The United Kingdom fireball of 30th March 2013: Observation and analysis using NEMETODE and visual data

William Stewart [1] *and Alex R. Pratt* [2]

This paper describes the fireball that was observed across England, United Kingdom at 00^h39^m UTC on 2013 March 30. The observations and subsequent analysis from NEMETODE, a network of low-light video cameras operated from Cheshire and West Yorkshire, are discussed as are visual observations submitted to online sources and periodicals. The method by which a correction to the observed magnitude derived from the video data is described and estimates are given of the radiant position, the path through the Earth's atmosphere and the orbital elements of the meteoroid. A speculative mass, size and origin of the meteoroid are given.

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1 Introduction

During the early hours of Saturday, 2013 March 30, multiple postings began to appear on the Twitter social networking service indicating that a fireball had been seen over the UK. In subsequent hours further reports were logged on various online forums. These indicated that in spite of the poor weather over substantial parts of the country, the fireball had been widely observed. During a review of data later that day the authors, William Stewart (WS) and Alex R Pratt (ARP), noted that two NEMETODE cameras had captured a fireball at a time consistent with the visual reports.

2 NEMETODE Equipment and Methods

William Stewart operates three Watec 902H cameras with Computar aspherical 8 mm $f/0.8$ lenses, one facing North, one facing North-East and the other facing South-East from Ravensmoor, Cheshire. Alex R. Pratt operates a Watec 902H2 camera with a Computar aspherical 3.8 mm $f/0.8$ lens facing South from Leeds, West Yorkshire. William Stewart and Alex R. Pratt both run their cameras every night, irrespective of forecast conditions, in order to maximise the number of meteors captured.

Meteors are detected and recorded by UFO Capture (SonotaCo, 2005) running on Windows PCs; each capture is displayed to 0.1 s (processed internally to 0.04 s), time-synchronised to an NTP server. The resultant captures are processed by UFO Analyser (SonotaCo, 2007), registering against the Sky 2000 star catalogue with average positional errors of < 0.3 pixels and $< 0.03°$, to determine shower membership. The Ravensmoor and Leeds cameras operate across a baseline of 107 km and multi-station events are processed by UFO Orbit (SonotaCo, 2009) to estimate radiants, start and end heights, geocentric velocities and orbital elements. For this analysis SonotaCo, the author of the UFO software suite, analysed NEMETODE data using the prototype software tool he has developed known as "Fireball Inspector" (FBI). Further details relating to NEMETODE can be found on the authors' website (`http://www.nemetode.org/`).

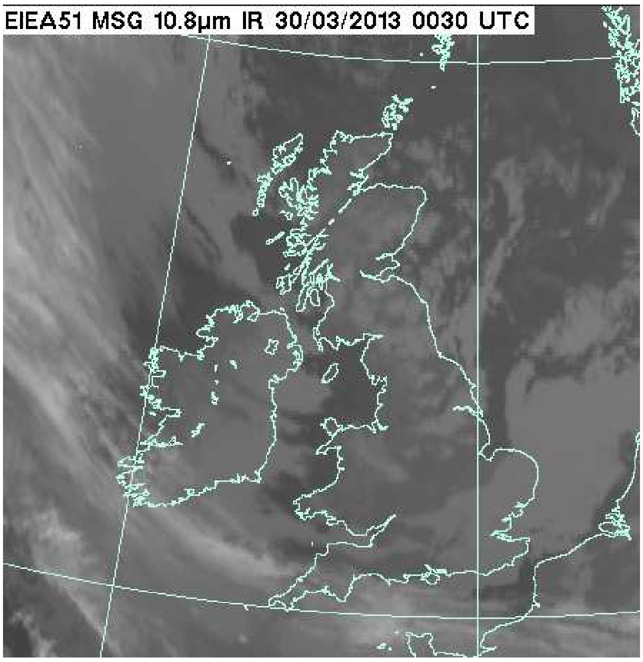

Figure 1 – Infra-red weather satellite image of the British Isles nine minutes before the fireball occurred.

3 Observing Conditions over the British Isles

Figure 1 shows the infra-red satellite view of the British Isles at 00^h30^m UTC on 2013 March 30, nine minutes before the fireball was observed[1]. Extensive cloud cover is evident over England with breaks from the Bristol Channel in the West, through the Midlands and towards The Wash in the East. The break in the clouds also extended North-West from the Midlands up towards Manchester and Liverpool then further North towards Cumbria. Some parts of Yorkshire are clear while others have broken cloud. At the time of the fireball, the waning gibbous Moon (91% illuminated) was in the South-South-East at an elevation between 14° and 18° as seen from most of England. Taking account of atmospheric extinction, the apparent magnitude of the Moon would have been approximately −11.5.

[1] West View Cottage, Swanley Lane, Ravensmoor, Nantwich, Cheshire CW5 8PZ, United Kingdom
Email: `ws@nemetode.org`
[2] 76 Latchmere View, Leeds LS16 5DT, United Kingdom
Email: `arp@nemetode.org`

IMO bibcode WGN-416-stewart-fireball
NASA-ADS bibcode 2013JIMO...41..190S

[1] `http://www.metoffice.gov.uk/`

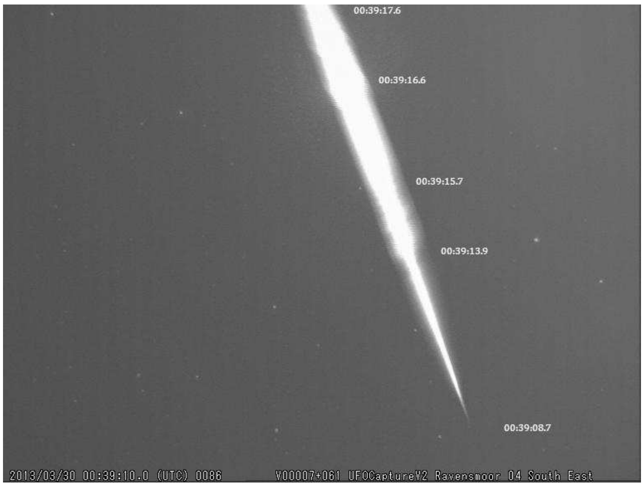

Figure 2 – Composite image of the fireball from the Ravensmoor South-East camera annotated with UTC time-markers. For operational reasons the camera has been rotated clockwise through 90° within its housing so what appears to be the bottom of the field of view is actually the left hand side. The "keystone" asterism in Hercules is visible in the lower half of the image, just to the left of centre.

4 Observation from Ravensmoor

The sky was clear and the faintest stars detectable in the real time video were between magnitude 4.5 and 5.0. The first detection of the fireball was by the Ravensmoor South-East facing camera at $00^{h}39^{m}08^{s}.7$ (all times given are UTC; NEMETODE timing accuracy is ± 0.1 s). Figure 2 shows a composite image of the fireball. The fireball continued to pass through the Field of View (FOV) and exited at $00^{h}39^{m}17^{s}.6$ (total duration of 8.9 s) leaving a wake that persisted for a further 0.3 seconds. No colours were determined as the camera system is black and white. The video of this fireball can be viewed on the authors' website.

5 Observation from Leeds

The sky had approximately 80% cloud cover and only one star was visible on the real-time video. The first detection of the fireball from Leeds was at $00^{h}39^{m}13^{s}.0$ as it passed into a gap in the clouds (see Figure 3). It traversed the gap and passed behind another cloud at $00^{h}39^{m}14^{s}.4$ before momentarily reappearing through very small cloud gaps at $00^{h}39^{m}15^{s}.5$, $00^{h}39^{m}17^{s}.1$ and $00^{h}39^{m}17^{s}.8$.

No colours were determined as the camera system is black and white. The video can be viewed on the authors' website. During the same evening, prior and subsequent to the fireball, four other meteors were observed using this same system. Between 5 and 9 reference stars were visible in these captures. The camera system is permanently mounted and is not changed from one night to the next. On clear nights the number of reference stars is in excess of 20. The authors therefore conclude that triangulation data based on this observation is valid, in spite of the presence of just one reference star on the Leeds' fireball video.

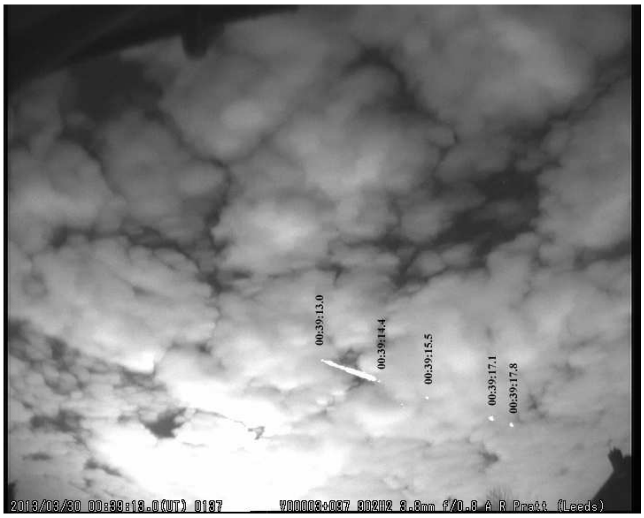

Figure 3 – Composite image of the fireball from Leeds with the Moon illuminating the clouds in the lower left.

6 Visual Observations

Visual observations were submitted by members of the public to various online forums including Stargazers Lounge[2], the Armagh Observatory Fireball Reports Database[3] and the Latest Worldwide Meteor / Fireball Reports Blog[4]. An observation was also submitted to "The Astronomer" (Hill, 2013). Where possible the authors contacted observers for additional follow up information however in the majority of cases this was not attempted as contact information for many of the submitters was not published.

A particularly detailed description was given by the experienced astronomical observer and founder of the Todmorden Astronomy Centre Peter Drew (PD) who observed the fireball from Bacup, Lancashire (53°42′ N, 02°12′ W)[1] (Drew P., personal communication):

"I was awake at 12.40am when I saw the fireball appear in full flight from the E side of a large Velux window that faces just E of S. It was relatively slow moving with a pure white head and a short fan shaped tail which contained orange and green hues. I sat up quickly enough to see it carry on westwards and gradually fade to nothing, there was no apparent after trail. The trajectory was pretty much parallel to the horizon and passed around 10 degrees above the Moon. The magnitude was at least −8 based on observations of Iridium flares, the observation lasted about 3 seconds during which the fireball covered around 30 degrees azimuth from 170° *to just over* 200°*."*

Another experienced observer, Christopher Hill (CH), also observed the fireball from Cheadle (53°24 N, 02°13 W), Greater Manchester (Hill, 2013; Hill C., personal communication):

"I was out observing Saturn at 00:40 GMT when I saw a bright fireball. Observing conditions were freezing cold but clear, some mist patches, still air at ground

[2] http://tinyurl.com/oy4hfl2 and http://tinyurl.com/q5xr2wo
[3] http://arpc65.arm.ac.uk/cgi-bin/fireballs/browse.pl
[4] http://thelatestworldwidemeteorreports.blogspot.jp/

level but east wind high up, bright Moon nearby. Initially noticed fireball at an azimuth of approximately 150° and it travelled slowly at 5°/s at an elevation of 30°, parallel to the horizon, dipping slightly. Brightness remained constant before dropping suddenly to extinction at an azimuth of 180°, to the west of Spica (confirmed via local known topography). The fireball was brighter than Venus at maximum though not as bright as the brightest Iridium flares the proximity to the moon made magnitude judgement challenging but estimate it to have been at least −5. No shadow observed though the bright moonlight would likely have drowned it out. The fireball had a very distinct orange (as opposed to white) head with orange sparkles falling away from it, somewhat reminiscent of a firework. No sound and no smoke trail."

7 Other Potential Data Sources

The authors checked other potential online resources for observations with some limited success. There are no reports of this event logged on the American Meteor Society (AMS) website[5]. At the time of the fireball the all-sky cameras of the University of Hertfordshire[6] located at Bayfordbury and Exmoor were experiencing 100% cloud-cover as were the Church Crookham and Clanfield 2 cameras of the UK Meteor Observation Network (UKMON)[7] (Campbell-Burns P., personal communication). A search for "fireball" or "meteor" on the online photo sharing website Flickr[8] for the date of the fireball, a strategy which has proved useful in the past, also proved fruitless. The Met Office (The UK's National Weather Service) checked weather radar data but saw no evidence of an object entering the earth's atmosphere at the time of the event.[1]

Michael Morris (MM), observing from a location 0.8 km North-North-East of the city of Worcester in the West Midlands (53°12′ N, 02°13′ W) with a Samsung SDC 435 low light video camera equipped with 2.1 mm lens, obtained a video of the early stages of the fireball[2,9] (Morris M., personal communication). North is to the top and East is to the left of the FOV. Being an internal reflection of the Moon, the bright object in the upper right is 180° out of position. Michael Morris has stated that the time code is accurate to ±2 seconds. The time code as the fireball first becomes visible is $00^h39^m06\overset{s}{.}7$. Based on the duration and brightening of the object as it exits the FOV at $00^h39^m10\overset{s}{.}6$, the authors believe that this video does not show the fireball at its brightest.

The same video system was used to capture a 77° elevation pass of the International Space Station (ISS) later that night[10], a pass for which the estimated maximum brightness was magnitude −3.5[11]. The authors have compared the two videos and it is clear that observing conditions were better for the pass of the ISS compared to those for the time of the fireball. In spite of this, the early stages of the fireball are significantly brighter than the ISS. The authors conservatively estimate the difference to be 1 magnitude brighter. The ISS passed close to the centre of the FOV whereas the fireball was close to the edge. Vignetting from a 2.1 mm lens would be expected to make objects close to the edge of the FOV appear dimmer but the impact of this has not been quantified and a correction factor not applied. Michael Morris has also confirmed that the fireball appears *"... much brighter than Jupiter is when it appears in a video..."* (Morris M., personal communication). At opposition, Jupiter has a maximum magnitude of −2.9. The authors therefore conclude that the initial stages of the fireball had an observed magnitude of at least −4.5.

8 Trajectory Analysis

Having processed the Ravensmoor and Leeds data through UFO Analyser, the authors attempted to determine key parameters relating to the velocity, the atmospheric trajectory and orbital elements of the meteoroid using UFO Orbit. The software classified this as a Q1 event i.e. the data is only of sufficient quality to meet minimum conditions for normal radiant computation. This is most likely due to the cloud cover affecting the Leeds observation. Although a reasonable ground track and orbit could be determined using this software, the authors had concerns relating to the derived deceleration values during the object's path through the atmosphere. These concerns were discussed with the software developer, SonotaCo, who in turn offered the use of a new tool that he has developed (though not publically released) called "Fireball Inspector" (FBI) (SonotaCo, personal communication). This tool has been designed for the precise measurement of fireballs and can adjust for timing errors and errors in radiant direction and entry point. The authors provided their data to SonotaCo for analysis with FBI v1.02.

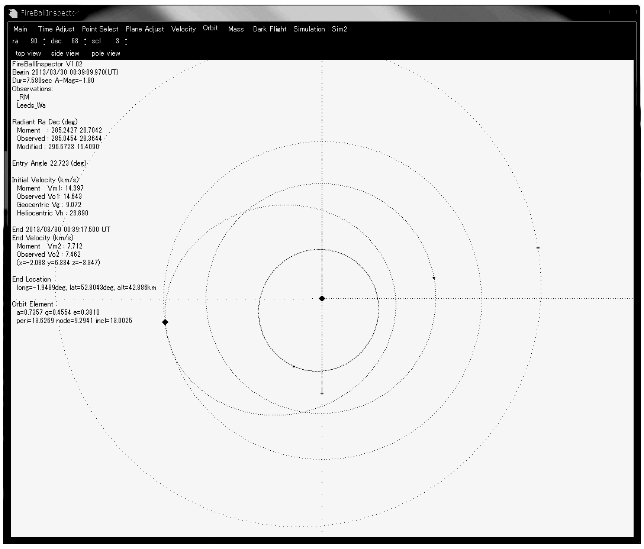

Figure 4 – FBI orbit estimate (courtesy SonotaCo).

[5]http://www.amsmeteors.org/fireball_event/2013/
[6]http://star.herts.ac.uk/allsky/about.php?c=1
[7]http://ukmeteornetwork.co.uk/
[8]http://www.flickr.com/
[9]http://www.youtube.com/watch?v=zdnoPoAQ1J0
[10]http://www.youtube.com/watch?v=UBuY3TOkMYo
[11]http://www.heavens-above.com

Table 1 – FBI estimate for the orbital elements of the meteoroid (courtesy SonotaCo).

a (AU)	q (AU)	e	ω (°)	Ω (°)	i (°)
0.74 ± 0.07	0.46 ± 0.13	0.38 ± 0.12	13.6 ± 10.6	9.29 ± 0.0	13.00 ± 10.0

The timing adjustment works by matching the light curves from the two separate observers. Unfortunately this was not possible as the cloudy conditions in Leeds prevented a light curve being generated that could be matched to the Ravensmoor observation.

SonotaCo's analysis indicates that the instantaneous radiant direction (direction at the time of entry point ignoring the effects of the Earth's rotation, movement and the effect of gravity) was RA 285.24°, DEC +28.70°. The instantaneous entry velocity was 14.4 km/s and the observed velocity was 14.6 km/s. This allows an orbit for the meteoroid to be estimated as shown in Table 1 and Figure 4.

As shown in Figure 5, the velocity remained reasonably constant for 5 seconds before slowing down to 7.7 km/s at the end of the Ravensmoor video. This velocity figure is significantly different from that determined by UFO Analyser. SonotaCo believes this is a consequence of the small cross angle Q_c (3.6°) between the two observing sites; that the FBI software has provided a significant correction and that the revised figure of 7.7 km/s is much more accurate (SonotaCo, personal communication).

Figure 6 shows (in light grey) the derived ground track as determined by SonotaCo's FBI software. The trajectory adjustment converged to a reasonable result with the first data-point (at $00^h39^m09\overset{s}{.}6$) being an altitude of 83.2 km at 53°04′ N, 00°36′ W. The authors note that the first evidence of the fireball on the video sequence was at $00^h39^m08\overset{s}{.}7$ and that the first 3 seconds of data commencing $00^h39^m09\overset{s}{.}6$ in Figure 5 show reasonably constant values for the velocity and the rate of decrease in altitude. They have therefore extrapolated backwards in time to $00^h39^m08\overset{s}{.}7$ in order to estimate the position of the meteoroid at the time it first became apparent on the video. An entry altitude of 88.3 km is estimated at 53°05′ N, 00°25′ W which is approximately 17 km South-South-East of the city of Lincoln in Lincolnshire, UK.

The entry angle was 67.2° to the zenith. The fireball continued on a bearing of 252.8°, passed directly over the city of Nottingham, carried on just to the South of Derby before exiting the Ravensmoor South-East FOV at 52°48′ N, 01°57′ W by which time the altitude had dropped to 42.8 km. This location is approximately 17 km South-East of the town of Stone in Staffordshire. This equates to an observed ground track length of 107.4 km and an atmospheric path length of 116.3 km.

As the meteoroid continued on its trajectory the velocity would decrease until it was below the threshold for atmospheric ionisation (circa 2 – 4 km/s) after which the fireball would no longer be visible even as it continued to travel downrange. Christopher Hill was closer to the ground track than Peter Drew (65 km compared to 100 km) and so his extinction azimuth estimate may have less uncertainty. However his extinction azimuth estimate was closer to the bright moon and so it may have been more challenging to see the fainter part of the trail against a relatively bright background.

While the authors have confidence in that part of the trajectory captured on video, the remainder of the meteoroid's path (shown in black in Figure 6) is speculation. SonotaCo in particular cautions against reading too much into this part of the plot as the potential flight path after the object left the Ravensmoor FOV is based on a number of assumptions: that atmospheric density was typical for each altitude, that there were no winds and that the residual mass of the object was 0.1 kg. For reference, the weather conditions at the closest weather station to this part of the trajectory (Shawbury, Shropshire at a distance of 12 km) reported the following for 00:50 UTC on 2013 March 30[12]: Conditions: −2°C, Partly Cloudy; Humidity: 76%; Visibility 10 km; Pressure 1010.84 mb steady; Wind: N 10 km/h.

[12] `http://uk.weather.com`

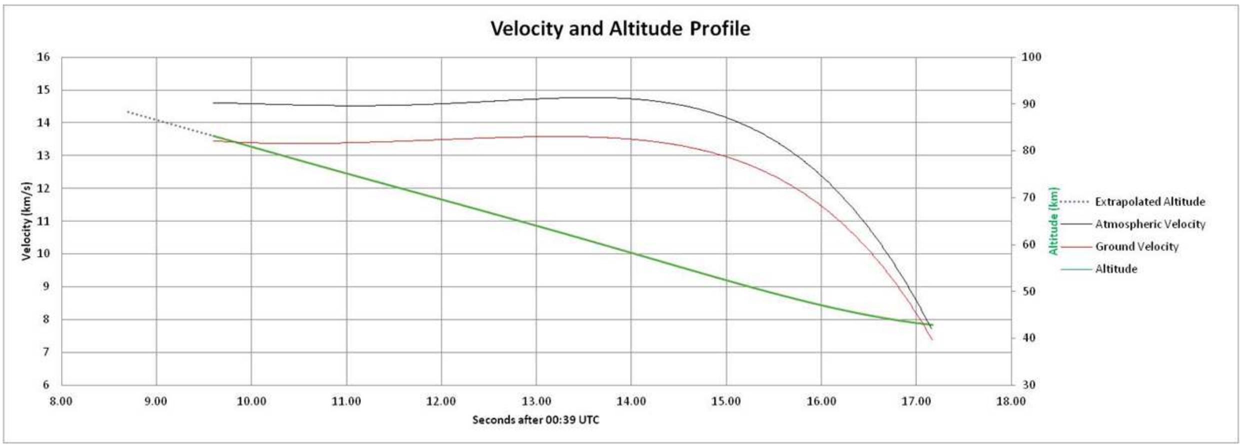

Figure 5 – Velocity and Altitude plots (data courtesy of SonotaCo).

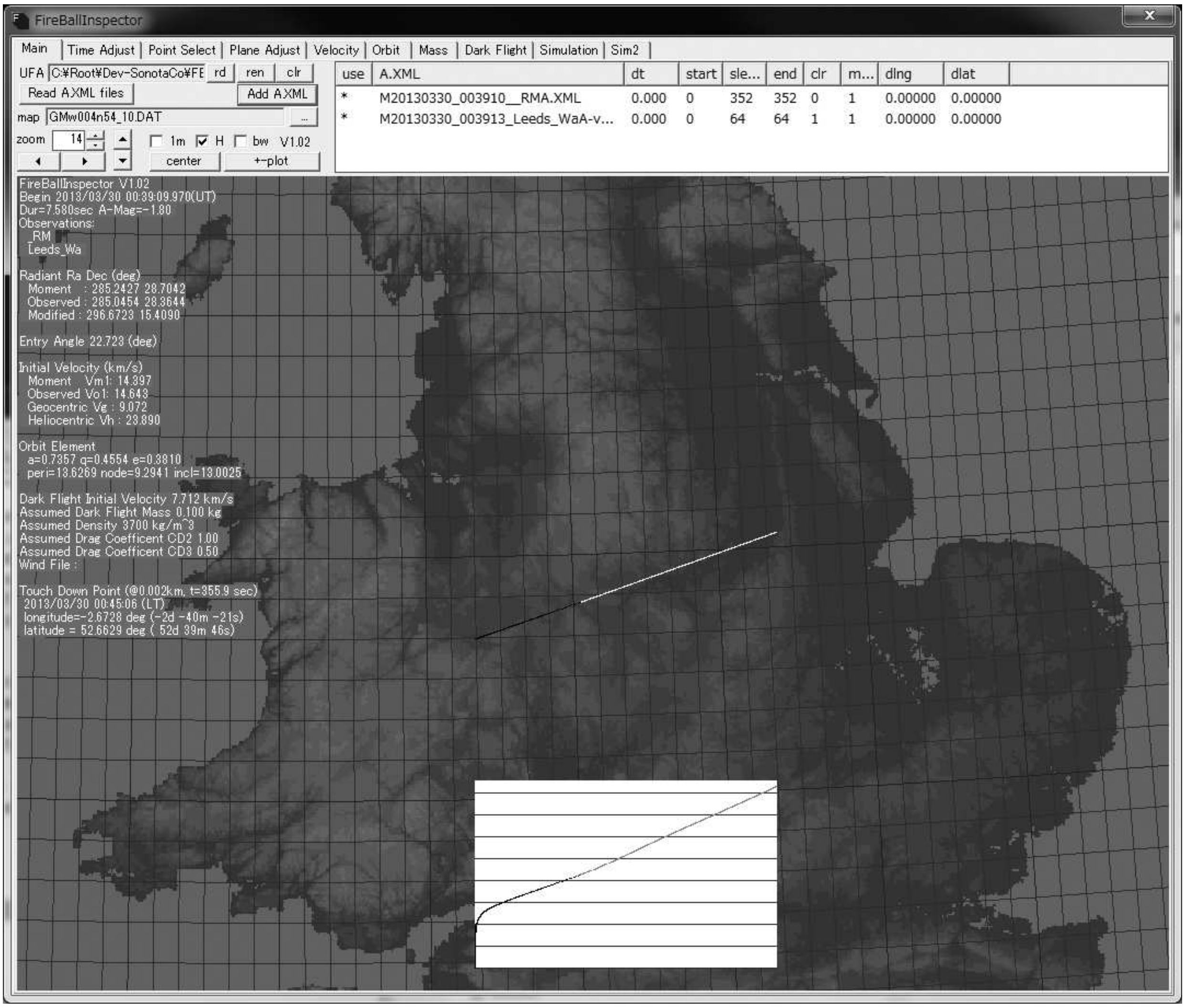

Figure 6 – FBI Ground track and altitude profile (courtesy SonotaCo).

Had there been a surviving object (or fragments thereof) they would have come down somewhere within a distribution or dispersion ellipse, the semi-major axis of which would be aligned with the trajectory. A touchdown point of 52°40′ N, 02°40′ W is given which lies approximately 7 km to the SE of Shrewsbury in Shropshire. This position lies on a bearing of 195.5° from Peter Drew's observing location and is approximately 12 km up-range from the point on the ground-track given by his extinction estimate of "just over 200°". From Christopher Hill's observing location the bearing of the touchdown point is 201.1° which is approximately 32 km downrange from his stated fireball extinction azimuth of 180°.

Based on typical densities, a 0.1 kg object would have a radius in the region of 20 mm. Due to the small size, the uncertainties in the extinction azimuth, assumptions in the analysis and the terrain in the vicinity of the touchdown point, the authors have not attempted to recover any fragments, should any fragments have survived down to the Earth's surface.

9 Observed Magnitude

The authors have been able to extract magnitude data from the Ravensmoor South-East video sequence between $00^h39^m09\overset{s}{.}5$ and $00^h39^m17\overset{s}{.}3$ using UFO Analyser (SonotaCo, 2007). There are some gaps in the data, particularly between $00^h39^m13\overset{s}{.}2$ and $00^h39^m15\overset{s}{.}2$ due, it is suspected, to limitations in the video system's ability to record very large and rapid fluctuations in brightness. Some magnitude data is also missing from the start and end of the trail. Variations in magnitude are apparent from Figure 2 and can also be seen in the video sequence on the author's website.

The observed magnitude is denoted by the solid black line in Figure 8. Attention is drawn to the observed magnitude (left hand) scale. Estimates of the magnitude of the meteor from visual observers are much higher than that indicated by the scale on the graph. There are a number of contributing factors to this, one of which is that the camera used, a Watec 902H, has an 8 bit sensor and therefore has 256 brightness detection levels. The camera system has been optimised for sensitivity to very faint meteors and as a consequence when very bright events occur, the CCD pixels become saturated. Another factor is that the algorithm implemented in UFO Analyser determines observed magnitude by comparing the brightness of the transient event (in this case the fireball) with the brightness of the reference stars within the FOV. In order to reject the effect

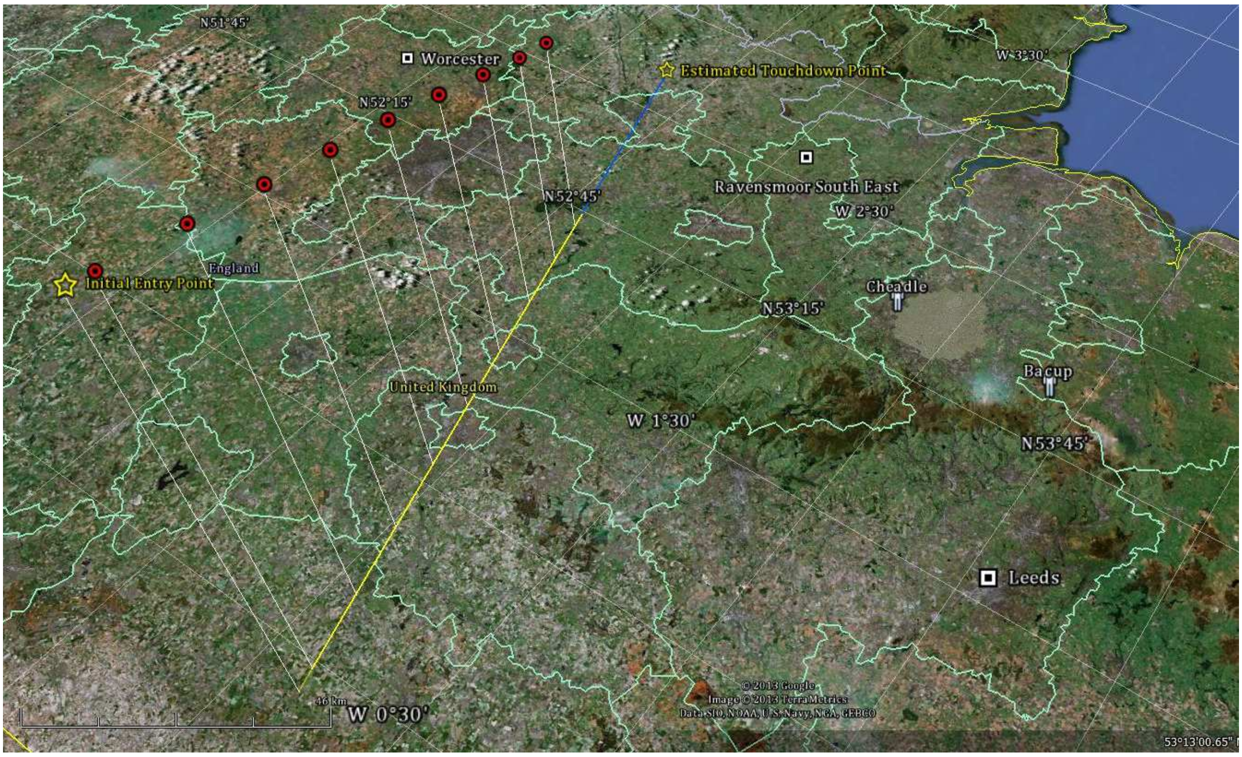

Figure 7 – Annotated ground track based on SonotaCo analysis of NEMETODE data and visual observations from an altitude of 200 km looking South-West. The red dots are time-markers for seconds with the first one after Initial Entry Point being $00^{\mathrm{h}}39^{\mathrm{m}}10^{\mathrm{s}}$ UTC on 2013 March 30.

of afterglow, the algorithm ignores those pixels that do not change in value in successive frames. This fireball was very bright and had a very low angular speed across the FOV – as a consequence the algorithm ignored the saturated pixels and hence underestimated the observed magnitude (SonotaCo, personal communication). Only the observed magnitude is underestimated, the magnitude variation data is still valid.

It is clear from Figure 6 and Figure 7 that the meteoroid's trajectory was taking it towards the Ravensmoor South-East camera. If the fireball had maintained a constant luminosity then the observed magnitude at Ravensmoor would therefore increase. It is also clear from Figure 2 that the observed elevation was increasing and from Figure 5 that the meteoroid altitude was decreasing. Both of these would reduce the dimming due to atmospheric absorption. Corrections were therefore applied in order to determine the absolute magnitude at each stage in the trajectory.

The magnitude at a distance of 100 km was calculated using the formula:

$$m_{100} = m_{obs} - (2.512 \log L_{inc}) \tag{1}$$

where m_{100} is magnitude at a distance of 100 km, m_{obs} is the observed magnitude and L_{inc} is the increase in luminosity given by the formula:

$$L_{inc} = (\frac{d}{100})^2 \tag{2}$$

where d is the distance (in km) between the observer and the meteoroid. The air mass along the observation line of site was estimated using the Rozenburg equation:

$$\text{Air Mass} = \frac{1}{\cos z + 0.025\mathrm{e}^{(-11 \cos z)}} \tag{3}$$

where z is the zenith angle (Rozenberg, 1966). Each air mass was assumed to lead to a reduction in magnitude of 0.28. As the decrease in vertical distance between the meteoroid and the observer was due to the meteoroid losing (as opposed to the observer gaining) altitude, the magnitude reduction factor of 0.28 was used for all calculations.

The absolute magnitude is denoted by the solid grey line in Figure 8. As expected, the variation in magnitude between maximum and minimum has been reduced, in this case from 2.5 to 1.5.

Many visual observers commented on the brightness of the object with some comparing it to that of the Moon or the ISS. The authors have taken account of these reports[3,4] and, based on observer locations and the trajectory, determined an average absolute magnitude of −10. However, these reports were more likely to be submitted by members of the public as opposed to astronomers and, as already noted, even experienced observers can reach different conclusions when attempting to quantify just how bright an object is, particularly when it occurs unexpectedly. In the absence of a range of reference objects it is not possible to say that an object was brighter than X but fainter than Y. Experience, the relatively large size and the slow angular speed can all contribute to an over-estimate of the brightness and for this reason the authors urge caution when attempting to draw conclusions from these estimates. Peter Drew estimated the maximum magnitude to be "*... at least* −8 ..." while Christopher Hill estimated it to be "*... at least* −5 ...". Applying equations (1), (2) and (3) for the meteoroid's estimated position at $00^{\mathrm{h}}39^{\mathrm{m}}15\overset{\mathrm{s}}{.}0$ leads to an absolute magnitude estimate

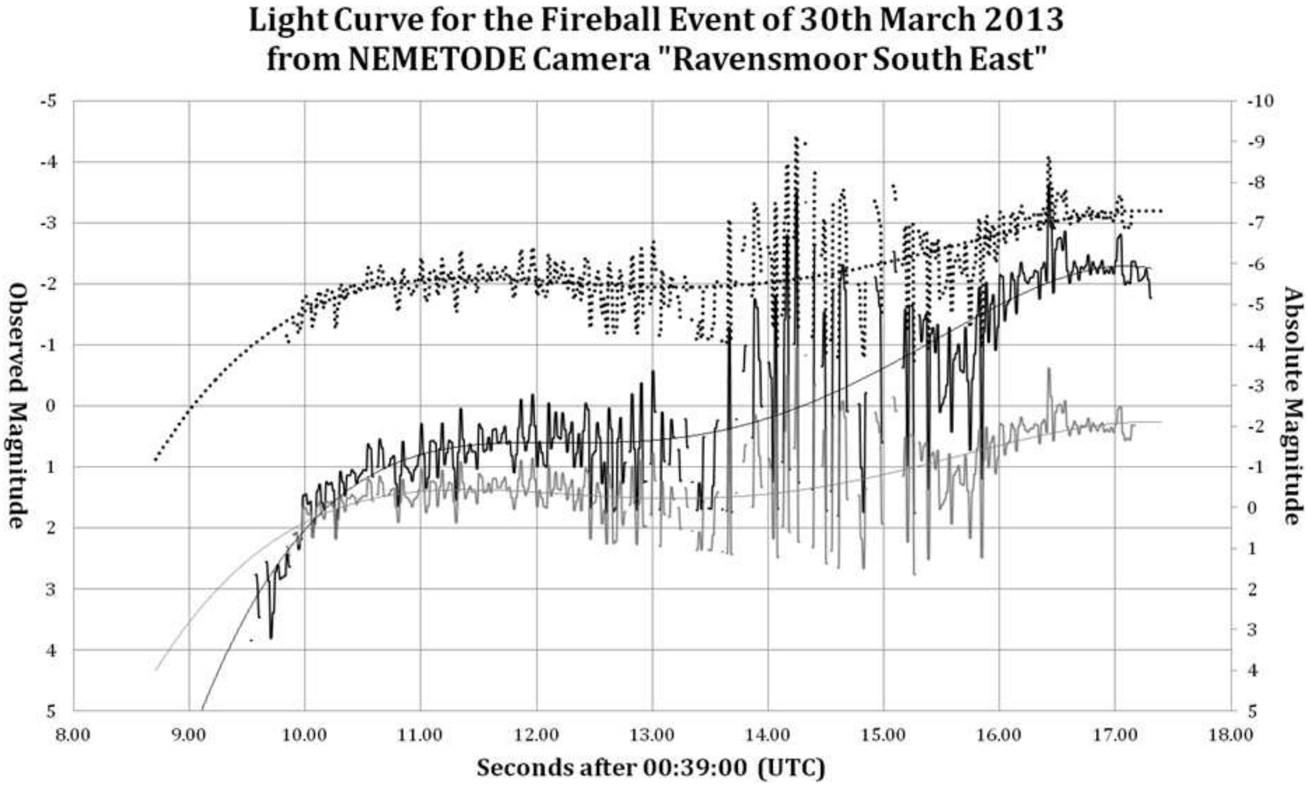

Figure 8 – Observed Magnitude (solid black line) extracted from the Ravensmoor South-East video sequence. The solid grey line is the Absolute Magnitude, taking account of distance and atmospheric extinction. The dotted black line is a scale adjustment of the Absolute Magnitude, correcting for the magnitude under-estimate in the original NEMETODE data.

of at least −8.8 for Peter Drew's observation and −5.2 for Christopher Hill's observation. Obviously there is a significant difference in these two values. Christopher Hill's observing location would have placed the fireball's path across the sky closer to the Moon but in the absence of additional information, it is difficult to draw any firm conclusions other than to place a lower limit of −5.0 on the maximum absolute magnitude.

The author's assertion that the Michael Morris video only showed the early stages of the fireball is further reinforced by noting that the fireball left the FOV of the Worcester camera no later than $00^{h}39^{m}12\overset{s}{.}6$ (time-code of $00^{h}39^{m}10\overset{s}{.}6 \pm 2$ s). Comparing this against Figure 8 (bearing in mind that Michael Morris timing data is accurate to ±2 s whereas NEMETODE timing data is accurate to ±0.1 s), it can be seen that this was prior to the fireball reaching its greatest magnitude. In order to convert the observed magnitude estimate of at least −4.5 into an absolute magnitude estimate, equations (1), (2) and (3) were applied for the meteoroid's estimated position at $00^{h}39^{m}12\overset{s}{.}6$ and an absolute magnitude estimate of at least −5.5 obtained for this early stage of the fireball. Applying the correction earlier (when the meteoroid was further from the observer) leads to an increase in the absolute magnitude estimate of 0.2 magnitudes per second (i.e. at $00^{h}39^{m}10\overset{s}{.}6$ the absolute magnitude estimate rises to −5.9).

As can be seen from the solid grey line in Figure 8, the Ravensmoor data shows the early stages of the fireball having an absolute magnitude of approximately −0.5. For reasons already discussed, this is known to be an under-estimate. By making use of the absolute magnitude estimate for the early stages of the fireball from the analysis of Michael Morris's data, a correction can be applied to the absolute magnitude for the Ravensmoor data to scale the absolute magnitude of the early stages of the fireball to match that obtained from the analysis of the Michael Morris data. The dotted black line on Figure 8 has this scale adjustment applied.

Having combined all these observations the authors conclude that the absolute magnitude was in the range −5 to −9 and, based on the available video evidence, suggest that an absolute magnitude of -7 ± 1 is a reasonable estimate.

10 Magnitude Variations from Ravensmoor Video Data

Commencing $00^{h}39^{m}09\overset{s}{.}5$, the first 1.5 seconds show a steady rise in brightness from observed magnitude +3.3 to +0.5 after which it remained reasonably constant for 2.5 seconds. Commencing $00^{h}39^{m}13\overset{s}{.}9$ there is a series of flickers / flashes accompanied by a brightening to an average observed magnitude of −0.8 with spikes to −2 and −3. This is accompanied by a broadening of the width of the fireball (see Figure 2). From $00^{h}39^{m}15\overset{s}{.}7$ the flickers / flashes stop but the observed magnitude continues to increase to an average maximum of −2.7 before reaching a plateau then decreasing slightly after $00^{h}39^{m}17^{s}$.

The video evidence suggests that the fireball had reached maximum brightness and was beginning to fade as it exited the FOV of the Ravensmoor South-East camera. Many of the visual observations mention that

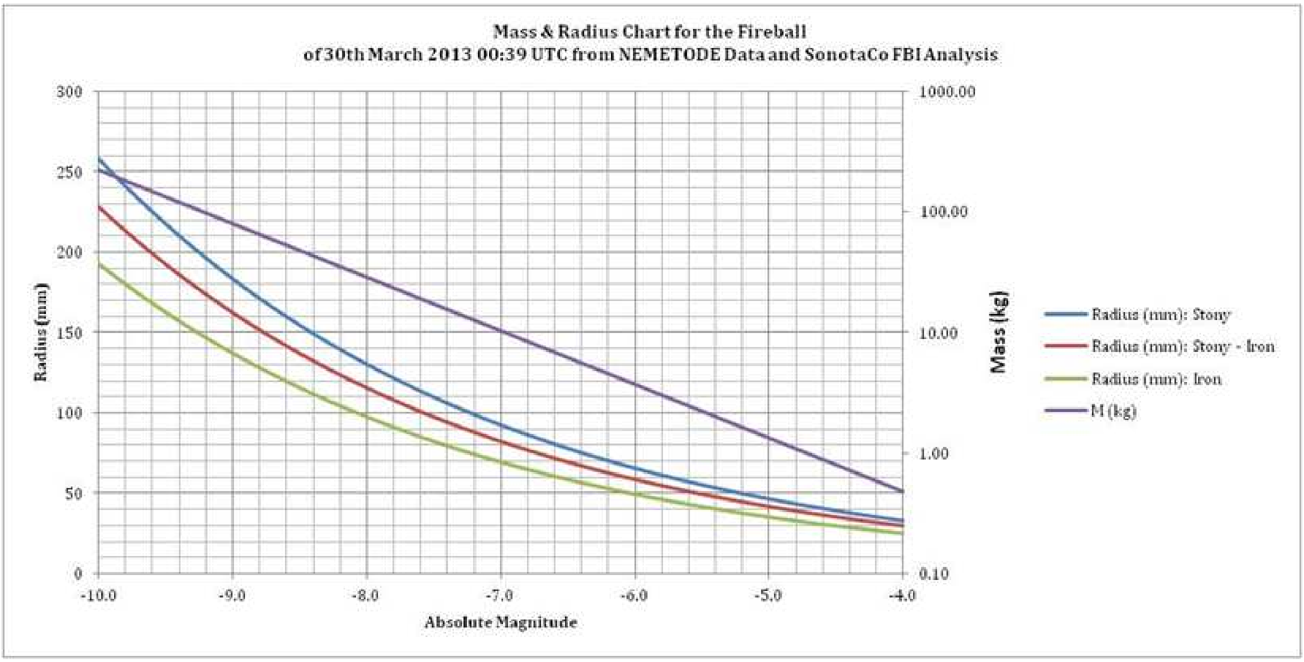

Figure 9 – Radius and Mass plot based on Jacchia's formula for the derived V_g and z from SonotaCo Data. Typical densities for Stony, Stony-Iron and Iron meteorites are assumed to be 3.2, 4.5 and 7.5 g/cm^3 respectively.

the object faded from view but it is not clear how abruptly this occurred. Christopher Hill mentioned that the *"Brightness remained constant before dropping suddenly to extinction. . . "* whereas Peter Drew stated that it *". . . gradually fade[d] to nothing. . . "*.

11 Fragmentation and Tail Development

There is a suggestion in Figure 2 and from the visual reports that during the course of the event a tail developed. Peter Drew described it as being "fan shaped" this may explain the significant broadening of the trail seen in the Ravensmoor data after $00^h39^m13\overset{s}{.}9$.

At least three visual observers mentioned fragmentation or parts falling away in their reports[4] (Hill C., personal communication). It is reasonable to suggest that commencing $00^h39^m13\overset{s}{.}9$ there was a fragmentation event (characterised by the aforementioned flickers / flashes) that gave rise to multiple trails that were too close together to be individually resolved by the NEMETODE cameras. As these fragments are likely to have a range of masses and cross sections, they would likely decelerate at different rates and a broad tail would develop. As can be seen from Figure 5, significant deceleration commenced at $00^h39^m14^s$.

Observer used many colours to describe the tail – predominantly orange and green but also red, yellow, blue and purple. It is not clear if these colours are due to the excitation of and subsequent photon emission from particular species of atmospheric gases or whether they are indicative of the meteoroid's chemical composition.

The authors have compared the data in Table 1 with the observation that the object was able to penetrate the atmosphere to an altitude of approximately 60 km (see Figure 5 and Figure 8) before undergoing the presumed fragmentation event. Taken together, this suggests that the meteoroid was possibly asteroidal in origin and the authors note that the orbital parameters bear some similarity to those of the Apohele family of Interior Earth Objects.

12 Meteoroid Size

Jacchia's formula for maximum visual magnitude

$$m_v = 4.84 - 2.25 \log M - 8.75 \log V_g - 1.5 \log \cos z \quad (4)$$

may be used to estimate the mass of a meteoroid from the maximum absolute magnitude where m_v is the maximum absolute magnitude, M is the original meteoroid mass, m_g is the geocentric velocity and z is the zenith angle (Jacchia et al., 1967). Figure 9 shows a plot of Radius and Mass against Absolute Magnitude for $V_g = 14.5$ km/s and $z = 67.2°$. Assuming a maximum absolute magnitude of -7, the authors estimate that the meteoroid had an original mass of the order of 10 kg and a radius of the order of 80 mm.

13 Conclusions

From a combination of visual and video observations the authors conclude that at $00^h39^m08\overset{s}{.}7$ UTC on 2013 March 30 a meteoroid of approximate mass 10 kg and radius 80 mm entered the earth's atmosphere at an altitude of 83 km and a zenith angle of 67.2° over Lincolnshire in the UK, producing a fireball with a duration of at least 8.9 seconds and an absolute magnitude of the order of -7. The fireball proceeded on a West-South-West trajectory over Nottinghamshire at approximately 14.5 km/s before fragmenting at an altitude of 60 km, rapidly decelerating and continuing over Derbyshire, Staffordshire and (in all likelihood) Shropshire. An estimate of the orbital elements suggests that the meteoroid may be related to the Apohele family of

Interior Earth Objects. The use of online social and reporting tools has been demonstrated to be of value in locating supplementary information to aid this type of analysis.

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[13] http://meteorobserver.proboards.com/index.cgi

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