77	0.33	Folinsbee et al. 1969
Archie	8	1.5	0.81	0.47	Wylie 1948
Norton C’nty	8	1.5	0.87	0.42	LaPaz 1949
Nikolskoe	4	3.8	0.91	0.76	Krinov 1960
Tilden	1	1.7	0.95	0.45	Wylie 1948
PN median	6.9	2.0	0.98	0.49	Wetherill et al. 1981
MORP ”	6.8	1.93	0.96	0.54	Halliday et al. 1989

to this high inclination tail. Thirteen out of 15 meteorite orbits listed in Table 2 have higher inclinations than the median values quoted by Halliday et al. (1989) and Wetherill & ReVelle (1981). The average inclination of < i >= 13.2” is equal to that of the population of near Earth asteroids (< i >= 14o see Weissman et al. 1989), which have larger inclinations on average than the main belt asteroids (< i >= 8”). The distribution of orbits of recovered meteorites may reflect the same physical mechanism responsible for the distribution of orbits of the near-Earth asteroid population, i.e. a broadening of inclinations due to chaotic motions in the resonances (Weissman et al. 1989) and possibly an important contribution by the ν_6 secular resonance.

Compared to Tab. 2, the MORP (< i >= 10.3) and PN (< i >= 8.3) data contain a preponderance of orbits with low inclination and q close to 1. It does not necessary follow, however, that the criteria used to discriminate between meteorite producing and ordinary fireballs are incorrect. Because there are not well understood selection criteria that determine which meteorites are finally recovered. The meteorites with a high inclination orbit descend with a higher entry velocity on average. Those that survive are more massive and produce many fragments per fall, thus increasing the probability that one of the fragments is recovered (analogy: shooting a rabbit with small shot). In the Glanerbrug case, where one fragment hit the roof of a house, we expect another 5-10 kg of material to have fallen in the area, but none of it was found.

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