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An Initiation of Ball Lightning in an Aircraft

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ABSTRACT

The detailed observation of ball lightning in an aircraft gives strong evidence that the ball lightning was initiated by preceding corona from metallic diverter strips attached to the surface of the radome. These diverter strips are designed to direct current from a lightning strike to the radome towards the aircraft fuselage in order to protect the radar antenna. The charging of the aircraft can be generated by ambient atmospheric electric fields or by precipitation when rain or fog droplets collide with the surface of the aircraft. Corona and thus copious ions were produced in close proximity to the front cockpit windows. The observation supports proposals that ball lightning can develop from electric fields within an aircraft fuselage, or indeed within a house, originating from the accumulation of ions at the outside surface of an aircraft windshield or a window pane. The observation suggests that ball lightning may be initiated through a corona discharge without the necessity of an initial lightning strike. Both authors have personally observed ball lightning.

1. Introduction

The formation of ball lightning was observed inside a C-133A cargo aircraft close to the windshield by the four members of the cockpit crew, all intently watching the outside of the aircraft. There was no lightning or thunderstorm anywhere near the aircraft, only a dense fog. This observation has been reported in Lowke et al. (2012).

Ball lightning has been observed by thousands of people, who report approximately similar properties. The ball often has a diameter in the range of 10–20 cm, it floats above the ground and moves at about walking speed. It emits light that is well visible but not blazing. In a number of particularly enigmatic cases, it first appeared near closed glass windows and also inside of aircraft. Its lifetime ranges from a few seconds to – very rarely – several minutes. A recent statistical evaluation of the properties of 282 ball lightning events observed in France has been published by Piccoli and Blundell (2014). While it commonly has innocuous behavior, there are cases where ball lightning has been the cause of fires or bodily injury, as described by Brand (1923).

Section 2 describes the actual observation. In Section 3 we give an account of the role of diverter strips embedded in the radomes of aircraft in producing corona. In Section 4, the field enhancement at the tips of the aircraft is demonstrated. Section 5 describes how accumulation of ions on the insulating surface of the aircraft windshield or any glass window can create an intense electric field inside of the aircraft and possibly initiate a discharge on the inside surface of the windshield to produce ball lightning. Section 6 presents additional observations by others. In Section 7 we discuss some properties of ball lightning.

2. An observation of ball lightning

Ball lightning inside a USAF C-133A inflight

In the mid 1960s, I was a lieutenant in the US Air Force and was the crew navigator aboard a C-133A cargo aircraft flying from California to Hawaii. We were at an altitude of 18,000 feet, it was at night and we were flying in a continuous horizontal layer of thin cloud which had the density of "soup". The C-133A *had four propellers driven by four turbine engines and, at the time was the U.S. Air Force's largest cargo aircraft. On the nose of the C-133A there was a radome that was visible from inside the cockpit. The radome was a dome shaped shell used to cover the radar antenna and was about 36 inches across and had a rounded dome front. As Navigator, I was monitoring the radar for any significant weather clouds in front of us. There was only the fog.*

After we had been flying in the fog for about 15 min, there developed on the radome two horns of Saint Elmo's fire. It looked as if the airplane now had bull's horns on the radome. The curved horns, each about a foot long, were glowing with the blue of electricity. The two Pilots, the on-duty Engineer and I enjoyed watching and discussing the horns for a relatively long time. The horns were not at all of concern as we had seen Saint Elmo's fire several times

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previously when in similar flight weather conditions. We thought of it simply as static electricity.

The on-duty Engineer and I were standing behind the pilots as we all were actively discussing the Saint Elmo's fire decorating our radome. Suddenly, within sight of all four of us – we were all looking at the horns – a glowing ball of golden fire about the size of a volley ball appeared just inside the windshield, midway of the windshield and above the central Pilot console. It touched nothing and made no sound (or none that could be heard above the usual airplane noise) but slowly floated downward into the cockpit between the Pilots, then between the Engineer and me, coming within a foot of me at my waist, *now staying about three feet above the floor, then slowly turned left toward the crew lounge doorway, went through the open doorway, turned right 90 degrees and toward where the Loadmaster was sitting. We, the Pilots, the Engineer and I lost sight of it then because of the wall between the cockpit and the crew lounge. About 20 s later, the Loadmaster burst into the cockpit yelling "Did you see THAT ???". The Loadmaster said that he saw a ball of golden fire come from the cockpit into the crew lounge. It floated toward him, came within a foot of him but turned to exit through the open stairway door and down the stairway into the cargo bay - then to float above the cargo down the exact middle of the airplane toward the tail of the airplane - and then just disappeared as it went through the metal tail ramp & door at the rear of the airplane. We all exchanged what we each had seen, confirming with each other that we had seen the same thing. We told the second Engineer, who had slept through the event, all the details. The Engineers and Loadmaster searched for any damage to the airplane and, finding no damage, we continued the flight uneventfully.*

Upon landing at Hickam AFB in Hawaii, the Pilot directed Maintenance to search the aircraft inside and outside for any sign of lightning damage. No damage was found. The crew made a detailed written report of the incident to the Base Command Post.

At no time during this flight were there any thunderstorms along our route. We were flying through a fog-like layer of cloud and there was no turbulence. We never saw any lightning outside the aircraft, neither close by nor in the distance. We did not see any lightning flash whatsoever. No individual clouds ever appeared on the radar which I was monitoring closely; only a pea-soup-like fog layer was evident. The radar was at full power during the time that the St. Elmo's horns and the ball lightning occurred and the radar beam was in the narrow Pencil shape. The ball lightning appeared about halfway between Travis AFB in California and Hickam AFB in Hawaii.

Don Smith, USAF Retired

The flying altitude was 18,000 ft and the cabin altitude will have been set to the atmospheric pressure at 8000 ft or somewhat above. From the approximate location and the NOAA weather database (NOAA), we can estimate that the outside temperature will have been around - 15 °C. It is very probable that the layer of fog consisted of ice crystals. Of particular interest is that the ball lightning was preceded for some minutes by the observation of corona outside of the airplane. No observation was made of the ball lightning having any existence outside of the airplane. The path of the ball lightning is shown in Fig. 1 and its appearance in the cockpit is depicted in Fig. 2.

3. Radome diverter strips

We have now become aware of the existence of metallic "diverter strips" within the structure of the radome, as are shown on the photographs of Fig. 3a and b. The radome is situated just ahead of and below the cockpit windshield, as shown by the photograph of Fig. 3a. The two "horns of corona" originated from two of these diverter strips, as illustrated by the blue lines drawn on Fig. 3b. There are 8 diverter strips for the C-133A aircraft, distributed around the radome, being alternately about 120 cm and 90 cm in length and 1 cm wide. The two corona "horns" originated from two of the long diverter strips on the upper part of the radome. A further two long diverter strips are on the underside of the radome, not visible to the pilots. It is highly likely that corona has developed on these strips as well, for a total of four corona discharge "horns". [1]

The purpose of the diverter strips attached to the radome is to protect the radar antenna from catastrophic destruction in case of a lightning strike. Evidence exists that approximately 80 % of lightning-aircraft interactions are caused by field intensification from the aircraft itself, rather than from lightning initiated in a thundercloud. The metallic strips are connected to the body of the fuselage, so that any lightning current is transmitted through the metallic diverter strips to the body of the aircraft, from where it will then exit again into the atmosphere at another location on the fuselage, instead of passing through the radar antenna. A review of the role of diverter strips, their structure and design within radomes is given in Karch et al. (2017).

These diverter strips are a common feature of most aircraft today, which should create the same effects under the right atmospheric conditions, when the static dissipator "wicks" near the wingtips are overloaded and corona starts to develop at other points on the aircraft as well.

Corona discharges on aircraft produce wideband RF noise, which is able to interfere with radio communications and can disturb or damage the aircraft's instruments. When the radio receiver senses a strong signal, its AGC function can reduce the sensitivity to a low level, effectively disabling the receiver for the duration of the corona. Therefore, no such radio interference was noticed by the crew in this case.

4. Field enhancement by the conducting fuselage

Aircraft can be flying in regions of significant surrounding electrostatic fields. Thunderclouds have potentials of millions of volts and there can be high atmospheric field strengths even without severe weather. The aircraft's conducting metal fuselage shields the interior against any electric field from outside. Any potential difference within the metal produces electric charge motion along the surface regions of the fuselage, until the electric field within the fuselage is zero. As a consequence, the electric field immediately outside of these metal surfaces is enhanced. This enhancement is significant and can be more than a factor of 10, and thus cause ionization at the extremities of the aircraft, namely at the radome, tail and wingtips.

Numerically calculated absolute field strengths for an actual aircraft for a background electric field of 0.1 MV/m are shown in Fig. 4, from Karch et al. (2017). Maximum field strengths on the order of 2.6 MV/m are calculated in the region of the radome, an amplification on the order of 25. At atmospheric pressure near sea level, field strengths of 2.5 MV/m are sufficient to initiate ionization, as for electric fields of greater than 2.5 MV/m, electron ionization coefficients are greater than electron attachment coefficients to oxygen molecules. These coefficients are a function of E/N, where E is the electric field and N the gas number density. For a flying altitude of 18,000 ft, the threshold electric field for ionization will be lowered to 50 %, as the air pressure and thus the value of N at 18,000 ft are only about 50 % of the atmospheric pressure and density at sea level. The cabin pressure in the aircraft is also reduced to an equivalent atmospheric pressure at 8000 ft. This reduces the corona inception field strength in the cabin to 74 % of that at sea level or about 1.8 MV/m.

While the C-133A was flying through a layer of ice fog, it collected its excess charge from collisions with the ice crystals in the fog. These leave a negative charge on the aircraft, while the fog itself is left behind with a positive charge. This is essentially a constant current source which charges the aircraft more and more, until the developing corona dissipates the additional charge that is collected on the aircraft's surfaces. A review of precipitation charging is given by Perala (2009). The aircraft

[1] The radar of the C-133A was an AN/APN-59 weather radar, operating at 9.375 GHz (X-Band) with a pulse power of 75 kW. The corona horns did not develop in the plane of the radar beam and glowed with a steady intensity, while the radar antenna was continuously scanning from side to side.

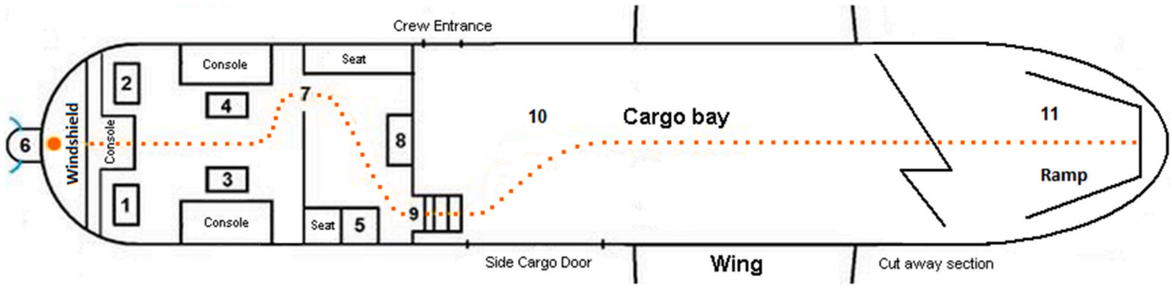


Fig. 1. USAF C-133A – Cockpit and Flight Deck floor plan. 1 Pilot, 2 Copilot, 3 Navigator, 4 Flight Engineer, 5 Loadmaster, 6 Radome with Saint Elmo's Horns, 7 Doorway (open), 8 Coffee console, 9 Doorway & Stairs down to cargo bay, 10 Cargo bay, 11 Ramp & Tail Door. ● Ball Lightning. • Path taken. The ball lightning travelled the total distance of about 55 m from the windshield to the end of the cargo bay in approximately 25–35 s - Drawing by D. Smith.

Fig. 2. The ball lightning originated immediately next to the metal divider post at the center of the windscreen, just under the C-12 standby magnetic compass which was attached near the top of the metal post. In reality the cockpit was dark, except for the illumination of the instruments. – Cockpit photo by M. Meltzer.

will not have been polarized by flying through a potential gradient in this case, but it will have developed the same enhancement of the field strength at the extremities of the wings and fuselage. The corona horns are an indicator of the amount of charge on the aircraft, which produced a field strength of several MV/m at the radome. The actual charge level of an aircraft can be determined experimentally with an electrostatic voltmeter - a "field mill" - that is embedded in the fuselage of some research aircraft. The use of such field mills for the study of lightning strikes that can be initiated by the aircraft is described in reference Laroche (2012).

a b

Fig. 3. a – Location of the black hemispherical radome below the cockpit windshield of the C-133A. Photo by USAF, Wright-Patterson AFB, b – The blue lines indicate the positions of the observed horns of corona from the metallic "diverters" shown by the faint grey lines on the radome.

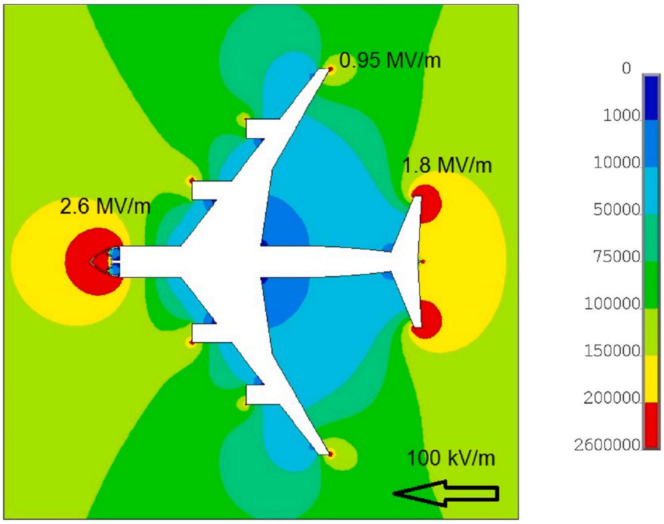


Fig. 4. Calculated electric field strengths of up to 2.6 MV/m around an aircraft in an ambient field of 0.1 MV/m. From C. Karch, with kind permission.

5. Field enhancement by glass windows

An aircraft can acquire a high electric charge due to either cross field charging – by flying in a region with a high atmospheric field strength such as near a thundercloud – or by precipitation charging from rain, snow or fog.

The proximity of the radome and diverter strips a few meters in front of the pilot windshield, as shown in Fig. 3, means that any initiation of corona at the diverter strips will produce a stream of ions or charged fog particles, which move with the airflow in the direction of the cockpit, where some of the charges will be stopped and accumulated on the outer surface of the windshield. Such an accumulation of charges can result in a high electric field inside of the aircraft as well, under certain preconditions.

The outer side of the cockpit windshield in Fig. 5 represents one side of a capacitor, which is charged both triboelectrically by the collision with uncharged fog particles and also by the impinging ions and charged particles. The field strength $\mathbf{E_B}$ behind the window is proportional to the amount of charge **Q** that has collected on the front side of the window with a capacitance **C**, which depends on the area **A** of the window and the distance **d** to the next conductive surface behind it. The relative permittivity ε_r is 1 for air and 4–6 for plate glass, ε_0 is the vacuum permittivity. This gives the field strength as $\mathbf{E_B = Q/(C^*d)}$ and $\mathbf{E_B = Q/(\varepsilon_r\, \varepsilon_0\, A)}$. This field strength is totally independent of the field strength in front of the window. We can distinguish two cases, depending on the type of the window.

Fig. 5. Discharges from the windshield of a Boeing 737NG to the fuselage, repeating with a period of about 3 s. From YouTube/PilotsTubeHD, with permission.

1. Normal window without coating

The amount of charge that a window pane can collect is limited. At some point, the accumulated charges on the outside glass surface will discharge to the window frame or fuselage, causing periodic flashovers. These periodic pulses will then release and repel any charges of opposite polarity from the inside of the window, which will soon be collected again as the outer side of the window recharges. If there is any gain by secondary ionization in the number of ions released, then the amount of ions in back of the window will quickly increase. This will in effect ignite a low power RF plasma in the air behind the window, an electrodeless discharge. The criterion for discharge inception is discussed in Chvyreva et al. (2018).

2. NESA™ type heated window

Many aircraft windows have a transparent conductive coating for electric heating on an inner surface of the glass sandwich (Lockheed 1988). The heating power for the C-133A cockpit windows is supplied by a transformer, which has a tap that is grounded to the fuselage (USAF 1963). This also grounds the area of the window, but it has a high impedance for sufficiently high frequencies. The field of an electrostatic charge cannot penetrate the conductively coated windows, however, high voltage pulses can do this. These will always be generated when the outside of the window is discharged by a flashover.

These periodic discharges, due to the capacitance of the windows combined with the constant current ion source which charges them, form a relaxation oscillator in both cases. The main difference here is, that the electrically heated window represents a relatively high capacitance of 2–5 nF for the ions that accumulate on it, while a normal uncoated window of the same size has a capacitance on the order of 10 pF and is only able to collect a small amount of charge.

This relaxation oscillator has a time period of $\mathbf{t_0 = U_B{}^*C/I}$ in the range of seconds for a cockpit window and will oscillate with the frequency $\mathbf{f_0 = 1/t_0}$ as is shown in Fig. 6. The flashover voltage is $\mathbf{U_B}$, **C** is the capacitance of the window and **I** is the charging current. The energy of a single pulse is $\mathbf{W = ½\, CU_B{}^2}$ which is on the order of 1–10 J for pulses in the 25–50 kV region. However, due to the short time span of the discharge, the momentary power delivered during a pulse can be in the hundreds of kilowatts to multi-megawatt range.

During the flight of the C-133A through the fog, such bright flashes as those in Fig. 5, which discharge the entire windshield at once, were not observed. This leaves us with the possibility that smaller and less intense, hence less visible, but more frequent discharges were taking place around the circumference of the windshield to the fuselage.

The effect of charge accumulation is further illustrated by the numerical calculations of Fig. 7. The calculations are for a stream of negative ions driven by an electric field towards a glass window or plate, from Lowke (2019). The charges accumulate on the left side of the glass, with the calculated logarithm of charge densities given in units of e^-/cm^3 in Fig. 7a. The calculated electric fields in kV/cm are given in Fig. 7b, being relatively low to the left of the glass and to the right of the glass very much higher than the 25 kV/cm threshold for the initiation of ionization.

A corona discharge in the cockpit is likely to develop on metal components in the vicinity of the windows, such as at the chamfered vertical divider post in the center of the windshield. This is the location where the ball lightning in the C-133A aircraft was first observed.

6. Additional observations

The following experience was brought to our attention by J. Abrahamson and bears some similarity to ours. From Abrahamson (2002): "Lightning strike near nose of aircraft", communicated by Jim Mills (commercial airline pilot, Alaska Airlines, USA). Email 2000.

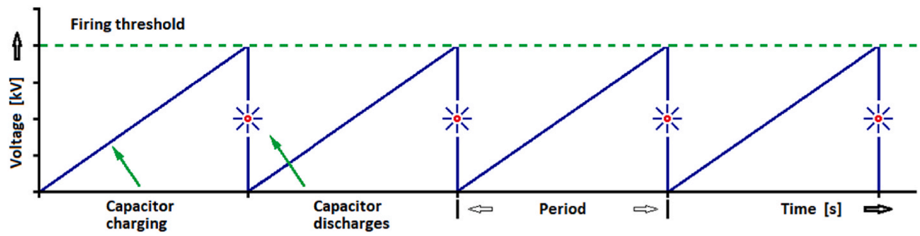
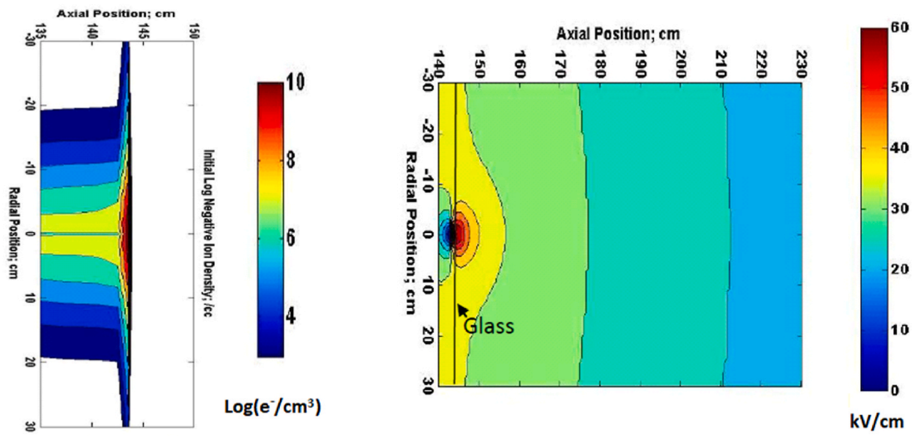


Fig. 6. Relaxation oscillator.



a b

Fig. 7. Field enhancement behind a glass window pane. From J. Lowke, with kind permission.

"*At the time of the incident, I was employed as a pilot for Horizon Air, a northwest regional airline owned by Alaska Airlines. During a daytime trip in a Fairchild Metroliner III, I observed, along with a number of passengers on board, a ball lightning phenomenon. We were flying at 16,000 ft near McCall, Idaho, USA, when our aircraft was struck by a bolt of lightning near the nose area. After the strike, a bright glowing object slowly drifted down the aisle of the aircraft in clear view of the passengers, floated to the rear and disappeared with an audible 'pop'. We could think of no other explanation other than that the object was ball lightning. Some minor damage was found on the aircraft as a result of the strike.*"

"The aircraft appeared to be struck on the right front nose baggage access door, as well as on the stall avoidance system (SAS) vane, also on the right side of the plane. The strike welded the SAS vane in place, rendering the system inoperative. It also damaged the internal components of the system. The strike may have indeed vaporized some small amount of aluminium, as two or three pinholes were present on the nose baggage door, but this does not explain how the ball lightning could enter the pressure vessel of the aircraft. This aircraft is pressurized and the ball lightning would have to pass through a sealed pressure bulkhead to enter the cabin area. No loss of pressure was experienced."

An example of the observed passage of ball lightning through both a glass window and a glass patio door occurred during a torrential rain in South Devon, UK. - From Michael Dodd, Paignton, UK, 2017, personal communication.

During a fierce thunderstorm on September 8, 2017, M. Dodd was sitting in his lounge on the first floor of an apartment building. After a very loud clap of thunder, he noticed an intensely bright blue ball of 30–40 cm in diameter, which entered the room through a closed window. The ball was not transparent, sharply delineated and had an orange tail attached to it. It moved from left to right approximately 6 m at a height of about 1.5 m. The ball passed by him at a distance of 1.5 m and then disappeared through the closed patio door without causing any visible damage. Both the window and door are double glazed. The appearance lasted about 2 s. No ball lightning was seen on the outside patio by M. Dodd after it had left his room through the glass door. A blue sphere moving across the car park of the building was observed by a neighbor and it was assumed to have been the same ball lightning.

A lightning bolt had struck the block of flats next to M. Dodd's house near the roof level, where it destroyed the large communal Sky TV dish and all of the satellite receivers in the house, as well as the lift control panel and some ceiling lights. There was no lightning damage to the house where the ball lightning was seen. The initial lightning strike was detected by the lightning location network EUKLID and determined to have been a negative CG lightning bolt with a maximum current of −15.7 kA, reported in Boerner (2019).

Another report of this occurrence is given in the Devon News of September 11 by Henderson (2017).

7. Properties of ball lightning

We wish to emphasize that the plasma or cloud of ions that forms behind the windshield or window is not necessarily the ball lightning itself, which has observably different properties, such as a high stability and a long lifetime and whose nature is as yet unknown. However, this discharge appears to play a part in the process of its formation. The conditions for the initiation of ball lightning appear to be very similar to those for the development of corona.

Direction of movement - Ball lightning in aircraft almost always seems to originate from the cockpit area, as reported by Stenhoff (1999). The reason for this will be that the highest electric fields exist at this exposed part of the aircraft and that the cockpit windows are large openings in the otherwise electrically shielded fuselage. The movement of the ball lightning appears to follow the draft of air inside of the aircraft. It has mostly been observed to move from the cockpit area to the rear, very rarely in the opposite direction. [2] In a commercial airliner, the air is replaced 3–4 times faster in the cockpit than in the passenger cabin, in order to supply the pilots with ample fresh air. The remainder of the air then enters the cabin from the sides. The air from the pressurized cabin leaves the aircraft through a venting valve located in the rear of the fuselage. Due to the laminar airflow in the cabin, the ball lightning will have a tendency to move to the center of this flow, where the air is flowing fastest and then follow it to the end of the cabin.

Beyond moving with the air stream, ball lightning also appears to evade contact with - or is repelled by - most objects in its path. As the loadmaster of the C-133A reported, the ball lightning rose again and floated over the cargo on its way to the back of the aircraft, while moving along the exact centerline of the cargo bay. This could be accomplished if the ball lightning has the property to spray charges onto its surroundings, which would then repel it and guide it along its path. - An experiment by Cawood and Patterson, reported in Cawood (1931), demonstrates the peculiar behavior of a charged aerosol dust cloud, which they created in a large glass chamber by means of a fan and an electrostatic brush discharge. As soon as the discharge and the fan were switched off, large particles began to arrive at the center of the chamber. The charged walls of the chamber repelled the equally charged aerosol particles, which then formed a stable sphere in its center.

Apparent passage through windows - Many modern houses have double glazed windows with an insulating gas layer between the two window panes. These windows may also have a conductive inner coating, which reflects infrared radiation. Ball lightning has been observed to pass unhindered through such windows. Boerner (2019) discusses several of these cases. This work suggests that the alleged ability of ball lightning to pass through closed windows may be an optical illusion of the observer. A small discharge near the window, which then grows in size or intensity, would create the impression that a luminous object has been approaching from outside. Nevertheless, there are a considerable number of observations that report a passage through windows. Bychkov et al. (2016) describe damage in a glass pane which was attributed to ball lightning.

A glass window pane represents a dielectric barrier on which charges can accumulate. In this way, a very high electric field strength can develop between the window and a conductive object nearby, even in relatively moderate atmospheric conditions in front of the window. Without such an insulating barrier, a nearby lightning strike would be needed to create similarly high field strengths. An alternative way to generate such high field strengths on a natural insulating surface with the capability to produce earthquake lights and possibly ball lightning would be through tectonic stress on rocks, suggested by Freund (2019).

Luminous intensity of ball lightning – The ball lightning observed in the aircraft by D.S. had the luminosity of burning embers, which made it well visible in the subdued lighting of the cockpit. It cast no shadows.

My observation was of a sphere that had inside flickers like, and the colors of, a fireplace log *fire - reds, golds, oranges - all of varying intensities like the flames in a fireplace. The inside of the ball appeared to be totally filled with many moving tongues of fire. It didn't have the blue that the radome horns had. Just before we entered the "soup" I had used the work light at my desk to calculate a three-star celestial fix, but that star fix never happened because we entered the 'soup'. - It was at night, the cockpit lights were just all the various gauges on the various panels and they were usually red gauge lights. No overhead lights were on in the cockpit. It was just a normal cockpit night situation. I had also turned down my navigation desk work light to very low, as I was not actively at that time calculating nor plotting on my map on the desk. The sweep on the radar scope made very little greenish light and contributed very little light to anything.* – Fig. 8 shows a rendering of this sphere.

[2] A notable exception where ball lightning appeared at the rear end of the cabin happened after a lightning strike to a Lockheed P3 Orion. This particular aircraft has a magnetometer boom extending from the rear of the fuselage, which is protected against lightning damage in the same way as the radome.

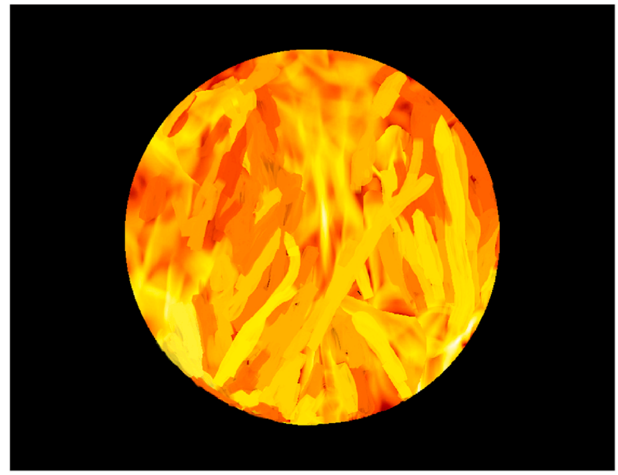


Fig. 8. Appearance of the ball lightning. Artwork by D. Smith.

In order to replicate the subjective impression of such a luminous object at night, a ground glass sphere of 20 cm diameter was fitted with various incandescent lightbulbs and a dimmable RGB light source. The light intensity on the outside surface of the sphere was measured with a photometer. A photo of this sphere is shown in Fig. 9. An incandescent lightbulb with a rating of 40 W produces a luminance of the sphere of 200 cd/m^2. An observer would estimate this lamp to have at least 100 W. Due to its large size, it appears brighter than it is. The RGB light source was programmable in steps of 0.6 cd/m^2 and adjusted such that all colors would have the same brightness for each step. Surprisingly, a luminance of 1.2 cd/m^2 at the surface of the sphere is already quite bright and a fiery apparition in a darkened room.

We estimate that the ball lightning in the cockpit had a surface brightness of no more than 4–8 cd/m^2, which is in the range of an incandescent lightbulb with a rating of about 1.2 W and a light output of 12 lumens at a luminous efficiency around 4 %. The power of the light emission itself will have been on the order of 50 mW.

It appears that the luminous intensity of ball lightning is commonly overestimated by two orders of magnitude. This may be due to suggestive questioning by the interviewers and because the observers have no suitable comparison for the intensity. The closest estimate was given by Roger Jennison after his observation of ball lightning in an aircraft. He assessed the optical output as approximately 5–10 W, which he most probably also compared to a tungsten filament lightbulb of this rating in

Fig. 9. Glass sphere at 1.2 cd/m.^{2}.

Jennison (1969).

The total energy of ball lightning must include all other emissions in the UV and infrared range and at radio frequencies, ejection of charged particles, excitation of metastable molecules and chemical losses through the production of ozone and nitrous gases. In this view, the emission of visible light does not seem to be a major path of energy loss for the ball lightning. One may indeed wonder, if species of "invisible" ball lightning exist, which emit no noticeable light in the visible spectrum at all. Such an observation appears to have been made by J. S. Ames [3] and is reported in Humphreys (1936).

Color of ball lightning – An unsolved mystery of ball lightning is its light emission, which can apparently have any color of the spectrum, with the more commonly observed ones reported as blue, white, yellow or red/orange, that is, every color except green, which is rarely observed. This has remained unchanged since the overview in Brand (1923). More exotic descriptions were silver, golden-blue or transparent with blue dots. The same ball lightning can have several colors and the color may change over its lifetime. We can attempt to explain the red component which has often been seen.

The excited $^1\Delta_g$ singlet state of oxygen molecules has an energy very close to 1 eV, which corresponds to an emission in the infrared at 1270 nm. It is metastable because its direct transition to the triplet ground state $^3\Sigma_g^-$ is spin-forbidden, resulting in a long radiative lifetime. When two such metastable oxygen molecules collide, they can combine their energies and emit red light in the regions of 636 nm and 704 nm (dimer emission of $[^1\Delta_g]_2$), as measured by Jockusch et al. (2008) and shown in Fig. 12. The intensity of the light emission therefore increases with the square of the metastable molecule's number density. Another singlet state of oxygen with a higher energy of 1.6 eV is $^1\Sigma_g^+$, which has an emission band in the deep red around 765 nm.

The corona horns observed on the radome by D.S. had a clear blue color without any tinge of red. In contrast, the ball lightning in the cockpit had a yellow-orange color, an indication that it may well have contained some percentage of metastable oxygen molecules.

A ball lightning observed by W.H. before a thunderstorm in the summer of 2006 had a fuzzy red halo and a blue core. The size of the halo decreased with time, while that of the core remained constant. After several minutes, the halo had almost completely disappeared and only a speckled blue sphere remained. This event has been reported in Heil (2006). A rendering of an intermediate stage of this observation is shown in Fig. 10. For comparison, metastable oxygen was produced by chemical means as in Fig. 11, by bubbling chlorine gas through an alkaline solution of H_2O_2 as described by Kahn and Kasha (1963) and Adam (1981). The red-orange light emission of this reaction matches well with the observed color of the halo of the ball lightning. The color is similar to that of an LED peaking at 640 nm. It appears that ball lightning can create metastable oxygen in air if it is sufficiently energetic. Therefore, this red emission will only be seen when the ball lightning has enough energy to excite a sufficiently high density of singlet oxygen. This emission may be useful as a signature to identify ball lightning in the atmosphere.

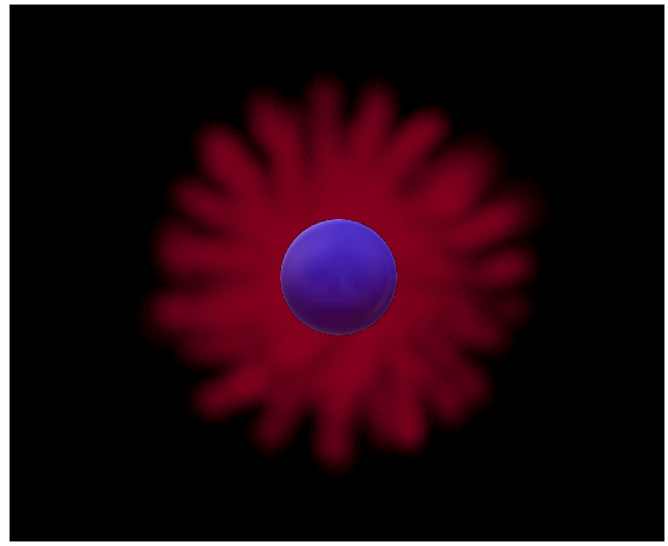


Fig. 10. Ball lightning with a red halo. Illustration by W. Heil.

Fig. 11. Luminescence of singlet oxygen. Photo by M. Kasha, from Adam (1981), with permission by ChiuZ/Wiley-VCH.

8. Conclusion

This study links the appearance of ball lightning with an initial production of ions from a corona discharge. Associated calculations suggest that accumulation of these ions can produce high fields within enclosed structures such as aircraft and also houses. These fields are so high that an electric discharge would be initiated within the structure.

The production of metastable oxygen may be a specific signature of a high energy form of ball lightning, resulting in the red component of its color, which is not normally seen in atmospheric discharges at ambient pressure. It was found that the luminous intensity of ball lightning can actually be quite low. This may mean that its luminous efficiency is small and that other energy losses are more prevalent. The often reported apparent penetration of ball lightning through glass windows seems to be an optical illusion of the observer. This opens the field again for material models of ball lightning which do not require its passage through solid objects.

[3] Joseph S. Ames, longtime director of NACA, in whose honor the NASA Ames Research Center is named. During a thunderstorm, he observed a quivering motion in the air between the floor and the hand of his wife who was standing on a rug. A small luminous fireball, that appeared to be shining through a haze, developed at her extended finger and disappeared after a flood of lightning strikes.

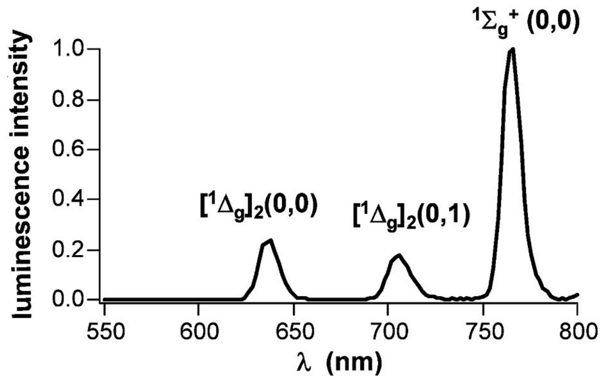


Fig. 12. Singlet oxygen emission spectrum, from Jockusch et al. (2008), reproduced with permission from the Royal Society of Chemistry.

The present paper gives direct evidence that ball lightning can follow after the production of copious ions from a corona discharge and suggests that further development of gas discharge explanations of the properties of ball lightning could be fruitful, as is also suggested in Lowke (2021). Other models, such as those which represent ball lightning as a magnetic knot described by Ranada (1998) or as an MHD vortex similar to a Spheromak suggested by Tar (2006), cannot be ruled out. While the nature of ball lightning remains to be resolved, a corona discharge appears to be required or at least helpful in the initiation phase of its creation.

Individual author contributions

Wilfried Heil. Wrote most of the manuscript, created Figs. 2, 6, 9 and 10 and redrew Fig. 1, obtained Figs. 3a, 4 and 5, 7, 11 and 12. Don Smith. Wrote the detailed report of his experience of ball lightning, created Figs. 1, 3b and 8.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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