

Green fireballs and ball lightning

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This paper presents evidence of an apparent connection between ball lightning and a green fireball. On the evening of the 16 May 2006 at least three fireballs were seen by many people in the skies of Queensland, Australia. One of the fireballs was seen passing over the Great Divide about 120 km west of Brisbane, and soon after, a luminous green ball about 30 cm in diameter was seen rolling down the slope of the Great Divide. A detailed description given by a witness indicates that the phenomenon was probably a highly luminous form of ball lightning. A hypothesis presented in this paper is that the passage of the Queensland fireball meteor created an electrically conductive path between the ionosphere and ground, providing energy for the ball lightning phenomenon. A strong similarity is noted between the Queensland fireball and the Pasamonte fireball seen in New Mexico in 1933. Both meteors exhibit a twist in the tail that could be explained by hydrodynamic forces. The possibility that multiple sightings of fireballs across southeast Queensland were produced owing to fragments from comet 73P Schwassmann–Wachmann 3 is discussed.

Keywords: ball lightning; green fireballs; meteors; corona discharge; sprites; bolts from the blue

1. Introduction

The term *green fireball* is often associated with meteors of sufficient velocity and mass to create a shockwave hot enough to produce highly luminous green fireballs. There have been numerous sightings of green fireballs, probably the most notable being the Peekskill Meteor seen by many people in the American northeast on the 9 October 1992 (Brown *et al.* 1994). The green colour is thought to be due to ionized oxygen and has been reported as being similar in colour to green aurora owing to 557.7 nm emission from metastable neutral oxygen (Halliday 1960). The term green fireball is also associated with objects historically seen in the vicinity of research and military installations in New Mexico such as the Los Alamos and Sandia National Laboratories (http://en.wikipedia.org/wiki/Green_fireballs).

Ball lightning has been the subject of a great deal of interest (Donoso *et al.* 2006), and although many mechanisms of production have been postulated (Turner 1998), a complete theory remains elusive (Stenhof 1999). Theories that have been put forward to explain ball lightning include antimatter (Ashby & Whitehead 1971), electromagnetic standing waves within a ball of plasma (Watson 1960), retinal after images (Argyle 1971;

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Charman 1971), electromagnetic knots (Ranada & Trueba 1996), oxidation of nanoparticles (Abrahamson & Dinniss 2000), corona discharge generated by dissipating electrical ground currents (Lowke 1996), microwave interference (Ohtsuki & Ofuruton 1991), plasma surrounded by hydrated ions (Turner 1994), superconducting plasma vortices (Dijkhuis 1980), polymer composites (Bychkov & Bychkov 2002), light bubbles (Torchigin & Torchingin 2007) and even black holes of cosmic origin (Muir 2007). Ball lightning is usually associated with thunderstorms, although it has been associated with earthquakes and volcanoes (Durand & Wilson 2006).

2. Sightings of a fireball over Queensland on 16 May 2006

On the evening of Tuesday 16 May 2006, a bright light was seen passing over the city of Brisbane and the Gold Coast in southeast Queensland, Australia at about 06.18 h (08.18 h UTC). Sunset occurred at 17.00 h and the Moon (2 days past full) was below the horizon. Venus was not visible being a ‘morning star’ at this time. Numerous people in Brisbane reported the sighting to the local media and some photographs taken with mobile phone cameras were sent to a local TV station. Air traffic controllers in the control tower of the Brisbane airport also saw the fireball. Reports of the sighting appeared in the *Courier Mail*, which is the main newspaper for Brisbane (Finnila 2006; Thompson 2006).

A New Zealand newspaper, *The Christchurch Press*, reported that a commercial airline pilot coming in to land at Wellington reported seeing a meteorite breaking up as it entered the Earth’s atmosphere. Further information obtained by the author from the Rescue Coordination Centre (RCC) in Wellington, New Zealand, revealed that the pilot saw the meteor shatter into three pieces, which turned green as they descended. The RCC received calls from people in Westport, Nelson and Paraparaumu who reported seeing green, blue and red–white flares at about 19.20 h local time (LT) (07.20 h UTC). These sightings are just 1 h earlier than the Queensland fireball sightings suggesting a possible connection. The sightings were out to sea, i.e. in the direction of Australia.

The author was contacted by a local TV station and asked to comment on some photographs of the phenomenon sent in by the public. (Three of these photos are presented in this paper.) Information was also supplied to the author by acquaintances that actually saw the fireball. From news reports, it was apparent that the fireball was seen by a large number of people over a wide area of stretching from Caboolture to the north of Brisbane to the Gold Coast and Ballina to the south in New South Wales (NSW). An online survey was developed and conducted to find out more about the object, in particular to ascertain the geographical area over which the fireball was seen. It was also hoped that some video material would have been forthcoming to enable orbital data to be obtained—as was the case for the Peekskill meteor, for example.

The online survey, advertised by a university press release, resulted in 148 responses, 126 of which were deemed to be reports of genuine sightings (i.e. correct date, time of day, etc.). In addition, some people responded to the request for further information by sending letters to the author rather than filling in the online survey. Unfortunately, no extra photographic or video materials were

forthcoming. The author contacted some of the survey respondents and people who sent photos to the TV station for further information.

Common descriptors in the survey data were the brilliance of the light. One respondent described the light as being much brighter than the Moon but not as bright as the Sun. Many respondents emphasized the green colour of the ball—one respondent noted that the light was ‘traffic-light’ green. Many people also noted explosions and fragmentations. The speed of the object was also noted; in most cases, the object was seen only for a few seconds.

Several respondents noted that the fireball appeared to follow a horizontal trajectory; in particular two people reported that they originally thought the fireball was some kind of electrical phenomenon associated with nearby power lines. Taken as a whole, the reports received are consistent with the object being a green fireball of meteoric origin rather than space junk returning to Earth, which was a possibility suggested by some astronomers at the time.

The survey revealed that the fireball was seen over a much larger area of Queensland than originally appeared to be the case from media reports in the southeast of the state. For example, the fireball was seen as far south as Ballina in northern NSW, and as far north as North West Island on the Great Barrier Reef about 600 km northwest of Brisbane. Sightings were also reported at a location 30 km south of Mitchell in central Queensland, about 500 km west and inland of Brisbane. There were numerous other sightings within this area, mostly along the coast between Brisbane and Gladstone (figure 1).

The key sightings are summarized as follows. One fireball was seen passing over Brisbane heading in a northwest direction and seen from Caboolture, Bribie Island, Buderim, Maryborough, Bundaberg and Fraser Island. Although no photographs of this northern fireball were forthcoming, figure 2 shows a drawing produced by a graphic designer who observed the fireball from Burpengary (just below Caboolture, figure 1) north of Brisbane. Significantly, the fireball was seen travelling in a northwest direction and to extinguish close to the zenith at Iveragh, about 30 km south of Gladstone. A group of school students at a campsite on North West Island, 75 km northeast of Gladstone, saw the fireball in the south. These two sightings mark the upper boundary of the track of this ‘northern’ fireball.

However, another group of people reported seeing the fireball travelling in an east–west direction over Brisbane and the Gold Coast, and extinguish to the west of Toowoomba about 120 km to the west of Brisbane. A number of people reported seeing the fireball fairly high in the sky (i.e. at an elevation of about 45° or above) in the vicinity of Toowoomba. Every single person reported that this fireball travelled in an east–west direction. A person driving from Warwick to Toowoomba saw the fireball passing behind a hill and noted that it appeared to be disintegrating with sparks being ejected. Another person heading north out of Warwick saw the fireball pass directly overhead. A group of observers camping on the beach at Waddy Point on the east coast of Fraser Island saw the fireball low on the horizon in the southwest.

A very interesting photo was taken by a member of the public of a fireball travelling over the Central Business District (CBD) of Brisbane (figure 3*a*). A number of features should be noted. The person taking the photo was clearly taking a photo of the CBD and fortuitously took the photo just as the fireball was passing. If a photo had been taken of only the fireball, we would expect

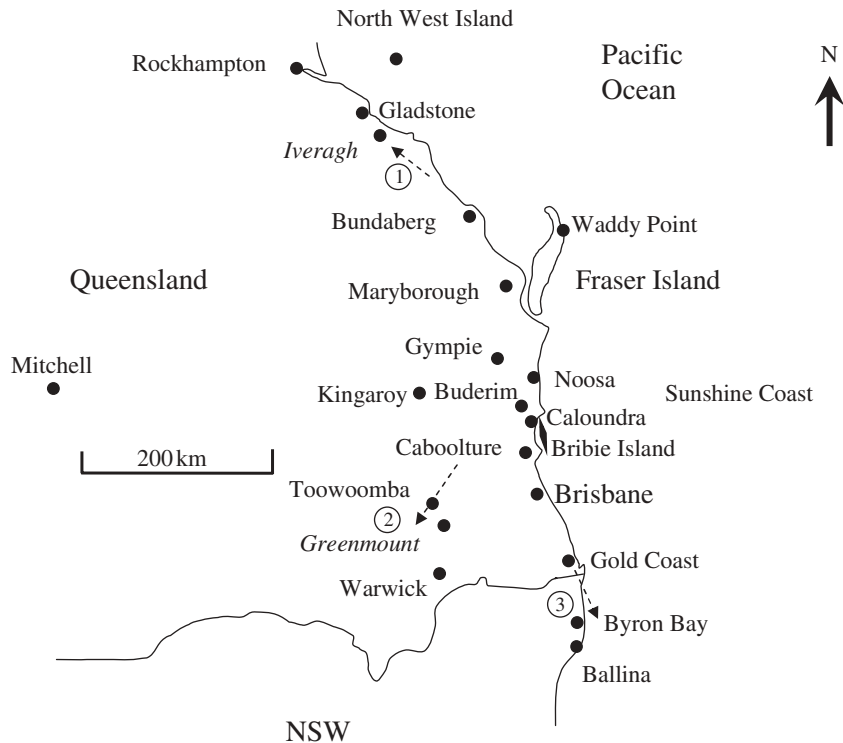


Figure 1. Map showing locations of some of the fireball sightings in Queensland and northern New South Wales (NSW). (1) One fireball was seen to extinguish above Iveragh, about 30 km southeast of Gladstone after travelling in a northwesterly direction. The fireball made a fizzing sound and extinguished without an explosion. (2) A second fireball was seen passing overhead somewhere between Warwick and Toowoomba and was travelling in a southwesterly direction. This fireball was seen by a number of people in towns around Toowoomba and was associated with some form of ball lightning seen rolling down the slope of the Continental Divide near Greenmount. (3) A photograph of a third fireball over the Gold Coast region was taken from the Brisbane CBD.

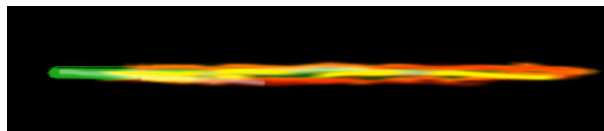


Figure 2. A diagram of the ‘northern’ fireball drawn by graphic designer, David Sawell of Burpengary (about 7 km south of Caboolture), who saw the fireball travelling in a northwest direction. The character of this fireball seems to be different from the western and southern fireballs. (Online version in colour.)

the fireball to be somewhere in the centre of the photo. In this photo, none of the pixels constituting the fireball has saturated and there is a smooth transition from the main body of the object down to the tail. The object is clearly green or blue/green in colour. That only one photo has been made publicly available, suggests that the object was only visible for a few seconds. There tends to be a

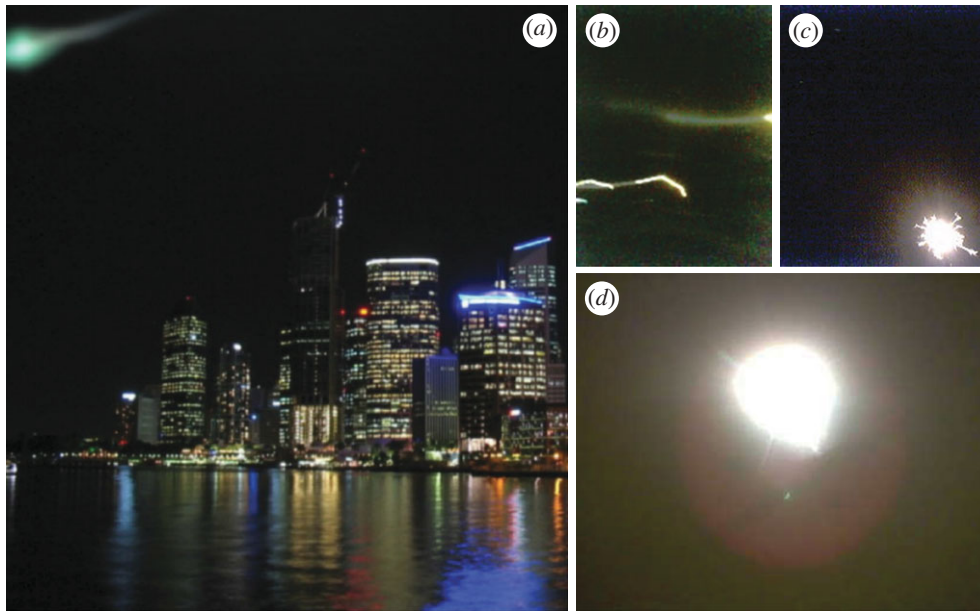


Figure 3. (a) Photograph taken by a member of the public from the CBD of Brisbane. The presence of the trail indicates that the fireball could be at a height of 80–100 km. A visit to the place where the photo was taken ascertained that the fireball was about $40 \pm 5^\circ$ above the horizon, in which case the fireball could have been 95 km away and, therefore, somewhere above the Gold Coast. Given that this fireball is directly south and that the trail lies in the direction of motion, the fireball was travelling in a southeasterly direction. Note the similarity between the trail in this photo and in (b) taken at the Gold Coast. (This photo was first published in the Brisbane based *Courier Mail* newspaper, which obtained it from the *Channel 9* TV station in Brisbane). Note that the city lights are in focus, therefore, the tail cannot be a blurring effect owing to camera motion. This is probably the fragment seen by witness P.V. break away from the fireball heading for Greenmount and heading south. (b) Mobile phone photo of the edge of the fireball and trail taken from Palm Beach, Gold Coast, Queensland, showing what is probably a green ionization trail. The green ionization trail indicates that the fireball was probably 80–100 km above the ground and moving faster than 20 km s^{-1} . The bright trails beneath the main trail are probably owing to fragments that have broken off from the main fireball. (c) Mobile phone photo of fireball passing over Brisbane showing the object undergoing fragmentation. The sharp tracks emanating from object indicate that these are not due to camera shake. Several observers noted debris in the tail. The main body of the object is so bright that the pixels are clipped at their maximum value. However, the pixel values of the explosion tracks are slightly under the maximum value. (d) Photo of the fireball passing over Brisbane. Note the oval shape. This photo gives a sense of the intense brightness of the fireball. In this case, the pixels in the centre of the photo are saturated owing to the brightness of the fireball. There is some evidence of fragmentation tracks. (Online version in colour.)

large number of people with cameras and mobile phone cameras in a CBD and, therefore, were the object visible for several minutes, we would expect several photographs to have been taken and made public owing to the very unusual nature of the object.

The author visited the location where the photo was taken and estimated the direction of the fireball as being nearly directly due south with an elevation of $40 \pm 5^\circ$. The presence of the green ionization trail in the photo indicates that the

fireball was probably at a height greater than 80 km, since most trails occur at a height of 80–100 km (Trowbridge 1907). If this was the case, then the fireball was in fact somewhere above the Gold Coast. Note the similarity between the trail in this photo and a photo taken from the Gold Coast in figure 3*b*. The photo of the fireball in figure 3*a* is very similar to a photograph of the Pasamonte meteor taken in 1933 (Nininger 1934*a*), which is discussed in more detail later in this paper.

The fact that a fireball was seen travelling in different directions and to pass overhead at locations separated by about 600 km (i.e. Iveragh in the north, Toowoomba in the west and the Gold Coast in the south) indicates that at least three fireballs were involved. Since fireballs are known to extinguish at a height of about 20 km (Halliday *et al.* 1978), it would be impossible to observe the same event close to the zenith at locations separated by 600 km. This may be the first time that at least three fireballs have been observed at about the same time. In this paper, these three fireballs will be designated the northern, western and southern fireballs, respectively.

The fact that at least three fireballs were seen is itself noteworthy. It is extremely unlikely that three unrelated fireballs would enter the atmosphere at the same time. A possible explanation is that a large meteor exploded in the upper atmosphere somewhere between Brisbane and the Gold Coast producing fragments that travelled away from each other at an angle.

3. All-sky camera images

During the course of this research, the author discovered two images taken by an all-sky camera at Siding Spring Observatory (SSO), NSW, Australia, part of the Night Sky Live network (<http://nightskylive.net/index.php>). The images were taken on the evening of 16 May 2006 at 19.24 h and 19.28 h LT (09.24 h and 09.28 h UTC) and can be downloaded (<http://nightskylive.net/sd/sd060516.html>). The image taken at 19.24 h LT shows an elongated nebulous patch close to Jupiter. The image taken at 19.28 h LT shows an elongated object more luminous than Jupiter. The observing log for the Anglo Australian Telescope (AAT) for the night of the 16 May 2006 was accessed (http://site.aao.gov.au/AATdatabase/aat/log_book.html). Observing conditions were clear all night with a seeing of 1.4 arcsec when the images in figure 4 were taken. Soon after the all-sky images were captured, the seeing reduced to 1.1 arcsec and remained at that value for the remainder of the night. There appears to be no cloud visible in the Night Sky images so the night was probably photometric and therefore, it is unlikely that the nebulous regions were random patches of cloud.

The time of these two observations is close to 1 h later (09.24 h compared with 08.18 h UTC for the southeast Queensland observations). It is tempting to display these two images as a movie loop, which gives the semblance of an object to the east of SSO (i.e. towards the coast) on a southerly trajectory. However, the two images do not necessarily show the same object as images were taken 4 min apart and the second image shows a brighter object. Normally, we would expect a faint trail to follow a bright object. It is possible that the Siding Spring sighting is connected in some way to the Queensland fireball events.

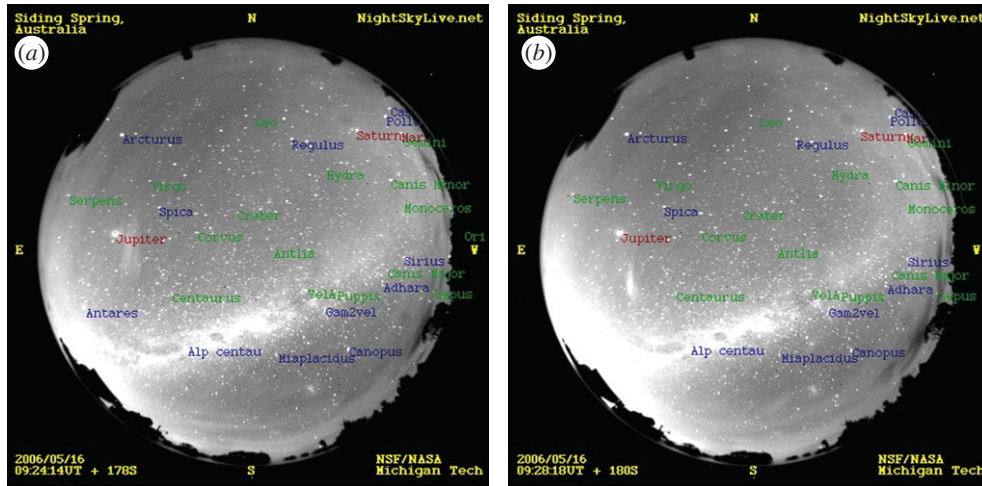


Figure 4. Two all-sky camera images taken at the Siding Spring Observatory, NSW, Australia, on the night of 16 May 2006 at 09.24 h UTC (a) and 09.28 h UTC (b) (<http://nightskylive.net/sd/sd060516.html>). An elongated nebulous region is seen close to Jupiter. In view of the photometric conditions and stable seeing on the night of the 16 May 2006 it is unlikely that the nebulous patch is due to random cloud. (Online version in colour.)

4. Infrasound data

Data from infrasound detectors in Australia and the South Pacific were analysed for signals that may have been generated by the fireball. An International Monitoring System (IMS) has been set up to detect violations of the Comprehensive Nuclear Test Ban Treaty (CTBT) that comprises a range of detectors including infrasound transducers. Fireballs are regularly detected by IMS infrasound sensors either as shock waves or bolide explosions. The Australian component of the IMS has three infrasound sensors: IS07 at Warramunga (about 20 km north of Tennant Creek) in the Northern Territory, 2080 km from Brisbane, IS05 at Hobart, Tasmania, 1770 km from Brisbane and IS04 at Shannon, Western Australia and 3590 km from Brisbane.

Infrasound data from 26 April to 26 May 2006 were checked for signals that could have been generated by a meteor but only one possible meteor signal was detected that could have been due to a meteor. This was detected by IS07 at 10.47 h UTC, 16 May 2006. The 0.4–2 Hz component of the signal indicated a steep trajectory at a velocity greater than 4 km s^{-1} , and the 2–7 Hz band indicated that the object was travelling with a velocity greater than 5 km s^{-1} with a backazimuth ranging from 31° to 90° over a period of 40 s. Infrasound data from IS22 in New Caledonia were checked for 16 May but no potential meteoric signal was detected.

Since bolide explosions can be detected over distances greater than 10 000 km, it can be concluded that no such event was associated with the Queensland fireball sightings. This means that it is unlikely that the northern, southern and western fireballs were the result of the explosion of a parent body within the

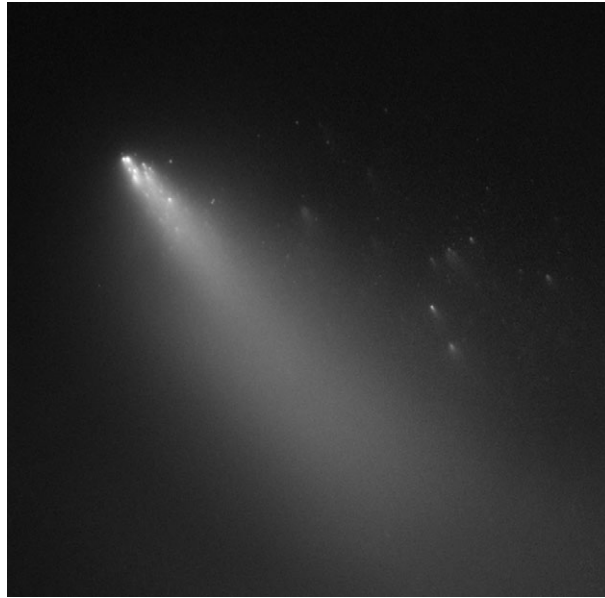


Figure 5. Image of comet 73P taken by the HST on 18 April 2006 (NASA, ESA, H. Weaver (APL/JHU), M. Mutchler and Z. Levay (STScI)).

atmosphere, but rather entered the atmosphere independently. Unfortunately, owing to security issues, data from US Department of Defense infrared satellites could not be obtained to check for a bolide explosion.

5. Comet 73P/Schwassmann–Wachmann 3

An interesting question is whether the New Zealand and Australian observations between 07.20 h and 10.47 h UTC could be due to fragments of comet 73P/Schwassmann–Wachmann 3 (Wiegert *et al.* 2005). It is interesting to note that at the time of all the sightings, the radiant of the τ -Herculid meteor shower was less than 20° below the northeast horizon. One of the eyewitness at Greenmount, Queensland, saw the fireball travelling from the northeast, which would be more or less exactly in the direction of the τ -Herculid radiant although the radiant was below the horizon.

Prior analysis of the orbit of 73P indicated that fragments would be unlikely to reach the Earth. For example, Wiegert *et al.* (2005) calculated that some of the fragments, C, B and E would pass within 0.0515, 0.0735 and 0.0505 AU of the Earth, respectively, in May 2006. In other words, no fragment would approach closer than 20 times the Earth–Moon distance (approx. 7.6×10^6 km). Images taken by the Hubble Space Telescope (HST) of 73P as it passed the Earth show fragmentation (<http://hubblesite.org/newscenter/archive/releases/2006/18/image/1/a/>). Figure 5 shows one of the images taken by the HST of 73P on the 18 April 2006. Note the wide lateral displacement of the fragments.

Howell *et al.* (2007) used spectral line observations to measure the outflow velocity of material being ejected from fragments B and C of 73P between 17 April and 22 May 2006 as $0.73 \pm 0.04 \text{ km s}^{-1}$. If fragments were ejected at this speed normal to the orbit it would take approximately 122 days to travel the distance required to intersect the orbit of the Earth. Fragments ejected at this velocity around the middle of January 2006 could have impacted with the Earth on 16 May 2006. Therefore, it is possible that the fireball sightings of 16 May were owing to fragments of 73P. The fact that the sightings fall on roughly a straight line between the channel between the north and south islands of New Zealand and Tennant Creek in the Northern Territory and ordered in time is suggestive of the passage of the Earth through an elongated trail of debris.

6. Similarities between the Queensland and Pasamonte fireballs

An interesting feature of the photo of the Queensland fireball taken from the centre of Brisbane (figure 3*a*) is the curved structure of the tail. It is apparent that the structure of the tail is very similar to a photo (figure 6) of the Pasamonte fireball, which streaked across the skies of New Mexico in the early hours of the morning of 24 March 1933 (Nininger 1934*b*).

The veracity of the Pasamonte photo has been called into question as, according to the account by the photographer, the camera could have moved during the exposure. However, it is difficult to see how camera movement could have obtained the twisted structure of the tail. It is possible that although the camera shutter may have been open for some time and the camera moved, the meteor and tail could have ‘flashed’ enabling a sharp picture to be obtained.

A key point to note is that the photo of the Queensland fireball is clearly in focus as the city lights are in focus. Therefore, the curved tail cannot be a motion artefact. The similarity between the photos is corroborating evidence that the Pasamonte photo is a genuine photo of the fireball and not the trail persisting after the passage of the fireball. A point of debate has also been whether the photo of the Pasamonte fireball (figure 6) is of the actual fireball or a bright section of the trail still visible after the meteor had passed. Curved trails have been noted before and these are usually attributed to high-altitude winds.

The photo of the Pasamonte fireball has been interpreted as evidence of a corkscrew motion of the fireball. However, it is difficult to conceive of what process could cause a meteor travelling at several tens of kilometres per second through the rarefied atmosphere to follow a spiral trajectory. A substantial force would have to be applied at right angles to the direction of travel. In the case of the Pasamonte and Queensland fireballs, the curvature in the tail is probably owing to a combination of high-altitude winds, the electric field and hydrodynamic forces as the meteoroids impacted with denser layers of the atmosphere.

In both the Queensland and Pasamonte fireballs, the tail seems to initially curve upwards. This could have been owing to the hot meteor trail rising up in the lesser density of the ionosphere. Zinn & Drummond (2007) describe simulations of parallel meteor trail pairs associated with buoyant rise. However, in these simulations it took of the order of 40 s for the twists to be fully formed whereas

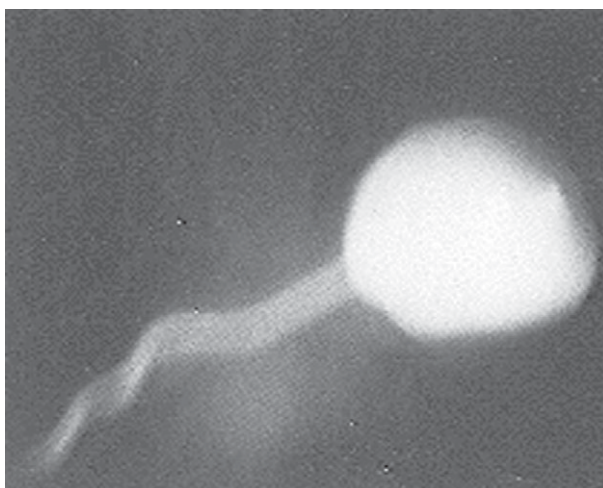


Figure 6. Photo of the Pasamonte meteor. The photo was taken by a ranch foreman Mr Chas M. Brown using a Kodak camera at about 05.00 h on the morning of 24 March 1933. The photo was taken when the fireball was at an elevation of 40° as it was approaching the photographer. The fireball then passed overhead.

in the Pasamonte and Queensland fireballs, the formation must have occurred in just a few seconds. The bright, tear-dropped shape region at the head of the meteor is clearly much larger than the size of the meteor.

Dokuchayev (1960) has postulated that the ‘luminous aureole’ is generated by corona discharge in the vicinity of the head and is 1–2 km in diameter. A meteor leaves a dense ionization trail in the wake. Ions diffuse away from the flight path and so the ionization trail stretching back from the meteor is needle-shaped with the point just behind the meteor. The plasma effectively behaves like a pointed conductor and, therefore, the electric field is greatest at the point with the smallest radius of curvature, i.e. the tip, enhancing the ambient electric field by a factor of 10^6 , accelerating free electrons causing air glow.

7. Eyewitness report of a luminous green ball

A very interesting phenomenon was reported by Don Vernon (D.V.), a farmer living on a property at Greenmount, 28 km south of Toowoomba on the Great Divide (figure 7). The witness saw a luminous green ball rolling down a slope of the Great Divide (figure 8) just after he saw the fireball passing over the Great Divide. The witness reported this phenomenon to the police, originally supposing he had seen an aircraft crash on his property. The next day a local TV station sent a helicopter that searched the area under the direction of the witness. No obvious disturbance that could be attributed to the fireball was seen, although a burnt tree from a previous lightning strike was seen.

The witness wrote a letter to the author in response to hearing a radio interview about the fireball. The author contacted the witness over the phone and then conducted a more extensive interview at the farm. According to the witness,

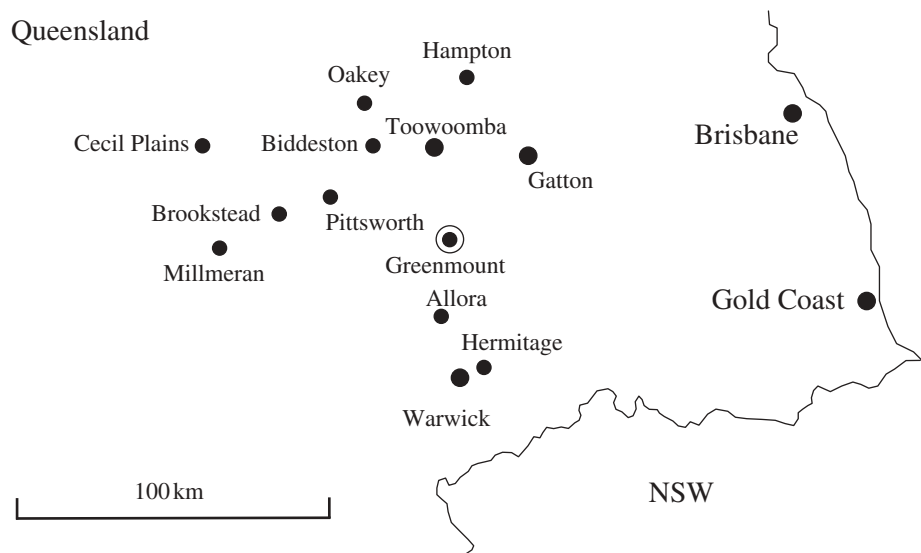


Figure 7. Approximate locations of sightings of the green fireball around Greenmount where the ball lightning phenomenon was seen.

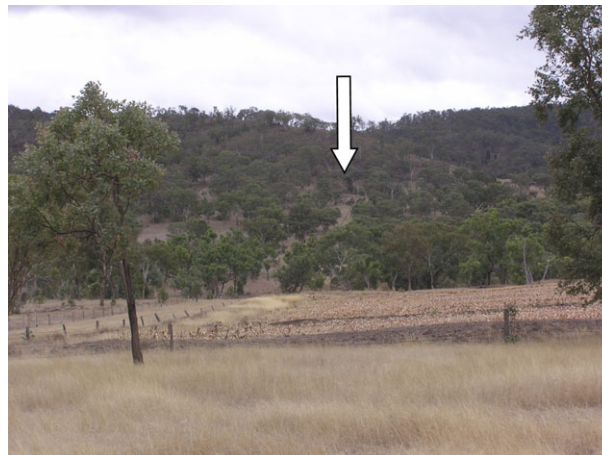


Figure 8. The site on the Great Divide where a green ball of light was seen rolling down the hill. (Note that the grass in the foreground is brown indicating very dry conditions. An incandescent ball would almost certainly have started a fire rolling down the slope indicated by the arrow). It is quite possible that the ball followed the line of the wire fence running between the trees (arrow). (Online version in colour.)

the fireball just cleared the Great Divide and appeared to be coming from the northeast and falling steeply. The object was brilliant white with a green tint and a blue tapering tail. Three incandescent fragments surrounded by red flares were seen to break off the main body of the object. The red flaring extinguished during the descent. A schematic of the object drawn by the author in conjunction with the witness is shown in figure 9.

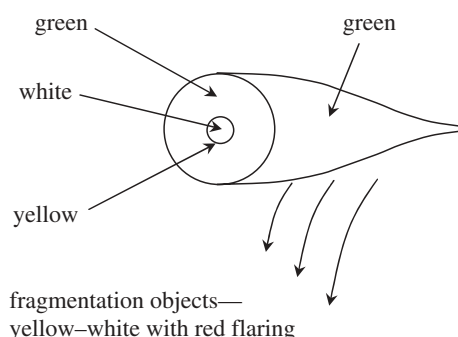


Figure 9. Green fireball drawn by the author with input from the farmer who saw the fireball cross the Continental Divide on the east coast of Australia. The centre of the fireball was perceived to be white encircled with a yellow annulus surrounded by green. The tail of the fireball was also green with a blue tapering section at the end. As the object passed over the Great Divide, yellow–white fragments with red flaring were seen breaking off.

The witness lost sight of the object behind a ridge, about 2.4 km away, but the sky was brightly lit and trees appeared in sharp relief. According to the witness, the intensity of the light was sufficient to read a book at a distance of 2.4 km. After the fireball disappeared behind a ridge, a green ball, about 30 cm in diameter was seen rolling down the slope of the range about 1 km from the witness. In the opinion of the witness, the ball was less bright than a 100 W light bulb and faded to about half the brightness over the period of 5–6 min that the witness observed the ball. The witness said that the ball was a soft phosphorescent green like a soft glow stick and faintly illuminated the ground out to a few metres around the ball. The ridge above the range remained lit for a while as the ball descended suggesting that the main object continued on. This is consistent with sightings of the object further west of Greenmount.

D.V. reported that the green ball took between 2 and 3 min to roll down the hill, eventually stopping about one-third of the way down where the slope levelled out. The ball was seen to stop and restart on its journey down the hill and was seen to bounce over a rock. In the opinion of the witness, the ball was a ‘solid lump’ similar to a beach ball and did not appear to be electrical in nature. D.V. said that a neighbour 7 km away in the next valley reported hearing a sizzling sound—which is interesting in view of other reports of sounds associated with fireballs (Keay 1980, 1993). The object was still glowing when the witness drove off after 5–6 min. In the opinion of the author, D.V. did not appear to be the kind of person to fabricate this story. A relevant piece of information is that the witness was an artillery observer in the reserves, which increases the confidence that can be placed on his observations. Unfortunately, no photographs were taken, as D.V. did not have a camera to hand at the time.

The fireball was also seen by Peter Vernon (P.V.), the son of D.V., who observed the fireball from his property about 1.2 km from where D.V. saw the fireball and slightly higher up. P.V. reported seeing the object being ‘hundreds of miles’ away in the direction of Fraser Island. The light was a pin-point that was very bright and very green (‘the green colour was just spectacular’) and was increasing in brightness as it approached. A piece was seen to break off the top and travel south

appearing to track along the east coast. (This could be the fireball photographed over the Brisbane CBD in figure 3*a*). P.V. saw another piece break away from the bottom of the fireball as it continued travelling towards Greenmount (figure 1).

According to P.V., at least six to eight pieces broke away as the light came in at a shallow angle—much less than 45° and probably close to 30° . P.V. saw the fireball disappear behind the ridge, but did not see the green ball that rolled down the hill that was seen by D.V. P.V. noted that the fireball and fragments were bright enough to cause retinal after-images (P.V. likened the effect to looking at sparklers being waved in the dark).

P.V. also spent about 2.5 days within a week of the sighting searching the area for a meteorite or any marks on rocks, etc., P.V. noted that part of the mountain side had been burnt the year before and the terrain was composed of stumps and ash. The vegetation was sparse owing to drought conditions and so at least in this area there would not have been much fuel if the fireball was capable of igniting a fire.

P.V. also commented that over the decades, he and his father (D.V.) had noticed that lightning strikes follow the ridges and also that iron bark trees in the area were the most commonly struck trees. The region also contains large iron ore plugs. P.V. also recounted an experience his father once had of lightning striking the ground behind a tractor towing a plough.

8. A possible connection between the passage of the fireball and luminous ball

The above account is strong evidence for a connection between a meteor and a luminous green ball rolling down a hillside. It is difficult to imagine any other explanation for the luminous ball if it was not connected to the meteor sighting. The connection is intriguing for a number of reasons. Meteoroids do frequently come down to Earth; however, the current understanding is that meteoroids cease to ablate about 20 km above the Earth and are dark for the remainder of the flight.

In this case, the witness clearly saw a green light rolling down the slope of a ridge very soon after the passage of a bright ‘parent’ object. This implies that the parent object was physically close to the ridge. The witness saw red, incandescent ‘flares’ break off and fall (see figure 6); therefore, if the parent object was close, some of these red flares could have reached the ground before being extinguished.

D.V. reported that the object appeared to be solid. However, the fact that the ball was seen to start and stop as it rolled down the hill and even jump over a rock argues against the object being a meteorite. Meteorite are generally irregular in shape. A spherical meteoroid 30 cm in diameter has never been found anywhere in the world, and one was not found on this occasion although the site was searched on four occasions. Such a large regular object would easily be found in a search. A rocky ball 30 cm in diameter would not roll slowly down a hill and bounce over rocks, as observed by D.V. Another problem is that a 30 cm diameter meteoroid would not gently impact with the ground but would be travelling at several kilometres per second and would certainly produce a crater on impact.

One possibility is that the green ball was some kind of ball lightning phenomenon. The description of the object and its movement is consistent with some reports of ball lightning. Turner (1994) describes balls that hover

above the ground and are repelled from nearby objects, which could be due to balls being charged and following the electric field lines above the Earth.

Could the witness have seen some kind of ball lightning (or some other electrical phenomenon akin to ball lightning) coincidentally with the fall of a meteor? It is extremely unlikely that a green fireball should pass over the Great Divide at exactly the same time as the occurrence of ball lightning phenomenon owing to some unrelated cause. A search of lightning strike data conducted by Global Positioning and Tracking Systems (GPATS) revealed that there were no lightning strikes within 100 km of where the ball lightning was sighted between the 15 and 17 of May 2006. It should also be noted that this is outside of the thunderstorm season for southeast Queensland. Therefore, it can be concluded that this fireball was not produced in the same manner as ‘regular’ ball lightning, assuming that the phenomenon is some kind of ball lightning. Also, this event was unlikely to be a bolt from the blue (BFB) lightning strike that can occur in a clear sky several kilometres from a thunderstorm (Krehbiel *et al.* 2008).

The absence of any evidence of burning suggests that the ball lightning was cool. A hot, incandescent object would be expected to cause a fire, especially bearing in mind that the whole area was very dry owing to several years of drought.¹ This is consistent with ball lightning radiating little heat, for example, Jennison (1969) reported ball lightning travelling down the central aisle of an airplane with no noticeable heat radiation. Also, a hot ball of gas would be expected to rise being of lower density than surrounding air; however, the luminous ball seen by D.V. stayed close to the ground consistent with the behaviour of ball lightning.

According to the account by D.V., there was a bright source of light on the ridge. We will assume that this was as bright as the full moon. The full moon (magnitude -12.7) is about 500 000 times dimmer than the mid-day Sun (magnitude -27), which has a brightness of about 1 kW m^{-2} at the surface of the Earth. Therefore, the brightness of the moon is approximately 2 mW m^{-2} . At a distance of 2.4 km, the total power output of the light would be approximately 145 kW. It is possible that the green ball that rolled down the hill had broken off from a larger ball on the ridge. Since trees on the ridge were thrown in relief it would seem that the light source was on or just above the ridge.

The observations of the witness enable the power and energy density of the ball to be estimated. On the basis of the upper brightness limit of 100 W noted by D.V. and that the ball decreased in brightness by a factor of two as it rolled down the hill, it will be assumed that the ball had an average brightness of 75 W over the 6 min period of the observation and radiated isotropically. The total energy output over this period would have been $360 \times 75 = 2.7 \times 10^4 \text{ J}$. Assuming a diameter of 30 cm, the energy density would have been approximately 2 MJ m^{-3} . The brightness, diameter and energy content are consistent with previous estimates of the energy content and density of ball lightning by Bychkov & Bychkov (2002).

¹The trees seen in the photo are green in spite of the drought. Most trees in Australia are indeciduous and the leaves can remain green even in drought conditions. (For more details of this drought go to: http://en.wikipedia.org/wiki/Drought_in_Australia.)

9. A possible connection between the Greenmount phenomenon and laboratory ball lightning

The observations of the witness are extremely interesting in the view of the production of green fireballs in the laboratory by researchers at the Max Planck Institut für Plasmaphysik (IPP) and Berlin's Humboldt University (http://www.ipp.mpg.de/ippcms/eng/presse/pi/05_06_pi.htm). A video clip of the IPP experiment shows a very bright green ball very similar in character to the description given by D.V. In this case, the ball was created by the discharge of electric current in water. The balls were 10–20 cm in diameter that lasted for about half a second. This is much shorter than the duration of the ball seen by the witness, but the point is that the ball created at the IPP lasted several thousand times longer than a lightning flash. The brightness of the ball seen by the witness suggests this type of ball lightning rather than the dimmer forms of 'regular' ball lightning reported extensively in the literature. The IPP work also demonstrates that electrically generated luminous green balls can be produced at the ground level (i.e. in a laboratory) and that the green colour is not restricted to the ionosphere. Also, the 10–20 cm diameter of the IPP fireball is comparable to the diameter of the luminous ball seen by D.V.

10. How could the Queensland fireball provide a connection between the ionosphere and ground?

The observations described above are circumstantial evidence that there was some connection between an aerial fireball and ball lightning phenomenon of some kind on the ground. It is not the purpose of this paper to put forward a detailed theory but rather to note the possibility and suggest a mechanism.

In fair weather, electrical current flows from the ionosphere to the ground (part of the global circulation), the charges to support conduction being generated by cosmic rays and natural radioactivity. The hypothesis presented in this paper is that the passage of the fireball over Greenmount momentarily reduced the resistance between the ionosphere and ground increasing the flow of current providing energy for the observed ball lightning phenomenon.

In this scenario, the ball lightning would have been generated by the interaction of the charge with the ground. For example, it could have been generated by the mechanism described by Lowke (1996) in which charge dissipates in the ground along preferred paths creating a ball of glowing ionized gas above the ground. The ball lightning could also have been created by the mechanisms described by Abrahamson & Dinniss (2000) and in experiments performed by Paiva & Pavao (2007) involving the oxidation of nanoparticles in soil. It is of course possible that the ball could have been powered by something more exotic such as cold fusion (Lewis 2006).

An important observation relevant to this discussion is that ball lightning generated in an electrical storm has been observed to descend from the clouds to the ground (Turner 1998) and has been observed to break into two or more balls (Paiva & Pavao 2007). It is possible that in the case of the Queensland fireball, some of the plasma surrounding the green fireball broke away from the main object and descended to the Great Divide, possibly following an ionization

trail produced by one of the fragments seen to break off the main object. The fact that the ball seen rolling down the hill was the same colour as the fireball would seem to be evidence in favour of this scenario. It is also possible that the ball lighting phenomenon originated in the ionosphere and followed the meteor down to the Earth.

Another possibility is that one of the fragments that broke away from the fireball provided an ionization track between the fireball and the ground. If this was the case, and the fireball also had an ionization trail leading back up to the ionosphere, it is possible that a conduction path existed momentarily between the ground and ionosphere enabling charge transfer.

Symbalisty *et al.* (2000) have demonstrated a link between sporadic meteors, sprites and cloud-to-ground lightning, in effect demonstrating that an electrical link between the ionosphere and the ground is possible. An electrical link between the tops of thunderclouds and the ionosphere in the form of blue jets and sprites has also been demonstrated by Pasko *et al.* (2002) and Su *et al.* (2002). Boccippio *et al.* (1995) demonstrate a link between sprites, extremely low frequency (ELF) transients and lightning ground strikes. The existence of BFB lightning demonstrates that, in principle, a horizontal ionization track can extend for several kilometres. (In one case a motorcyclist was struck by lightning at a distance of 16 km from a storm, (Cherington *et al.* 1997)).

There are five possible mechanisms that could have reduced atmospheric resistance: (i) thermal ionization, (ii) chemical reaction, (iii) corona discharge, (iv) trail of neutral conducting atoms, e.g. carbon or metal, and (v) fracture charging and tribocharging. It is possible that all five mechanisms could have been involved, with different mechanisms dominant at different altitudes.

(a) *Thermal ionization*

As a meteor traverses the ionosphere, frictional heating produces a trail of ionization. Ionization tracks have been detected by radar and can persist for up to 45 min (Greenhow & Neufeld 1957). Experimental evidence indicates that in most cases meteors cease to become incandescent at an altitude of 20 km (Halliday *et al.* 1978) and, therefore, will no longer be capable of producing an ionization trail. The journey of a meteor from when incandescence ceases and impacting the ground is known as *dark flight*. Most meteors burn up on entering the atmosphere and, therefore, never enter dark flight (except for residual microscopic fragments).

In principle, it should be possible for some of the more massive meteors to remain incandescent below 20 km, especially if descending steeply. Eventually, the speed is slow enough so that the meteor cools below incandescence and the meteor is no longer emitting in the visible part of the spectrum. An incandescent meteor will not ionize the surrounding air when too cool to generate UV photons.

(b) *Chemical reaction*

Another possibility that should be considered is that oxidation (i.e. burning) could keep a meteor glowing below the normal altitude limit of 20 km for incandescence. The hydrodynamic partial pressure of oxygen would be very high on the front face of the meteor and it is well known that many substances burn more easily at higher air pressure (e.g. in hyperbaric chambers, Sheffield & Desautels 1997). The possibility of meteor oxidation has been suggested by Wilson

(1943), although there appears to be no subsequent discussion of this in the literature. In view of the observations of the Queensland fireballs maybe this possibility should be reconsidered.

(c) *Corona discharge*

Most meteors contain either carbon or metal and, therefore, could produce ionization via corona discharge, as occurs, for example, at the wingtips of aircraft flying in a thunderstorm, and from ships masts and lightning conductors on buildings (St Elmos' Fire).

Studies have shown that between 120 and 80 km meteors become positively charged owing to thermionic emission (Sorasio *et al.* 2001). Positive charging of meteors owing to thermionic emission could explain the acceleration of some meteors (Simek *et al.* 1997). Since the ionosphere is positively charged with respect to the ground, meteors in the lower regions of the ionosphere would be repelled and, therefore, accelerate. However, meteors are only positively charged while hot enough for thermionic emission to occur. When thermionic emission reduces, the positive charge of the meteor reduces, and eventually becomes negative as the meteor picks up negative charge (i.e. electrons) from the air, a process known as tribocharging.

A meteor could tribocharge via friction with the particles in the air (as happens with aircraft). When the potential is high enough, breakdown of the air occurs through corona discharge. Breakdown occurs at points on the airframe with the smallest radius of curvature. Aircraft wings have static wicks that are fine wires protruding from the rear of the wings to facilitate discharge to keep the electrostatic potential as close to ground as possible. In an aircraft, the energy stored in the static charge ($E = 1/2 CV^2$ where C is capacitance and V electrical potential) must be less than 1 mJ to avoid igniting fuel vapour.

Corona discharge occurs when the electric field (E) on the surface of an aircraft or conductive meteor reaches the breakdown potential of the surrounding air, i.e. approximately $3 \times 10^6 \text{ V m}^{-1}$. In the case of a conductive, spherical meteor 0.1 m diameter, the amount of charge that would have to be accumulated on the surface would be $Q = E4\pi\epsilon_0 r^2 \approx 0.8 \mu\text{C}$, which is comparable to the charge measured on some military aircraft. For example, Krupen & Rogers (1964) measured a charge of $-0.56 \mu\text{C}$ on a B-26 bomber and $-35.4 \mu\text{C}$ on an F-86.

However, if the meteor had protrusions with a radius of curvature much less than the gross size, a much lower charge would be required for corona discharge. For example, if a part of the meteor had a point with a radius of 0.5 mm (say owing to a fragmentation event), the amount of charge required to produce corona discharge would be a factor 10^4 less. It is conceivable that the electrical capacity of a meteor fragment could be 10 000 times less than a fighter aircraft.

The electron density of any ion track produced by a meteor would depend on the charging rate. The meteor would pick up electrons from the air which would be transferred back to the air through a point of minimum curvature with the electric field being maintained at the breakdown field strength for air. The density of the ionization track can be roughly estimated from the fact that tribocharging rates of greater than $120 \mu\text{A}$ have been measured on helicopters (De La Cierva & Perlmutter 1964). This is caused by friction of the air with the rotor blades and fuselage. The maximum velocity of a helicopter is about 300 km h^{-1} , i.e. subsonic

and, therefore, comparable to the velocity of a meteor in dark flight. We will assume that a helicopter with a cross-sectional area of 10 m^2 is charged at a rate of $100\text{ }\mu\text{A}$. Assuming that tribocharging scales approximately with the surface area presented to the air flow, we would expect a meteor diameter of 10 cm to charge at approximately $10^{-4}/10^3 \sim 10^{-7}\text{ A}$.

If the meteoroid has sharp edges corona discharge would occur at a lower charge, as happens, for example, with static wicks attached to aircraft. The number of discharges per second would increase and result in a denser ionization trail. Some iron meteorites do appear to have sharp edges, for example the Wallarenya and Willamette meteorites (<http://blog.oregonlive.com/clackamascounty/2007/10/Meteor.JPG>). Graphite is known to exist in some meteorites (Mostefaoui *et al.* 1998; Fries & Steele 2008; Steele *et al.* 2010) and could produce ionization trails in a similar fashion to the graphite used in static wicks on aircraft.

Assuming that the meteor is discharging 10^{-7} A via corona discharge, the number of electrons being deposited in the trail each second will be approximately $10^{-7}/(1.6 \times 10^{-19}) = 6 \times 10^{11}$. Assuming that the meteor is spherical and, therefore, electrons are being discharged uniformly from the surface and initially form a wake with similar diameter to the meteor and a velocity of 150 ms^{-1} (i.e. approximately half the speed of sound at sea level), the electron density will be approximately $4 \times 10^5\text{ electrons cm}^{-3}$ (6×10^{11} electrons deposited in a cylinder 10 cm in diameter and 150 m in length). This electron density is comparable to the electron density of the ionosphere ($10^4\text{--}10^6\text{ electrons cm}^{-3}$). Since the ionosphere is conducting, the corona discharge trail with a similar electron density would be expected to also be conducting.

It is possible that some of the electrons released by corona discharge could be accelerated in the electric field of the Earth, which is about 1 V cm^{-1} close to the surface of the Earth. If the electric field is enhanced in the vicinity of the meteor by a factor of 10^4 (Dokuchayev 1960), these electrons will be accelerated to greater than the ionization energy (33.8 eV) in only $38\text{ }\mu\text{m}$. This effect would increase the electron density in the trail.

If corona discharge during the dark flight of a meteor and the ‘pointed conductor’ effect were sufficient to create an ionization trail from the beginning of dark flight down to the ground, the channel so formed would be similar to a stepped leader, which is the precursor to a lightning strike. The ionization track would in effect project the potential of the ionosphere down to the head of the trail, i.e. the meteor fragment. As soon as the meteor hit the ground, or passed through an ionization trail rising from the ground, current could pass from the ionosphere to ground providing energy for ball lightning.

(d) Neutral conducting particles

Another possibility is that the meteor could have shed neutral conductive particles, either carbon or metal. Lidar studies have in fact revealed thin trails of neutral metal atoms after the passage of a meteor (Kane & Gardner 1993).

The amount of neutral atoms required can be estimated as follows. The electron density of the ionosphere is $10^4\text{--}10^6\text{ electrons cm}^{-3}$. We will assume that the density of the atmosphere between the bottom of the ionosphere (altitude approx. 80 km) and top of the troposphere (altitude approx. 17 km) is low enough for an

electron concentration of 10^6 electrons cm^{-3} to support electrical conduction. (At the top of the troposphere atmospheric pressure is about 10^{-1} bar and at the bottom of the ionosphere about 10^{-5} bar.)

If we assume that a meteoroid has a significant carbon content, maybe in the form of graphite, then 12 g will contain 6×10^{23} (Avogadro's number) carbon atoms. If a meteor was descending through the atmosphere at a 30° angle from an altitude of 80 km, the length of the path would be of the order of 160 km. Assuming a trail with a cross section of 1 m^2 , the volume of the column would be $1.6 \times 10^{12} \text{ cm}^3$. To be conductive, this column will need to contain $1.6 \times 10^{12} \times 10^6 = 1.6 \times 10^{18}$ atoms, which corresponds to $(1.6 \times 10^{18} / 6 \times 10^{23}) \times 12 \text{ g} = 3.2 \times 10^{-5} \text{ g} = 32 \mu\text{g}$.

If a meteoroid was mostly nickel or iron, the amount of material would be about 150 μg . This amount of material could easily be ablated from an incandescent meteor and would represent a very small fraction of a meteoroid capable of generating a green fireball since the lower initial mass limit of fireball meteoroids is 1 kg (Brown *et al.* 1994). A conductive trail could of course be a mixture of carbon, iron and nickel and other metals.

(e) *Fracture charging and tribocharging*

Lightning is commonly reported in the vicinity of volcanic eruptions, which is thought to be caused by charged ash particles (Mather & Harrison 2006 and references therein). Ships and structures in the vicinity of volcanos also exhibit St Elmo's fire. Ball lightning has also been associated with volcanic air pollution (Durand & Wilson 2006). Measurements indicate that ash particles are charged to the limit for corona discharge. This suggests that ash particles are charged on ejection from the volcano via fracture charging and tribocharging, and the particles discharge via corona discharge and remain charged for an extended period of time as air is a fairly good insulator and the potential of the particles is too low to discharge via corona discharge.

It is possible that the charged ash reduces the threshold for lightning, which could be triggered by the passage of cosmic rays (which is a suggested mechanism in thunderclouds). Volcanic lightning has been reported to occur at a distance of 30 km from the Katla volcano in Iceland. At this distance, the ash concentration could not have been very high and yet was able to trigger lightning. It is very interesting to note that measurements made in the plume of the Surtsey eruption in Iceland in 1963 revealed that the concentration of charged particles in the ash was 10^5 – 10^6 cm^{-3} , which is comparable to the electron concentration in the ionosphere and the value used in the neutral particle ablation calculation above.

11. Conclusion

Momentary electrical connections between the ionosphere and ground created by the passage of a meteor are probably very rare and fleeting. However, the observations described in this paper do provide circumstantial evidence for this and five possible mechanisms are suggested. All five mechanisms probably have to be involved at different points for a conductive path to be maintained even for a few seconds or minutes. Further work could be done using meteorites in wind

tunnels to test the ionosphere-to-ground conductive path hypothesis presented in this paper. It is of course possible that the observed phenomenon was due to something more exotic such as a mini black hole (Rabinowitz 2001), anti-matter meteorites (Ashby & Whitehead 1971) cosmic strings or some physical process as yet unknown. If confirmed, this hypothesis may be able to explain previously unexplainable UFO sightings and the so-called foo fighters and other aerial phenomenon (http://en.wikipedia.org/wiki/Foo_fighter).

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