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A fireball over the Isle of Skye

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On the cover

A fireball over the Isle of Skye

This spectacular view of a fireball, framed by the Cuillin mountains in the Isle of Skye, is a single frame from a time-lapse sequence imaged by Marcus McAdam on 2013 October 14. The complete time-lapse is available at **http://tinyurl.com/owcetzl.** A fuller analysis of this event, together with the resulting smoke train, is given in William Stewart's paper on page 75 of this *Journal*. *©2013 Marcus McAdam* (**http://www.marcusmcadam.com**)

A fireball over central Scotland on 2013 October 14

William Stewart

On the evening of 2013 October 14 several fireballs were reported over the British Isles. One was observed and imaged at 20:42 UTC over central Scotland and is notable for the smoke trail it deposited in the upper atmosphere. This trail persisted for at least 13 mins. and its evolution was recorded in a series of still images. This paper details the observations and provides an analysis based on the available imagery and witness reports. The possibility of a near simultaneous fireball over the Irish Sea is also discussed.

Figure 1. Marcus McAdam's fireball image (see also the front cover of this *Journal*). The field of view (H×V) is approximately 74°×40° and the two bright stars in the upper left are Hamal and Sheratan in Aries, with apparent magnitudes, corrected for extinction, of +2.4 and +2.9 respectively. The fireball itself passes down through the 'V' of Pisces from Andromeda towards Cetus. The intervening cloud makes it difficult to estimate the brightest portion of the fireball trail. Those with keen eyesight and knowledge of the sky will spot the planet Uranus in this image, partially obscured by the upper right hand edges of the cloud bisected by the fireball. (*Courtesy* ***www.facebook.com/MarcusMcadamPhotography)***

Observations

The highest resolution imagery of this event was fortuitously recorded on 2013 October 14 at 20:42 (all times UTC) by Marcus McAdam (MMc, **http://www.marcusmcadam.com/**), from a location at 57° 17' 31" N, 06° 10' 58" W, altitude 50m, near Sligachan on the Isle of Skye, who was taking a series of images for a time-lapse sequence.[1] The sky was reasonably clear, albeit with a significant amount of broken cloud. The Moon phase was 81% (mag –11.5, elevation 25° in the south).

MMc was using a Canon 5D II fitted with a 24mm TS-E f3.5 L II lens. The camera was mounted on a NEQ-6 German Equatorial mount, although the mount was not polar aligned: the RA axis was set to the vertical and the RA tracking set to the normal sidereal rate in order to have the planned time-lapse sequence pan horizontally across the landscape whilst maintaining a reasonably constant azimuth to the

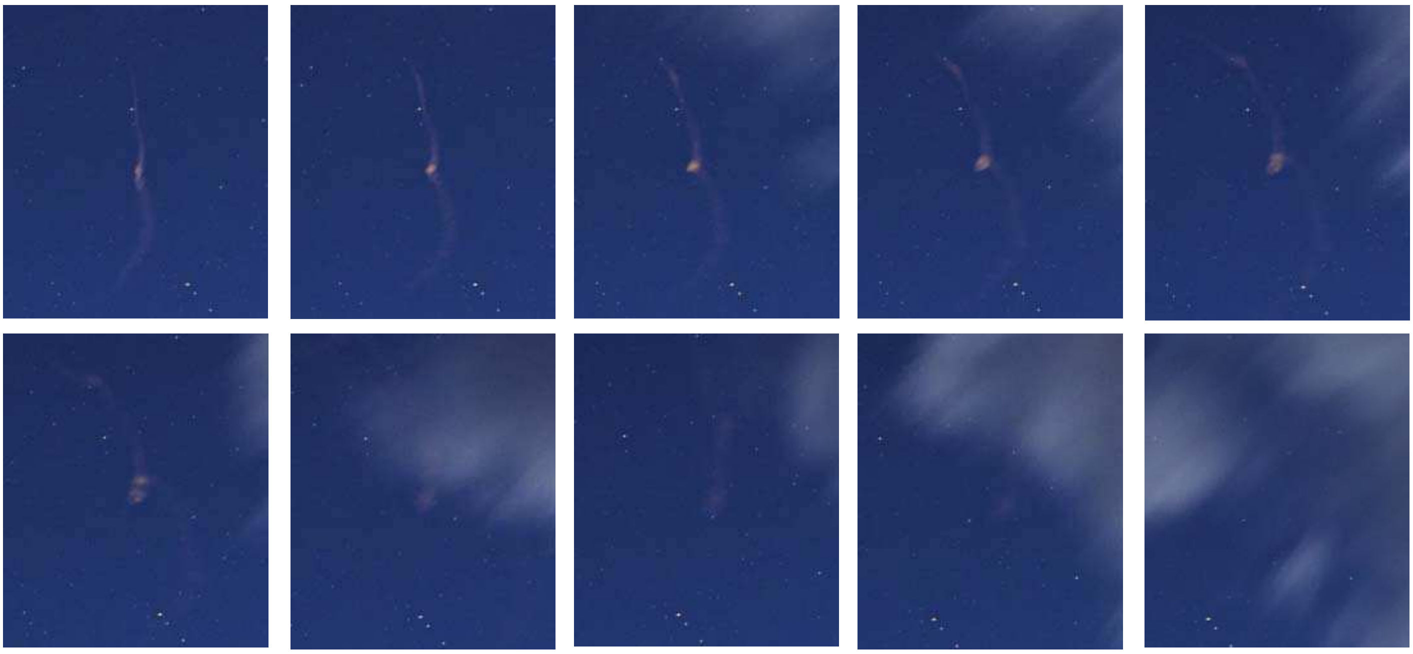

Figure 2. Cropped portions of Marcus McAdam's images of the persistent smoke trail at times +mm:ss after the fireball image. *Top row, left to right:* +00:30, +01:00, +01:30, +02:00, +02:30; *bottom row:* +03:00, +05:30, +08:00, +10:30, +13:00. An animation of the evolution of the persistent smoke trail is available on the NEMETODE website.[3]

Figure 3. Individual frames from Dr David Anderson's video of the event. The camera operates at 25 frames per second and two bright flares were visible in frames 48 and 52. The leftmost frame is no. 50. The centre image is the initial late flare while the final late flare is shown on the right. The bright star in the lower part of each image is Capella with Menkalinan to its lower left and Mirphak to the upper right. The fireball itself passes down through the eastern region of Ursa Major. Note the persistent ionisation train.

stellar positions within the field of view (FoV). Each exposure was 25 seconds at f/3.5 at ISO 1000 and the camera was pointed towards the south-east. The exposure interval was 5 seconds and the offset between the camera's onboard clock and UTC has been accounted for, leading to the conclusion that the event occurred between 20:42:12 and 20:42:37. The fireball image, which was the subject of a number of media reports,[2] is shown in Figure 1.

Having set the exposure sequence running, MMc retired back to the nearby Sligachan Hotel and was not aware the fireball had occurred until he reviewed the images the following morning. While the fireball itself is spectacular, the subsequent images are also of significant interest as they show the evolution of the resultant smoke trail in the upper atmosphere. Selected stills are shown in Figure 2 while a time-lapse is available on the NEMETODE website.[3]

This same fireball event was captured on video[3] by Dr David Anderson (DA) from 55° 16' 26" N, 4° 46' 40" W, altitude 84m (Low Craighead, near Girvan in South Ayrshire). DA operates a permanently mounted Watec WAT-902H2 Ultimate video camera fitted with a Computar ½" auto iris CS 4.5–12.5mm F1.0 lens in a waterproof enclosure. It was mounted at an azimuth of 39°, elevation 40°. Image capture was via *UFO Capture*[4] v2.22 and a series of stills is shown in Figure 3.

DA's timing has the event occurring between 20:42:09.6 and 20:42:13.0 (duration 3.4s) with the residual ionisation trail persisting for at least a further 0.6s at which point the video clip ends. While there is some overlap in the timings, DA has the event beginning 2.4s before MMc's exposure commenced. Neither party was using a live time correction utility; hence it has not been possible to determine which is the more accurate.

In addition to the photographic and video recordings, there was also a visual report[5] from Irvine in North Ayrshire at 21:42 (timestamp assumed to be BST), describing a bright flash to the north.

Table 1. Measured azimuths and elevations of key features in the MMc and DA images.

The smoke trail details are from the frame taken immediately after the fireball image (+00:30).

Feature	*MMc Az*	*MMc Elev*	*DA Az*	*DA Elev*
Start	126.024°	39.096°	06.376°	36.507°
Smoke start	125.286°	34.774°	(not visible)	
Smoke centre	125.449°	32.441°	(not visible)	
Smoke end	124.455°	29.377°	(not visible)	
Brightest	124.766°	27.461°	12.681°	25.783°
Initial late flare	124.051°	19.920°	15.153°	20.475°
Final late flare	124.016°	19.704°	16.041°	18.564°
End	123.892°	18.469°	16.143°	18.519°

A separate, simultaneous fireball?

Of note is a cluster of additional fireball reports time-stamped between 21:40 and 21:50 (again assumed BST). Observations from Devon,[5] West Yorkshire[6] and Cork[7] suggest there may have been a near simultaneous event over the Irish Sea. Additional fireball reports in this time period from Cheshire, West Yorkshire, Antrim, Co.Down, North Ayrshire and Kildare[5,6] are consistent with the confirmed event over Scotland or a postulated second event over the Irish Sea. The brightness was typically reported as being similar to that of the Moon and the majority of observers noted that the predominant colour was green.

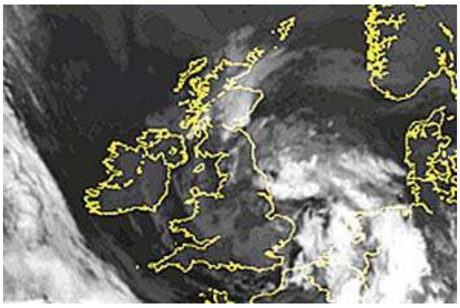

Figure 4. 10.8μm infrared satellite image showing cloud cover over and to the north of the British Isles on 2013 Oct 14 at 21:00 UTC *(courtesy of Sat24.com/Eumetsat/Met Office).*

The author has researched public domain video/photographic imagery but has been unable to find confirmatory evidence of this potential event over the Irish Sea – in the majority of cases the operational cameras that had the capability to detect it were either under a broad swath of cloud that lay across much of the British Isles (see Figure 4) or were not pointed towards the proposed event location.

Analysis

The stars of Aries and Pisces are clearly visible in MMc's fireball image. Key features in the fireball and smoke trail were measured against stellar positions using *Stellarium* v0.12.2,[8] configured to MMc's location and altitude and set to the temporal mid-point of each exposure. DA's video was reviewed frame by frame using *UFO Analyser*[4] in order to measure the azimuth and elevation of any corresponding features. In both cases the two flashes towards the end of the fireball trail are clear and unambiguous while the precise position of the brightest part of the trail in the MMc image had to be estimated as it was partially obscured by cloud.

The author had the greatest confidence in the commonality of the brightest part of the trail and in the initial and final late flares, and therefore used these to triangulate the trajectory. Having established the ground track, the azimuths and elevations from Table 1 were used to estimate the altitude of the key features in the fireball – these are given in Table 2.

Table 2. Derived altitude and locations of key features in the fireball and smoke trail

Figures for the smoke trail are estimates, due to the smoke having been shifted by upper atmospheric winds

Feature	*Alt. (km) (MMc img)*	*Alt. (km) (DA img)*	*Avge alt. (km)*	*Latitude*	*Longitude*
Start	104.52	108.50	106.51	56° 35' 10" N	004° 30' 28" W
Smoke start	097.55	N/A	097.55		
Smoke centre	088.01	N/A	088.01	56° 33' N	004° 19' W
Smoke end	083.36	N/A	083.36		
Brightest	074.76	069.65	072.21	56° 32' 24" N	004° 15' 17" W
Initial late flare	054.32	053.60	053.96	56° 31' 17" N	004° 09' 33" W
Final late flare	054.52	047.94	051.23	56° 30' 32" N	004° 07' 50" W
End	050.93	047.93	049.43	56° 30' 39" N	004° 07' 25" W

The fireball first became visible at an altitude of 106km, directly above a point 0.5km to the N of the western shore of Loch an Daimh, before proceeding on a bearing of 110°.6 at an entry angle of 23°.6 to the vertical. The smoke trail was deposited between altitudes of 98km and 83km to the SE of the loch with the centre being at an altitude of 88km above a point approximately 3km to the ESE of Moar. The values for the smoke trail are estimates as the smoke is not visible in the fireball image and the elevations are from the image taken immediately after the fireball image, by which time it had moved as a consequence of upper atmospheric winds.

The brightest part of the fireball was 72km above a point 2km east of the northern shore of Lochan na Lairige, while the initial and final late flares occurred respectively at altitudes of 54km and 51km over the western and eastern shores of the centre of Loch Tay. The fireball trail faded out 49km above a point 1km inland from the eastern shore of Loch Tay. The total observed ground track was 25km while the change in altitude was 57km.

Having established the ground track, the azimuth and elevation of the fireball in DA's video was measured over the first 25 frames (*i.e.* 1 second) after the fireball commenced and from this the average speed during the first second of re-entry was determined to be 20.9km/s. By this stage it had already descended to an altitude of 89.2km and hence would have undergone significant deceleration, but this value suggests a relatively low geocentric velocity which in turn may help explain why it was able to penetrate below 50km altitude.

From the ground track and entry angle a radiant position, not accounting for zenith attraction, is estimated as being RA 19h, Dec +57°, a position that lies between Cygnus and Draco. A review of the IAU MDC[9] does not show any good matches with known meteor showers. The closest is the October Draconids, though the fireball event occurred 7 days after their forecast peak.[10] The author therefore concludes that this fireball is likely to have been a sporadic.

Clearly this fireball came from a different part of the sky than the one observed earlier the same evening from the Isle of Lewis at 19:30[11] and hence the author concludes that the two events are unrelated.

UFO Analyser determined the maximum magnitude of the fireball from DA's video as being –5.6. MMc's image presented the opportunity to estimate the magnitude using a different source. The pixel values in the image are saturated (pixel value 255; MMc was capturing images in 8 bit .jpg format). The brightest part of the fireball trail is obscured by cloud and hence a line profile of pixel values, orthogonal to the fireball trail and crossing immediately prior to the cloud was taken and a normal distribution curve fitted in order to estimate what the values would have been had the pixels not saturated. Data from the red channel was used as those from the green and blue channels showed the greatest peak broadening due presumably to scattering from water vapour in close proximity to the cloud. This is shown in Figure 6, left.

A similar approach was adopted for the stars 71 Psc, 63 Psc, 60 Psc and HIP 3765 (the latter of which is shown in Figure 6, right) that are relatively close to the fireball and which have known apparent magnitudes (taking account of atmospheric extinction). The persistent ionisation train, being significantly fainter than the fireball, was assumed to make a negligible contribution to the profile. The maximum apparent magnitude can then be inferred via a comparison of the areas under the curves of the fireball and the four reference stars, and was determined to be +0.2±0.7.

This value will be an underestimate as the light from the stars had 25 seconds (the length of each exposure) to build up on the pixels in the image whereas the fireball, due to its movement across the sky, would have had much less time. Stellar trailing is apparent in MMc's image and close inspection shows it is approximately double the stellar width. The equivalent effective exposure duration for the stars was therefore estimated as 12.5 seconds.

From DA's video the fireball duration is estimated as 3.4 seconds. From MMc's image the fireball traversed a total of 2626 pixels and so the centre of the fireball is estimated to have spent 1.3ms over each pixel. This figure is an average that does not account for foreshortening while the fireball moved away from the observer. From the peak width in Figure 6, the trail width is esti-

Figure 5. Derived ground track of the fireball.

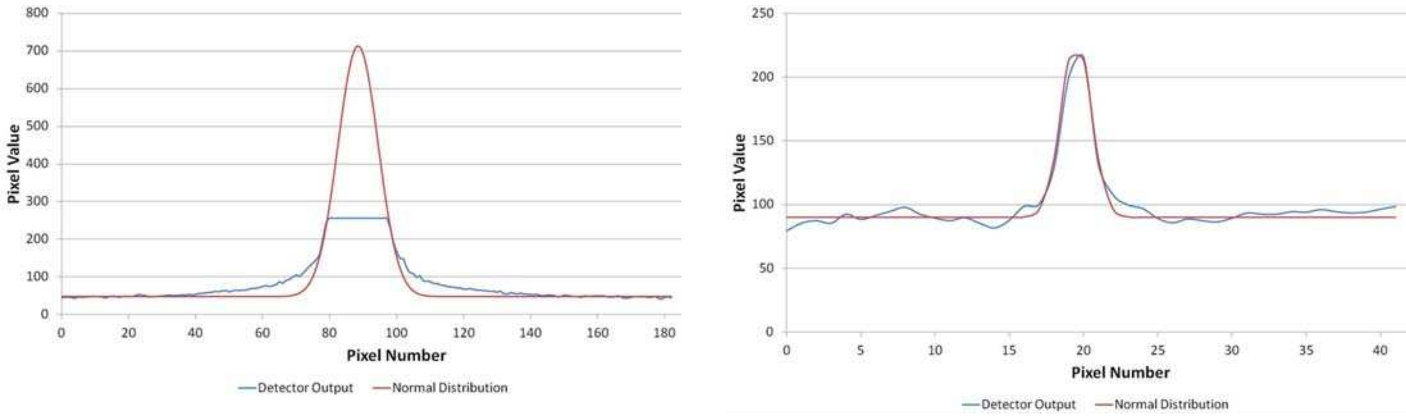

Figure 6. *Left:* Fit of normal distribution curve to orthogonal slice through a bright region of the fireball of 2013 Oct 14, 20:42 UTC. *Right:* Fit of normal distribution curve to slice through star HIP 3765 (apparent magnitude 6.11) from the same image.

mated as being 62 pixels, hence the fireball is estimated to have been over each pixel for 80ms which is 1/156 of the stellar effective exposure duration. Assuming a linear detector response a correction factor of ×156 may therefore be applied to the area shown in Figure 3, which raises the maximum apparent magnitude to –5.3. The distance to the brightest part of the trail from both observing locations is almost identical and hence the apparent magnitudes should be similar.

The author notes that the value derived from the MMc image is in good agreement with the *UFO Analyser* apparent magnitude estimate (–5.6) from DA's video.

The application of Rozenberg's equation[12] to account for atmospheric extinction was deemed unnecessary as in both cases the observed elevation of the brightest part of the fireball trail exceeded 25° and hence would have resulted in a correction of less than 0.1 magnitudes.

Fireball magnitudes are normalised to an absolute value defined as their apparent magnitude if they appeared at the zenith at an altitude of 100km (that is, through a single air mass). The magnitude at a distance of 100km was calculated using the formula:

$$m_{100} = m_{obs} - (2.512 * \log L_{inc}) \qquad [1]$$

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

$$L_{inc} = (d/100)^2 \qquad [2]$$

where d is the distance (in km) between the observer and the meteoroid.

Taking account of both MMc's and DA's apparent magnitudes, the average absolute magnitude is calculated as –6.3.

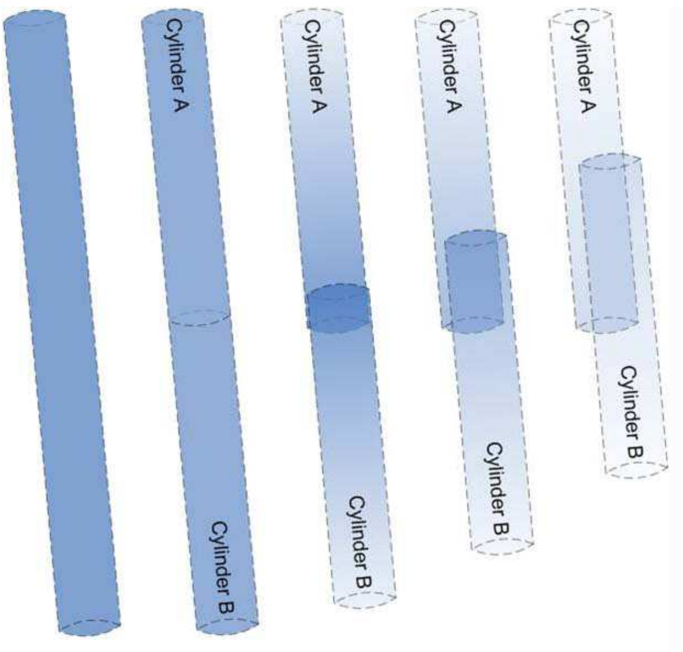

Figure 7. Diagrammatic representation of the evolution of the smoke trail. Following the initial deposition of the trail (left), wind-shear (indicated by the arrow) led to the lower portion of the trail (Cylinder B) moving forward and to the right of the upper portion (Cylinder A). From the perspective of the observer, the cylinders overlapped and hence brightened in appearance, particularly in those regions close to the wind shear boundary.

Smoke trail – analysis and discussion

The author notes that the smoke trail was deposited at an altitude 11–26km higher than the brightest part of the fireball trail and speculates that the smoke deposition may be the result of the vaporisation of a 'binding material' that was holding together a loose conglomeration of denser materials. In the absence of this 'binding material' the meteoroid rapidly fragmented, resulting in multiple trails and enhanced atmospheric ionisation, hence the increase in brightness. This is consistent with the 'dustball' model for meteoroids proposed by Hawkes & Jones.[13]

As the fireball penetrated ever deeper into the upper atmosphere, smoke was deposited in a shape resembling a cylinder for a vertical distance of the order of 14km (see Table 2). If the wind speed and direction was constant across all altitudes, an observer would expect to see the cylinder retain its shape, though the effects of perspective may make the base of the cylinder appear to slowly rotate towards or away from the observer depending on the wind direction. It is reasonable to assume that the wind speed and direction across such a vertical distance is unlikely to be constant and that there would be a particular altitude where there is an abrupt change, a phenomenon known as wind shear. The author therefore proposes the following in order to explain the evolution of the shape of the smoke trail.

Consider the aforementioned cylinder to be split into two sections, the break occurring at the bright region visible in the upper-left image in Figure 2. Let the upper section be 'Cylinder A' and the lower one 'Cylinder B' (see Figure 7). While both cylinders continue to move to the right, Cylinder B has an additional motion that brings it towards the observer faster than Cylinder A.

This has two consequences. Firstly, a bright region appears where the top of Cylinder B overlaps the bottom of Cylinder A (the brightness therefore being a consequence of there being more smoke along that particular line of sight as opposed to being due to additional smoke being deposited at that particular altitude). Secondly the top of Cylinder B appears to be at a higher elevation than the bottom of Cylinder A. The ring like structures seen in successive frames are the ends of the cylinders with the upper one being the top of Cylinder B and the lower one the bottom of Cylinder A. Clearly both cylinders have moved since being created and hence their precise positions are estimates but the ring width is judged, based on the angular separation of the two sides, to be of the order of 1.2km.

At the wind shear boundary, the speeds would have been relatively low with higher wind speeds expected at increasing distances from it. This helps to explain why the parts of the cylinder close to the boundary are so long lived – the lower winds speeds would have meant that they would take more time to dissipate. The progressive deviation in the linear shape of each cylinder clearly indicates differing wind speeds at various altitudes.

The presence of the smoke trail provides an opportunity to estimate the wind speed in that region of the upper atmosphere. The fastest angular displacement was observed to be on the mid-section of the lower half of the trail (the mid-point of Cylinder B) and hence this was chosen. The author assumed (from Table 2) that this part of the trail lay at an altitude of 85km and did not undergo significant vertical displacement during the first 2½ minutes (5 frames) after the fireball had occurred. The nebulous nature of the smoke trail (and the associated difficulty in identifying a constant feature within the trail) made it difficult to make precise measurements but an average value for the change in azimuth of $1.34° \pm 0.18°$ per minute was established. No significant change in elevation was observed. Combining this result with the range to the smoke trail (from Table 2) resulted in a wind speed estimate at an altitude of 85km of 232 ± 32 km/h. The brightest part of the smoke trail (the bottom and top of Cylinders A and B respectively) had an angular speed of approximately half this value and hence the wind speed at an altitude of 88km was estimated to be of the order of 115km/h.

These values are significantly lower than those recorded by B. Ward (BW) who observed a Geminid persistent train moving at 499km/h at an altitude of 80km.[14] U. von Zahn observed a value of 72km/h[15] while N. Bone noted 400 km/h.[16] To echo BW's conclusions,[14] this wide range serves to demonstrate the highly variable and dynamic environment that exists in the upper atmosphere. In addition, this event is another example of a smoke trail resulting from a relatively slow meteor, similar to the event observed by BW and contrary to the view that persistent trains are formed only by high velocity meteoroids.[17]

Conclusions

On 2013 October 14 at 20:42 UTC a fireball with an absolute magnitude of the order of –6 was observed to proceed on an east-southeast trajectory over the western extremities of Perth and Kinross in Scotland, just north of the border with Stirling. A smoke trail that persisted for at least 13 minutes was recorded and has allowed an estimate of the atmospheric wind speed at an altitude of 85km of 232km/h to be determined. The absolute magnitude and altitude penetration do not suggest a high probability that recoverable fragments could be obtained, particularly as the likely dispersion ellipse is over rugged terrain.[18] The value of high resolution, long duration DSLR imagery for recording the after effects of a passing meteor is noted. Finally, the possibility of a near simultaneous fireball over the Irish Sea is highlighted.

Acknowledgments

The author is deeply indebted to Marcus McAdam and Dr David Anderson who willingly shared their observations – without their generosity, much of this paper would not have been possible. Thanks also to those other individuals who took the time to report their observations and to Mark Bailey from Armagh Observatory for passing on the author's request for additional information. The author also wishes to acknowledge a valuable and insightful discussion with Dr John Mason regarding the morphology and evolution of the smoke trail and to Alex Pratt for his critical assessment of early drafts of this paper.

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Footnote

David Anderson's observation and subsequent contribution to this paper has led directly to his making a number of enhancements to his camera system and he is now a valued member of the NEMETODE observation team.

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