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# A Unified Theory of Ball Lightning and Unexplained Atmospheric Lights

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Abstract — Ball lightning has been observed in close proximity to atmospheric vortices such as tornadoes and weaker vortices. In some events it is difficult for eyewitnesses to differentiate between the two phenomena. Excluding a chance association, two causal possibilities present themselves. The first is that the vortex is somehow manufacturing ball lightning and its nature is, as yet, unknown. The second option is that ball lightning is a burning vortex (also referred to in this paper as a 'vortex fireball') in a continuum ranging from a small-scale (centimeters) to a large-scale (meters) vortex. Unusual luminosity is sometimes observed in vortices and this provides a clue to the ball lightning problem. Although one past suggestion used the electrical discharge hypothesis as a mechanism to illuminate a vortex, there is another possibility. The hypothesis is that gaseous combustion within the confines of vortex breakdown could account for ball lightning and other unexplained atmospheric lights.

Given the large air speeds that exist inside tornadoes the only viable mechanism would be that of ignition and continued combustion of a flammable fuel gas taking place within the low air speed, stagnation zone of vortex breakdown. Field evidence from meteorological reports and elsewhere suggest that such a vortex-combustion phenomenon exists. The theory has the added support of experimental demonstration of combustion within vortex breakdown. In addition to ball lightning, the theory can be applied to understand and interpret several difficult-to-explain UFOs.

Keywords: Vortex breakdown--combustion — tornado — balllightning — whirlwind — fireball — UFOs — meteor — tornadoes — Mar lights— Hessdalen — vortex — vortex splitting — meteors — earthquake lights — min mins — volcanoes — foo fighters — will o' the wisp

## 1. Introduction

The reality of ball lightning as a physical phenomenon is now rarely disputed (Singer, 1971). The next step facing investigators is to correctly resolve the nature of ball lightning. While several attempts have been made in this area over at least two centuries, with several well known scientists associated with the phenomenon (Faraday, Arago, Tesla, Kapitsa etc), not a single explanation has been accepted. Well known scientist and popular writer, Davies (1987) described the persistence of this meteorological riddle:

*The phenomenon responsible for these manifestations--ball lightning–4s one of the more bizarre scientific riddles of our age (p. 64)*

The problem of ball lightning has been thoroughly reviewed in books by Singer (1971), and more recently by Stenhoff (1999).

A common a priori assumption among theorists is that ball lightning is fundamentally an electrical phenomenon, even though ball lightning's primary energy source has not been elucidated. To the present day, various investigators continue to speculate on ball lightning's main type of energy. The continued use of the 'ball lightning' nomenclature (c.f. kugelblitz, boule de feu) might bias an investigator towards the assumption of an electrical origin. Such a premise is unsupported by existing research and conflicts with a number of field observations, such as ball lightning seen in fine weather unconnected with a lightning strike (Ofuruton *et al*, 1997).

To account for fair weather fireballs there is the possibility that ball lightning is a non-electrical phenomenon. Chemical models are attractive; not only do they have the inherent capacity of supplying fuel to a ball over a long time but the energy density of the fuel is sufficiently high to explain cases of sustained heating. Chemical theories proposed in the past by investigators, such as Muschenbroek in 1769 (Singer, 1971), required some method of assembling the flammable gas into a localized volume. Even if gas could be brought into such a volume, the burning of gas alone would not adequately explain other reported ball lightning features, such as the chemical to mechanical energy transformation involved in the boring of holes and trenches in the ground. In this paper a qualitative theory of ball lightning is discussed, which could overcome a number of obstacles and also account for a certain type of unexplained atmospheric light that was previously categorized as a UFO. The theory has its origin in a set of observations concerning the unexplained luminosity in atmospheric vortices, especially the fiery whirlwinds recorded in early meteorological journals. The theory presented here is that ball lightning and several related fireballs are the same fundamental phenomenon i.e. combusting vortices. The case descriptions that follow provide sound evidence that such atmospheric vortex burners do exist, though they have not been well understood.

## *Whirlwinds of Fire*

Vonnegut & Weyer (1966) and Vaughan & Vonnegut (1976) described unusual light emission from tornadoes, such as a yellow egg-shaped glow. Toroidal bands of light, spheres, discs, cylindrical glows, and lights of other geometries, located high up on the vortex funnel have also been seen. A correct interpretation of these tornado lights and other related effects might lead to an understanding of ball lighting. Vonnegut's interest in luminosity of tornadoes seems to be inspired by how this phenomenon might provide evidence for his electrical theory of tornadoes (Vonnegut, 1960). This theory postulated that a lightning discharge is the main energy source for a vortex. This idea had an earlier history, with Lucretius in 60 BC and Francis Bacon in 1622 both advancing this thesis. However, contemporary research demonstrates that this concept has not been accepted as the correct basis for tornado genesis and maintenance (e.g. Davies-Jones & Golden, 1975 a, b, c; Snow, 1987). The reasons are that there is a lack of statistical evidence of lightning near tornadoes, and credible alternative models of tornado creation have been proposed.

While observations of light emission from tornadoes have been recorded, and some might be a result of repeated lightning discharges, there is uncertainty over what is actually causing the luminosity in any given situation. In most instances the observer is usually standing at some distance from a vortex, but in some rarer events an observer was close enough on the ground to provide a more detailed description of the phenomenon. In such events these vortices[1] were described very much like they were actually on fire. The reports of whirlwinds contain what appear to be non-electrical flames, locally within the body of the vortex. Although these vortices were less intense than tornadoes, a similar process might actually be taking place within tornadoes. Because of the scientific importance of this phenomenon, three cases are quoted in detail. These cases were collected from the literature by Corliss (1982).

***Case 1—Whirlwind reported in Americus, Georgia, U.S.A. reported by* Anon *(1881)***

*... a small whirlwind, about 5 feet in diameter and sometimes 100 feet high, formed over a corn-field where it tore up the stalks by the roots and carried them with sand and other loose materials high into the air. The body of the whirling mass was of vaporousformation and perfectly black, the center apparently illuminated by fire and emitting a strange 'sulphurous fire' that could be distinguished a distance of about 300 yards, burning and sickening all who approached close to breathe it. Occasionally the cloud would divide into three minor ones, when the whole mass would shoot upwards into the heavens.* (Anon, 1881, Page 9)

*Comments:*

Case 1 shows what appears to be unequivocal evidence of a vortex unconnected with a storm or lightning. The lifting of objects into the air is a well-known mechanical property of a vortex. The 'sulfurous fire' could be hydrogen sulfide, which is known to have an odor like rotten eggs. Combustion of this gas with air is known to produce a blue flame. The product of combustion sulfur dioxide gas might explain the quotation, '... *sickening all who approached close to breathe it*' (page 9). *A* trained observer named Montgomery, also reported on air that smelt of burnt sulfur and hard to breathe, after the luminous Blackwell tornado passed by (Vonnegut, 1960). Silberg (1966) commented that a smell of sulfur or brimstone was often noted by observers who encountered tornadoes that can burn or scorch objects in their path. Furthermore, Turner (1998) cited Peltier (1841) who also recorded the smell of sulfur dioxides in his research of water spouts, tornadoes, and tornado analogues. The reference to cloud division into three parts could well be a case of 'vortex splitting', a documented property of vortices.

### *Case 2—Newbottle whirlwind of November 30th, 1872 that took place at Banbury, England reported by* **Beesley** *(1873).*

*About 12 o'clock we had a heavy storm of rain and hail, in the middle of which there was a very vivid flash of lightning, with almost instantaneous thunder of a very peculiar rattling sound. About five minutes afterwards, as I was leaving the house, my gardener called me to come and see the ball of fire. I was unfortunately half a minute too late, but I have seen four persons who saw it from different points, and who all agree they heard a whizzing, roaring sound like a passing train, which attracted their attention, and then saw a huge revolving ball of fire traveling from six to ten feet off the ground. The smoke was whizzing around and rising high in the air, and a blast of wind accompanied it, carrying a cloud of branches along and destroying everything in its way . . . Where it first began the breadth of ground traveled over was very narrow, but increased as it proceeded, till in the last field the debris covered a space quite 150 yards wide, and here it seems to have exhausted itself, as all witnesses agree that the ball of fire seemed to vanish at this spot without any explosion. Here the ground had been cut in places as if by a cannonball, but I could find no cause for this, and I saw no signs of fire on its route . . . William Marshall, gardener at Newhottle Manor, was returning from stables to the house. He heard a noise like a long railway train crossing a bridge, and saw leaves and branches whirled into the air above the Spinney, and immediately afterwards 'a dark ball, as big as a carriage', and sending up a 'a cloud of smoke' come out of the trees with a shower of branches, and roll 'over and over', down the hill in the direction of the bridle road; the cloud of smoke at the same time whirling 'round and round' with a 'buzzing noise'. He distinctly saw sparks of a red color emitted from the ball about six feet from the ground, and this is confirmed by another man, William Jilson, of Astrop, who, from a field on the west, saw fire and ran away affrighted.'* (Beesley, *1873,* Page 149)

*Comments:*

The first five sentences of this report demonstrate the typical elements observed in classic ball lightning reports, yet other features suggest that the entity was a burning vortex. The descriptions of smoke that whirled around and the blast of air clearly indicate such an explanation. Further behavior such as rotation, transported branches and the 'cutting' into the ground are known vortex effects. The downward blast of air would account for the removal of material from the ground. It appears the fuel gas supply to the vortex may have ceased, which may explain why the fireball flame extinguished even though the vortex continued to carve a path in the ground.

### *Case 3—Symond's Monthly Meteorological Magazine reported by* **Anon** *(1869)*

*a remarkably hot day . . . a sort of whirlwind came along over the neighbouring woods, taking up small branches and leaves of trees and burning them in a sort of flaming cylinder that traveled at the rate of about jive miles per hour, developing size as it traveled. It passed directly over the spot where a team of horses were feeding and singed* *their manes and tails up to their roots; it then swept towards the house, taking a stack of hay in its course. It seemed to increase in heat as it went, and by the time it reached the house it immediately fired the shingles from end to end of the building, so that in ten minutes the whole dwelling was wrapped in flames. The tall column of traveling calorific (i.e. energy/fire) then continued its course over a wheat field that had been recently cradled, setting fire to all the stacks that happen to he in its course. Passing from the field, its path lay over a stretch of woods which reached the river. The green leaves on the trees were crisped to a cinder for a breadth of 20 yards, in a straight line to the Cumberland. When the "pillar of fire'' reached the water, it suddenly changed its route down the river, raising a column of steam which went up to the clouds for about half-a-mile, when it finally died out. Not less than 200 people witnessed this strangest of phenomena. (Anon, 1869,* Page 123)

*Comments:*

The direct reference to a 'whirlwind' leaves no doubt as to the basic phenomenon. Vortices are known to be influenced by the local terrain. It is also known that a transfer of angular momentum to the rotating air mass can strengthen the vortex (Fujita, 1989). This may explain the increase in vortex size as it traveled along. A vortex breakdown fireball moving along could 'vacuum' up combustibles and burn them, as well as emitting radiation to burn leaves and scorch tree trunks.

## 2. A Solution of the Ball Lightning Problem

Past theories of ball lightning were well discussed by Singer (1971) and also by Stenhoff (1999). A recent emphasis solely on aerosol models, in a collection of papers published in the 2002 Philosophical Transactions of the Royal Society, like that of Bychkov (2002) cannot provide a complete explanation of ball lightning's reported behavior (Turner, 2003). As an alternative approach, it might be more productive to explore the luminosity in vortices, described above, and the reported association of ball lightning with atmospheric vortices.

The association of ball lightning with atmospheric vortices was known by investigators as early as 1890–1891. Faye, of the French Academy (Stenhoff, 1999) around this time, suggested that ball lightning formed from whirlwinds, cyclones and tornadoes. Ball lightning was reported by Faye, to detach itself from the lower tip of the funnel, inspired perhaps, by ball lightning, the size of billiard balls, seen in the air with a tornado. These fireballs created eight centimeter diameter holes in windows. Faye conceptualized ball lightning as a highly charged rotating sphere. Friction with water droplets, hail and other particulates were said to produce charge separation and presumably electrical discharges generated light in the vortex. This is the classic Leyden jar model as described by Singer (1971).

The idea that ball lightning is a vortex does have some historical precedence. Hands, in 1909 and 1910, and Lagrange in 1910, both thought ball lightning was light that emanated from a whirlwind (Singer, 1971). Botley (1966) cited M. J. Dessens (from the Centre of Atmospheric Research in France), who commented on a tornado's extraordinary ability to "hatch" fireballs from the lower tip of the spout. In other cases, several fireballs seemed to be embedded in the vortex air stream. Bonacina, in 1946 reported on the 1638 Widecombe disaster, in which a church was demolished by a whirlwind. A stylized drawing at the time showed a fireball connected to a funnel, indicating that perhaps the fireball was carried by the tornado or actually part of the vortex's air flow.

Large fireballs located high on the main axis of the tornado appear to indicate that the fireballs are part of the vortex air flow itself. Weeks (1995), cited by Turner (2003), reported on damage to houses attributed to a tornado. But at the same time there was a large ball lightning that moved along the road and destroyed houses at a height greater than the roof tops. The fireball and the tornado may be inextricably linked, and therefore be one and the same phenomenon. Further examples in this category include: the fireball of the Newbottle tornado (case 2 above) and the twisting ball of fire seen on the axis of the Dorset Tornado of 1989 (reported by Brown [1990] and cited by Vonnegut [1991]). The whirlwind–ball lightning event recounted by Campbell (1982) that occurred at Crail in Scotland, showed features that indicate that ball lightning and a whirlwind could be one in the same phenomenon. The quote '... *it was suddenly disrupted by a whirlwind, which hurled several deckchairs and other loose items in the air and dropped them 50 m down the beach towards the sea'* (Campbell, 1982, page 76) describes the whirlwind. The fireball description also contained elements of a vortex description, '... *about 20 cm in diameter, a dirty copper colour, trailed what looked like a 5 cm ribbon of copper, and made a whirring noise. It appeared to be rotating on a horizontal axis, clockwise as viewed by the witness, and 1.5 m from the ground'* (Ibid). A sketch of the fireball (Figure 2, Ibid) depicts ball lightning as seen by eyewitness, Elizabeth Radcliffe. Her drawing contains a representation of what appear to be airflow lines spiraling into the ball, indicating that a vortex breakdown fireball could well have rotated on a horizontal axis.

If there is a close causal connection between vortices and ball lightning, then either the vortex somehow produces the fireball by some unknown mechanism, or ball lightning has its origin as a vortex and perhaps belongs to the fiery whirlwind phenomenon already discussed above. If ball lightning is of this latter origin, then the cause of the luminosity in these fiery whirlwinds must be found. While the nature of this 'fire' in such episodes might be electrical in origin, there are difficulties with such an interpretation. The longevity of an electrical discharge over the time durations reported implies, under this hypothesis, that there must be an ongoing supply of separation of charged particles to prevent rapid recombination which is typically much less than a second.

An alternative hypothesis is advanced here to explain the fiery whirlwinds phenomenon represented by the three eyewitness reports above. This is to consider that the vortex was actually on fire in a localized zone within the vortex. Combustion is then the source of the luminosity. At night this emission of visible electromagnetic radiation would be nearly all that would be observed.

The light would move in accordance with the 'carrier' vortex and thus explain reports where ball lightning had an independent motion, like wobbling, loping (Jennison, 1997), and the ability to move with or against the wind. Hence a vortex could account for ball lightning's odd motion, as if it had a 'mind' of its own. In contrast, a sphere carried along by the prevailing wind, as some ball lightning theorists have proposed, would not have this capability. Passive sphere models of metallic vapor or joined particulates (e.g. the aerogel model of Smirnov, 1993b) have a difficult problem to overcome in explaining how ball lightning is able to remain hovering near or on the wings of a moving aircraft. Ingle (1971) reported a fireball above a moving aircraft's wing. It made to-and-fro movements but surprisingly it was not blown away by the 250 mph winds. Ingle considered this observation to be inconsistent with models advocating vaporized metal fireballs. Such passive spheres would simply be blown away and rapidly cooled by the high speed air rushing past. Under the vortex theory these fireballs may be combusting aircraft-generated vortices from wing tips.

A case for a vortex combustion theory, as applied to ball lightning and related lights was proposed by Coleman (1993, 1997a, b) who conceived ball lightning as an atmospheric vortex capable of burning a fuel, like natural gas, contained mostly within vortex breakdown. Breakdown is a lateral expansion of the vortex funnel and appears often as a globe-like shape, although other shapes have been categorized, e.g. Khoo *et al* (1995).

Given the high air speeds (several meters per second) within atmospheric vortices, like the tornado, any combustion flame would be expected to be extinguished. However, combustion could be achieved within 'axisymmetric' vortex breakdown because of the existence of very low velocity (lower than the flame speed) stagnation zones within the bubble recirculation region. In addition, the duration of luminosity is dependent on the fuel supply fed to vortex breakdown, assuming the vortex continued its existence. This would easily account for reports of long-lived ball lightning that last an hour or more.

The phenomenon of vortex breakdown is not just a theoretical concept. 'Breakdown', as it is sometimes known, has not only been observed in laboratory vortices, since its discovery by Peckham & Atkinson (1957), but also in atmospheric vortices (Pauley & Snow; 1988). A crucial experiment demonstrating that combustion could take place in atmospheric vortices was carried out in a chamber designed to model natural vortices (Coleman & Abrahamson, 1998).

With the addition of the combustion flame to vortex breakdown, basic ball lightning shapes reported could, in principle, be accounted for. Ball lightning has many geometries including sphere (the most common), hollow sphere, cylinder, disc, a cylinder appended to the bottom of a sphere, linked spheres, heart-shaped, elliptical, ring, cylinder, torus etc. Shape changes would correspond to changes in parameters, like the swirl ratio, which has been defined for artificial vortex generators. An amorphous fireball flame is possible under the vortex theory and is consistent with Grigorjev *et al* (1989) and Stakhanov (1979) who both found that 1.43% and 1.6% of their total ball lightning events were of no particular shape.

Studies of vortex breakdown, such as Sarpkaya (1971) and other investigators, showed that the 'bubble' recirculation region can move up or down along the axis of the vortex, corresponding to changes in volumetric air flow into the vortex. Increases in air flow tend to shift the bubble down while decreases tend to shift the bubble up. This property of vortex breakdown overcomes the objection that is frequently raised in respect of some ball lightning models that postulate a hot sphere of gases that would always rise up in the air. Theories that postulate the doping of hot air with a metallic vapor having a density greater than air could explain ball lightning events with downward movement but they are not flexible enough to contend with the unusual ability of ball lightning to rise and fall or move laterally in an apparently whimsical fashion.

### *Explanation of Ball Lightning Properties*

The author will present a preliminary case for the vortex-fireball theory based on support from ball lightning eyewitness observations. It is noted that even a casual scrutiny of published observations reveals an array of apparent contradictory properties (Singer, 1971). Frequently quoted properties include: seen in stormy weather/fine weather, motionless/moving (e.g. hopping, bouncing, against the wind etc) heat can be felt/not felt, quiet demise/explosive demise, spherical/non-spherical (e.g. elliptical, tube, hollow sphere, amorphous flame, ring two spheres connected by a 'umbilical cord', torus etc), steady shape/varying shape.

The vortex-flame phenomenon is capable of accommodating a diverse range of features, which, at first glance, appear to be paradoxical. The natural vortex phenomenon itself exhibits many features that show commonality with observed ball lightning properties. These include: movement against the wind, fireballs seen in tornadoes, rotation, bouncing, drilling holes or cutting trenches into the ground. By adding the combustion flame to the vortex many ball lightning shapes can be accounted for since the flame envelope is constrained by the airflow. A steady-state airflow to the vortex is likely to produce a stable flame geometry and transient airflow and changes in the fuel mixture ratio may alter the flame shape.

Photographs, individual eyewitness reports from the literature and interviews, and large databases with statistical analysis form a useful body of published ball lightning observation data. This was not always the case. Singer (1977) referred to only three collections of ball lightning at the time (though there existed more):

> *The properties of ball lightning have been considered in greater detail by de Jans (1910–12), Brand (1923) and Singer (1971). No surveys or collections of reports have been established since that major review of 1971, but a number of individual observations have been reported.* (Page *410)*

The number of databases available to researchers has since increased to double figures. A tentative list of published databases is useful for supplying evidence to test a given theory. Available databases include: Arago (1854), Sauter (1896), Mathias (1934), McNally (1966), Rayle (1966), Charman (1979), Stakhanov (1979, 1985), Keul (1981, 1989), Grigjorev *et al* (1989), Egely (1987, 1989), Hentschel (1993), Amirov *et al* (1991), Ofuruton *et al* (1997), Smirnov (2000).

Observers can often mistake ball lightning for another other phenomenon. Barry has argued that a large percentage of blue stationary spheres he studied had no detectable heat and were attributed to a low current coronal discharge, commonly referred to as, 'St Elmo's fire'. He rejected these sightings as cases of authentic ball lightning.

Consensus on a set of consistently observed properties is not always possible by those working in the field. Take for example the commonly held assumption that ball lightning is only associated with thunderstorms. There are a significant number of fair weather observations having no association with lighting, as Singer (1971) and others have pointed out. Any prospective ball lightning theory would need to address the report of Ofuruton *et al* (1997), page 17, who found that 89.10% were fine or cloudy weather ball lightning sightings. Unfortunately some researchers omit fair-weather evidence from their studies. Smirnov (1993a) presented several databases but worked out statistical parameters without the Japanese data.

If the author's theory were solely concerned with tornadoes then obviously a large percentage of smaller ball lightning sightings would logically need to be excluded, so it is important to emphasize that the vortex-combustion model presented in this paper is definitely not limited to fireballs in the tornado. There will be a continuum of size scaling down to smaller vortices a few centimeters in diameter.

A large percentage of ball lightning events were seen indoors ($\sim$ 50 %) and may simply reflect the fact that an observer is more likely to be indoors during a storm. Now since the theory allows for smaller vortices originating from say, a lightning strike, these could get into a room though an opening. It is well known that ball lightning can move though open windows, chimneys and small spaces. Corliss (1982) collected important ball lightning sightings from the scientific literature. On page 62 he cited a basketball-sized fireball (case X105) in Pennsylvania that entered one window and left another. It is possible a burning spherical vortex, the size of a cannonball, and with a sufficiently large angular momentum could avoid dissipation and last at least a few seconds to enter and leave a building through some opening. Singer (1971) cited a detailed Russian description to prevent ball lightning getting into buildings by shutting all windows, and air vents. For openings that could not be closed it was recommended that earthed metal grids using 2–2.5 mm wire with 4 $cm^2$ holes be utilized. The latter recommendation would be futile under the theory since if the nature of ball lightning was not electrical there would be no electrical 'shorting' out to earth. There are cases where ball lighting has passed right through metallic mesh door screens further contradicting the common assumption that ball lightning is electrical.

Scaled-down vortices, of the order of a few centimeters in diameter, will have correspondingly shorter lifetimes (seconds rather than hours). It is conceivable that lightning could produce a short-lived combusting vortex at ground level by igniting a combustible such as a solid or gas within the vortex breakdown. It is emphasized that the combusting vortex theory is not solely limited to burning a gaseous fuel, though that might be more common than solid combustibles. The theory cannot be easily dismissed when events take place in non–gas-producing areas, other than swamps and natural gas fissures. Since solid burning material could potentially be held within a vortex. **A** demonstration of this was documented and observed by Coleman (1990) who saw solid fibrous material carried in small circular orbits within a small-scale vortex. It is also well documented that mature vortices can carry an object several miles within a vortex (e.g. Nalivikan, 1983).

Previous ball lightning investigators have suggested that a lightning strike is a possible mechanism to generate a smaller vortex that would generate both a buoyant convective current and vorticity (Singer, 1971). The vortex is now better understood and there is a need to revisit this superposition especially in the light of our current understanding of vortex breakdown and other properties of a vortex such as vortex splitting etc.

The thermal energy released from a lightning strike is more than sufficient to create a vortex. Even lower energy discharges can generate a vortex. The mechanism has experimental support. Ryan & Vonnegut (1970) demonstrated that a high voltage discharge of 2.5 Amperes can produce and sustain a vortex from electrical heating. A single lightning discharge can typically produce a current of 100 Amperes which would more than suffice to create a strong miniature vortex a few centimeters in diameter. The rotation effects of a small burning vortex in a room may not be detected unless a tracer, such as dust, is present and may help to explain why the percentage cases of observed rotation is lower than one might expect. It is certainly true that rotation effects in experimental vortices are hard to detect unless there is some tracer.

There could be more than one form of ball lightning. However judging by the number of attempts to solve the problem of ball lightning using a single theory, there are obviously many investigators who believe that a single unknown phenomenon is implicated. Turner (1998) cited Stakhanov (1979) and Barry (1980) who provided evidence for two types, but concluded that there was only one basic phenomenon involved. Debate on this question will continue until a correct explanation is accepted by the scientific community.

Although the combusting vortex theory presented herein explains a specific subset of reported properties, it is limited in being able to account for all reported properties. The theory has a difficult problem explaining isolated reports of apparent materialization in a room, as typified by the report of Holmes (1934). Others include movement through a window without any effect on the glass (Singer, 1991), ball lightning moving down the aisle of an aircraft (Jennison, 1969), spheres appearing at finger tips and knobs (Singer, 1971).

Theories that utilize focused electromagnetic radiation. like the radiofrequency wave theories of Kapitsa (1955), or Ohtsuki & Ofuruton (1991) are capable of explaining the non-intrusive passage through a window.

Rotation is a frequently reported property consistent with the vortex theory described here. Singer (1977) noted that: *'several seem to roll along the surface of the earth. A few rise in upward flight. Motion directly against the wind is reported, and rapid rotation is observed in many cases',* page 410. Cade & Davis (1969) refer to the common occurrence of ball lightning (termed 'Rullende Lyn'), in Norway, which commonly rolls along the ground, precesses like a top, and has the capacity to uproot lamp posts. Ofuruton *et al* (1997), page 18 found that 4.7% of their 2000+ observations showed rotation, while Grigorjev *et al* (1989) found 5.1% rotation events from a similar data base of −2000. Single figure percentages were also found by Brand (1923) with 7% and McNally (1966) with 9%. Larger percentages were reported by Rayle (1966) –31%, Keul (1989) –22%, and Dewan (1964) −17.5%.

There are a number of ball lightning events that provide additional observational evidence for a combusting vortex. The fair-weather fireball event, reported by Campbell (1982) took place in Crail in Scotland and shows clear indications of a vortex. McMillan (1889) reported ball lightning being able to raise dust into the air, while Ryan (1895) described ball lightning that bored holes into a wall. Naturally-occurring two-celled vortices can possess an inner cell with a central downdraft (Pauley & Snow, 1988). This downward jet of air from vortex breakdown is capable of boring holes and trenches into soil.

The combined features of this vortex fireball theory make it capable of explaining several reported properties of ball lightning. Some, but not all, reported properties are listed below, followed by a brief explanation. While Singer (1971) included many of these features of ball lightning structure and behavior in his monograph, a few additional comments and references have been added to gain a better understanding of how the theory may explain the various aspects of fireball observations.

- Fireballs moving up or down. Explanation: It is known from studies on experimental vortex breakdown, such as Sarpkaya (1971), that increases1 decreases in the volumetric flow into the vortex, can move the vortex breakdown bubble downwards/upwards along the spin axis.
- Ball lightning fireballs detaching from the tip of vortex funnel. Botley (1966) cited Dessens who reported tornadoes that were able to vomit balls of fire from their funnel tips. Explanation: This observation is consistent with Justice (1930) who reported on small vortices that repeatedly formed at the lower tip of the funnel and broke away. This provides evidence that non-combusting vortices can be produced at the funnel tip. If a gaseous fuel were present feeding into these smaller vortices, it is conceivable that combusting vortices could also be produced from the funnel rim and detach as fireballs.
- Ball lighting ejected from volcanoes. Explanation: A volcano can possess

all three feature requirements to generate a fireball including; ignition source, combustible fuel, and a hot air convection current. Shearing winds across the buoyant convection current provide one mechanism to generate vorticity.

- Fireballs seen in close proximity to a main vortex such as a tornado. Explanation: A tornado is often reported as having small-scale vortices embedded in the large scale rotating flow (Fujita, 1989). It is these secondary vortices that might explain the smaller fireballs surrounding a tornado.
- Fireballs seen in fair-weather (Ofuruton *et* al, 1997). Explanation: The vortex fireball theory requires only that there be a vortex, fuel gas and a source of ignition. It follows that ball lightning creation is not solely dependent on a lightning stroke.
- Long lifetimes (from a second or so up to several hours). Explanation: The lifetime would depend on both the lifetime of the vortex and the fuel supply.
- Large diameters (several meters). Explanation: Vortex funnels and breakdown diameters are variable and can range up to several meters in diameter. As an example, Simpson *et al* (1986) reported waterspouts with diameters ranging from 4m to 75m from field work off the Florida Keys.
- Mechanical damage, such as circular pits or holes and trenches in the ground. Fitzgerald (1878) reported a 'globe of fire' that made a long trench 4 feet in depth in the Glendown Mountains of Ireland. Explanation: A high speed downward jet of moving air from the reverse flow of vortex breakdown would be able to excavate soil. Nalivikan (1983), pages 406–407 presented eyewitness accounts of tornadoes forming a trench across the Mississippi River.
- Splitting into two or more fireballs and recombination into a single fireball (sometimes repeatedly). Explanation: Vortex splitting is a vortex property where a main vortex breaks into a number of vortices rotating about a common center. Four or more vortices have been reported. Experimental studies have shown that for a high swirl (the ratio of tangential speed to vertical speed), a single vortex can spawn secondary vortices. A lowering of this ratio coincides with recombination back to a single vortex. Vortex splitting takes place in natural 'suction' vortices (e.g. Agee *et al,* 1975).
- Two or more balls linked in a horizontal or vertical direction (Soper, 1915). Explanation: Multiple vortex breakdown takes place when one or more vortex breakdown 'bubbles' are created and linked to a primary vortex. Vortices can be oriented horizontally or vertically in the atmosphere.
- Bouncing off ground and objects (Jones, 1977) Explanation: Angular momentum of rotating air mass of the vortex interacts with the objects (e.g. roof or ground). Direct field reports of natural vortices support this 'bouncing' effect (Fujita, 1989).
- Rotation. Explanation: This is simply explained as rotating air or flames of the vortex fireball.

- Movement with and against the wind. Explanation: Vortices, such as dust devils have the ability to move with or against the prevailing wind.
- Downdrafts of air, gusts of air and swirling and lifting of common objects. Explanation: The central downdraft and spiraling updraft can account for gusts of air. The swirling updraft of the outer cell of a vortex can explain the lifting of objects.
- Shapes, shape increases/decreases, and shape changes: disc, wheel, ellipsoid and sphere, with or without tube extension etc. Explanation: Ball lightning shapes represent the luminous flame boundary and parts of the vortex delineated by a tracer such as dust or water. For instance a glowing sphere with a cylinder extending from the base might be identified as combustion inside vortex breakdown extending part way into the main funnel. Singer (1971), page 73, stated *'Changes in size can involve either a decrease or an increase. Brand cited three examples of shrinking and Jive of expanding balls, while in Rayle (1966) nine became smaller and larger. Eight occurrences in Brand exhibited changes in shape; e.g. elongation etc.'* Shape changes will arise from airflow perturbations and changes in the fuel-to-air mixture ratio.
- Holes in windows. Explanation: The angular momentum of a spinning air mass and a high temperature flame can bore and/or melt a circular or elliptical hole. The theory cannot explain reports of the 'ghost-like' passage through a pane of glass without any effect on the glass. However it can explain the passage through a metal mesh screen which some observers have referred to as a 'window' or by melting or mechanically breaking a hole in the glass.
- Explosion or quiet demise. Explanation: The fuel-to-air ratio decreases and enters the explosive zone. However, one route for a quiet demise would occur when a vortex dissipates before the explosive regime is reached.

Any proposed theory, like this one, will have shortcomings in attempting to explain all known properties of ball lightning. It could be that some reported properties in the literature on ball lightning are not actual properties (e.g. Turner, 2003). But when a property is reported consistently by a large number of reporters it is quite likely that the property is real. The value of the vortex fireball model lies in its ability to explain a reasonable number of well-reported properties of ball lightning. In addition, there is supporting evidence that the actual phenomenon exists in nature. Furthermore the vortex fireball can be produced in the laboratory (Coleman & Abrahamson, 1998). The theory is therefore a plausible alternative to existing ball lightning theories.

The vortex fireball theory is also conceptually capable of overcoming the 'serious difficulties' outlined by Singer (1971) which are the continued luminosity, the observation of the ball lighting inside buildings, and lastly, the destructive passage through windows. In the vortex combustion theory reported here, so long as there is a continued supply of fuel gas to the vortex (assuming the vortex survives) the luminosity will continue. In principle this overcomes both the luminosity problem and occurrence inside a building, provided that there is some opening such as a window or hole as mentioned earlier.

A few comments will be made on possible mechanisms to assist vortex survival. Since some ball lightning cases involve only a few seconds it is conceivable that a vortex could comfortably last this long, especially if it had a large angular momentum and corresponding longer spin-down time. Larger vortices tend to last longer; individual tornadoes can last several hours. Natural vortices have an ability to extract angular momentum from the local surroundings (Fujita, 1989). Another mechanism for a longer duration vortex fireball could result from the hot buoyant updraft of gases from a combusting flame within vortex breakdown, which may be able to extend the life of the vortex. Ryan and Vonnegut (1970) demonstrated, at least for an electrical discharge, that heat energy transferred to the air can maintain a vortex in an experimental chamber. The electrical heating into the vortex generated an additional air updraft to further sustain the vortex. There seems no reason why a combustion flame could not substitute for the electrical arc discharge to sustain vortices from buoyant updrafts.

The third problem of entry through glass windows has already been addressed above. The theory can broadly explain the melting of holes, and the forming of circular and elliptical holes in windows from the angular momentum of the rotating air mass and its high temperature flame. A vortex moving slowly through glass is more likely to melt the edges of a hole while a fast moving, small-but-strong vortex could act like a cricket ball in punching a hole in the glass. It needs to be re-emphasized that even though some critics believe a vortex would dissipate quickly when moving towards a building, a small vortex with plenty of angular momentum could easily move through an open window or a metallic screen. Successfully penetrating a metallic screen is an obvious difficulty for self-contained Leyden jar electrical models since such fireballs, if they did exist in nature, would electrically 'short out' to the metal and this would be evident in eyewitness accounts.

### *Predicting Further Ball Lightning Observations Based on the Theory*

In addition to the usual ball lightning features reported, the vortex fireball theory predicts further properties that can be derived from both studies on vortices and combustion science. Results established in these fields might appear in future ball lightning accounts and test the theory's validity.

To illustrate the predictive ability of the vortex fireball theory, consider reports where ball lightning has been observed to split into a number of fireballs. Under the theory, this would be a case of vortex splitting, but more details can be predicted to occur in the field. Agee *et* al. (1975) have found evidence that vortices rotating about a parent vortex have the strongest suction vortices at the rear of the main vortex and virtually none at the very front. Since the vortices rotate about a common centre, around the circumference of a circle, the path of each vortex traces out a cycloid. This 'cycloidal signature', carved on the ground has been reported in tornado accounts and, in some cases, used as evidence to confirm multiple vortex splitting, where no other evidence exists (Agee *et* al., 1975). The theory predicts that a cycloidal signature may eventually be discovered in connection with ball lighting.

Another important prediction is that ball lightning might possess chaotic behavior within its interior. Evidence for chaos was found in numerical vortex breakdown in a cylindrical box with a rotating lid, by Sotiropoulous & Yiannis (2001) and may apply to both non-cornbusting and combusting atmospheric vortices.

## Predicted Localities *for* the Vortex Fireball

Past investigators have commented that the phenomenon is unpredictable in regards to its formation, but with a unified theory it is now possible to predict fireballs at locations where vortices, a fuel gas, and a source of ignition coincide. Areas with a high frequency of all three elements should correlate well with the frequency of occurrence of ball lightning. This makes volcanoes and earthquake faults favored areas. Since many volcanoes fall along active tectonic plate boundaries with gas emission, there should be a correlation of fireball sightings with the edges of plates and other seismic areas.

Volcanoes are especially suitable candidates with their dual combination of a fuel gas source and heat source. The latter is useful for both ignition and a source of thermal updraft for vortex formation. Strong vortices have been seen around erupting areas downwind from the island of Surtsey (Thorrinsson & Vonnegut, 1964). Vortex fireballs may account for what Bach (1993) described as 'gorgones' (fireballs connected with volcanoes) as well as the Russian 'geophysical meteors' described by Ol'khovatov (1998) that coincided with tectonic activity, whirlwinds. Swamps are able to supply 'swamp gas' (methane) from decomposing organic material and may help to explain fireball events reported in these areas. Hence the theory would help to pinpoint locations and remove some of the unpredictability associated with the phenomenon.

While plant material and debris can be lifted high into the vortex and bum, it is suspected that the main fuel gases in the atmosphere be flammable gases like natural gas (a mixture of hydrocarbons such as methane, ethane etc.) and hydrogen sulfide. It is well known that many volcanoes emit hydrogen sulfide during eruptions. In the sometimes high temperature environment of a volcano, hydrogen sulfide will auto-ignite at 260 degrees Celsius to produce sulfur dioxide and water as the combustion products. Hydrogen sulfide has also been known to ignite from friction as it moves over the ground, so a lightning discharge is not required. Thus, at least one ignition method is potentially available to account for fine weather ball lightning under this theory. Natural gas is a common emission product from mud volcanoes but it can also be released from other vents on land and from the seafloor. Earthquakes along fault lines can eject gas from fissures.

A commonly cited objection to chemical models is that ball lightning would be restricted to swamps and marshlands (Singer, 1971); however there are other gas-rich gas locations like volcanoes and faultlines. Terrestrial flammable gas emission is far more ubiquitous than is commonly supposed and with the ability of a vortex to bum combustible solids the scope for possible ball lightning creation sites is further extended.

## 3. Application of the Theory to UFO Lights

Several investigators like Benedicts (1951) and Klass (1966, 1968) have proposed ball lightning as an explanation of some UFOs. However, what is now required is a credible ball lightning theory that could explain some of the diverse properties of UFOs. The explanatory capability of the vortex fireball theory could be what is needed to more fully interpret a difficult-to-explain UFO that has generated world-wide interest (Coleman, 1997a, b). As a caveat, it should be pointed out that this theory does not in any way directly rule out the possibility of extraterrestrial craft. The theory may be applied to help filter out a class of events attributed to a natural atmospheric effect in vortices.

A certain proportion of UFO lights show typical features attributed to a combusting vortex. Such features are well described in many UFO publications (e.g. Hervey, 1978; Cade & Davis, 1969), and are summarized below. A larger table of UFO properties was presented in Coleman (1990) but for the purposes of this paper a shortened list will suffice.

- Shapes like tubes, spheres, linked to tube below, disc, etc.
- Sounds described as a swarm of bees or a moving train.
- Rotation. Comment: Rotation is a common feature when whirlwinds are reported by observers.
- A central fireball surrounded by other fireballs (sometimes appears as a 'wheel') that can split and recombine.
- Wind or rush of air and hovering motion.
- Tilting of luminous cylinders. Comment: This is a commonly observed feature of natural vortices. For example, Simpson *et al* (1986) reported on water spouts that tilt to 10–20 degrees from the increase in vertical wind speed with altitude (i.e. wind shear) pushing the funnel into an inclined position.
- Flames issuing from torpedo-shaped body (Cade and Davis, 1969).
- One UFO linked by a luminous thread to another one above (Zou, 1989).
- Holes and trenches in the ground, "excavated" by the fireball.

Although the theory of vortex combustion may implicate a number of reports of UFOs seen from a distance, it is the detailed eyewitness reports from short distances (e.g. 200 m) that tend to show more features consistent with the theory.

Cases 4 and 6 below were selected from many other UFO sightings on the basis that they are very good eyewitness accounts of the swirling flame structure. Case 5 is a close-up view of a burning cylinder. In each case the UFO could, in principle, be accounted for on the basis of combustion within a large vortex. Several other specific UFO sightings collected by the author also show details that are in accord with a vortex combustion theory. Features like rotation, tilt to the vertical, bouncing, splitting into several fireballs and recombining etc. UFO observations therefore demonstrate properties that are common with many ball lightning sightings.

### *Case 4—Spiraling flames UFO Western Australia, Tom Price reported by* **Mason** *(1997)*

*Our original barbecue observers, being some 200 meters directly below it by now, reported that it was an intense spherical ball of orange-red fire with the fire swirling in a spiral pattern and the James disappearing internally upwards into a central black "hole" or void within the spherical mass of flames. The fireball had no tail and made no noise at all – there was no ground seismic wave as experienced in many other recent Australian fireball events. It was described as a sort of "implosion ball of flames'' with all the fire or James originating in local space outside the fiery sphere-like form, the James being sucked into the center where they disappeared – "like a moving plasma ball in a local space-time warp around a central black hole" – "Never ever seen anything like it before – therefore difficult to describe accurately...*" (Mason, 1997, page 16)

*Comments:*

The above identification of flames being drawn inwards is an apt description of flames swirling into and around the combustion zone of a vortex breakdown 'chamber'. The spiral signature is consistent with air spiraling into a vortex.

### *Case 5—Burning tube UFO Florida, USA reported by* **Group** *(1987)*

In the book, *The Evidence for the Bermuda Triangle,* a couple, called the Wingfields, encountered a UFO while they were on a fishing trip in Florida, USA. The report showed evidence of burning inside a tube extending down to the sea surface. This UFO observation is in accord with the idea of vortex funnel on fire, especially the accompanying smoke and flames, While other sightings point circumstantially towards the fiery vortex theory, this report is more explicit in its reference to the main elements of the vortex-fireball theory presented here.

*About 6 kilometers off Boca Raton, Florida at 2pm, Jean notices a stream of smoke along the horizon ... As they neared the source of the smoke, the more it appeared to be a ship on fire ... they received a shock: the source was not a burning ship, but a pipe, 20–25 centimeters in diameter belching flames and thick smoke. They noticed the pipe was yellowish-colored, as was the smoke, and from 30 meters away produced no smell or sound. After they watched it for some time, the smoke and James gradually subsided, leaving just the pipe protruding from the waters."* (Group, *1985,* page 101)

*Comments:*

This aerial tube was seen a long distance out at sea and had no supporting structure. The reference to a 'tube' is a common way of describing a whirlwind or tornado condensation funnel. The most likely explanation was that it was a small burning waterspout. Waterspouts are common off the coast of Florida. Simpson *et al* (1986) noted that *'The life cycle of the plentiful (hundreds per summer month) Florida Keys waterspouts has been documented in a series of landmark papers by Golden (1968, 1973, 1974a, b, 1977)'*. The observed radius of the funnel is small in comparison to funnel radii obtained from larger waterspouts, which can range from 4–75 m.

### *Case 6—Recirculating Flames UFO, Waikawa, South Island, New Zealand, reported by* **Startup and Illingworth** *(1980)*

In the book, *The Kaikoura UFOs*, by the pilot Captain Bill Startup and journalist Neil Illingworth, the first chapter begins with a prominent UFO incident which took place four days before the major 1978179 Kaikoura, New Zealand UFO sighting. The event was on record as being seen by at least nine observers, such as Frank MacDonald from Waikawa, who observed the fireball through his binoculars. His detailed observations appear to show evidence of combustion in vortex-breakdown.

The UFO settled itself above a ridge near Waikawa Bay. Frank described the shape as being like an upside down sheath of wheat. This sighting is reminiscent of the 'upside down pine tree' observed of some Hessdalen lights. The UFO changed shape. A sketch drawn by the eyewitness at the time of 12.55 a.m. portrayed the object as a dome enclosing a diamond shape, with intense radiating beams. The length of the object was estimated to be at least 400 feet (– 133 m) in length. The object gave out light not like an electrical light suggesting perhaps a combustion flame. Certainly the quotation below suggests flames. Frank MacDonald, an untrained observer, described the light in the following report:

*It was more or less like an open flame. It wasn't like electric light or a car's lights. It was flowing light like living light. The light was flowing and billowing outwards from the object. It never billowed inwards. It was billowing down towards the earth and it flowed out into a circle down at its jeet and it was curling hack. And these flames, these beams of light billowing out, they were practically the same color as the whole object.'* Startup and Illingworth (1980), page 20.

*Comment:*

The above description contains important observations, particularly relevant to the vortex fireball hypothesis. The open flame, described as a 'flowing light', suggests a combustion process. The movement described above suggests air, flames and their combustion products transported outwards and downwards and back. This strongly suggests convective-like recirculation patterns observed in experimentally-produced vortex-breakdown studies.

### *Explaining scientific enigmas*

The phenomenon of combustion within a vortex may account for several other scientific enigmas that have eluded past attempts at explanation. These apparently distinct phenomena may have a common vortex origin. Space precludes a full discussion of each of these puzzles but they are discussed in Coleman (1997a, b, 2004). A shortened list of such UFOs and other effects that might be capable of being understood in terms of the theory described here include foo fighters, min mins (fireball lights seen by the indigenous people of Australia), fox fire, spontaneous human combustion, will o' the wisp, some earthquake lights, swamp lights, the Hessdalen lights, special slow moving meteors, the 'geophysical meteors' reported by Ol'khovatov (1997) and the inexplicable scorching of tree trunks on the side facing a tornado (Silberg, 1966). In the latter situation, Silberg calculated the heating effects of a hypothetical toroidal ring current some way up the tornado funnel. In actuality, the heating effects might also be accounted for by a combustion fireball high up on the main axis of the tornado. The tornado events cited by Silberg are remarkably similar to Case 3 above where vortex combustion could have generated heat radiation and burnt the leaves as the vortex moved to the river.

## 4. Photographic Evidence in Support of the Theory

While there is evidence from eyewitness accounts reported in meteorological records, there is another source of circumstantial field evidence in agreement with the vortex fireball theory. Rare photographs exist of ball lightning and some UFOs that are consistent with combustion inside vortex breakdown: some of these will now be briefly mentioned. The first is Berger's photograph of ball lightning taken in 1978 at Sankt Gallenkirch, Austria which is now widely available and touted as genuine. Norinder's photograph of ball lightning, presented by Singer (1971), is remarkably similar to a well known photographic still of the 1979 Kaikoura UFO reproduced on the cover of the book 'The Kaikoura UFOs' by Startup & Illingworth (1980). All three photographs show a luminous boundary consistent with the shape of vortex breakdown. The shape is approximately egg-shaped but cut off at the top. This part of geometry may be identified as the downstream section of vortex breakdown with reverse flow back into the bubble. The luminous boundary of the ball at the bottom tapers almost to a cusp shape and may be the zone where the approach funnel meets the lateral expansion of breakdown. The cut of oval shape described is consistent with the general rule found in vortex breakdown experiments that the diameter of the top re-entry of fluid into the vortex breakdown is wider than the funnel or core diameter (approximately three times as large).

There are a few photographs that more closely conform to the geometry expected of a burning vortex. In the book "The UFO Experience", by J. A. Hynek (Hynek, 1972) there is an exceptional photograph of a UFO with this type of geometry. The image comes originally from the film of television newsman Bob Campbell. The photograph was taken around 3 am August 2, 1965, at Sherman, Texas. The photograph shows what appears to be a slightly tilted funnel leading to a luminous globe-like zone which could be breakdown.

In another case, Australian park ranger Brett Porter took a photograph of what was later inferred to be ball lightning (Abrahamson *et* al., 2002). However, the object in question did not look at all like the classic spherical fireball. The fireball was said to be 100 meters in diameter with a lifetime of at least 5 minutes. The photograph appears to show a long twisting funnel extending up from a luminous globular region (vortex breakdown) contacting the ground. A 100 meter diameter vortex is not inconceivable since, as the author has already pointed out, natural vortices, such as waterspouts, have reported diameters of up to 75 meters.

## 5. Testing the Theory

The theory presented can predict in advance, possible formation sites for ball lightning and vortex burner UFOs, while also explaining why known sites would have fairly regular fireball UFO appearances. Such locations could be used to test the theory, by confirming the presence or otherwise of vortex fireballs. One candidate would be the Mexican volcano Popocatepetyl that became active in 1990, and subsequent years, with eruptions and gas emission, coinciding with UFO activity. Unusual lights have been seen numerous times in the area near Hessdalen, Norway. This site could be used to test the validity of the vortex fireball theory. Expeditions could be carried out to other areas known to have frequent UFO sightings, like Southwestern Texas that have been known to harbor the so-called ‘Marfa lights'.

At any chosen location, any visual evidence linking the UFO to a vortex fireball could be directly discovered with observational work, using aircraft to get in close to the object. Tracers, in the form of small balloons could be released below the fireball to verify the expected upward spiral trajectory from the invisible funnel. Other more robust tracers could be released to measure temperature, pressure and identify chemicals predicted to be present in the fireball. Fireballs could be photographed while additional support equipment could be employed to confirm the existence, or otherwise, of a combusting vortex in any particular case. This might include natural gas and hydrogen sulfide detectors and a method to sample their products. Instruments could be used to intrusively detect the presence of the vortex (e.g. pitot tube, anemometer, radar). Meteorological observers normally do not need any evidence other than simple observation of the funnel etc to confirm the presence of a tornado. The problem is that a large fraction of UFO observations take place at night. The funnel would not normally be seen, only the luminous glow from combustion processes within the vortex breakdown. During the day, the funnel might become visible through the presence of a tracer such as condensed droplets or dust.

## Conclusion

The paradigm that typically portrays ball lighting as a 20–30 cm electrical fireball produced by lightning under storm conditions has difficult problems. There are enough observations from individual eyewitness accounts and statistical surveys that refute this view. For instance ball lightning can be seen in fair-weather and the diameters of ball lightning can range from a few centimeters right up to meters in diameter closely matches that observed for natural vortices. Ball lightning reports of mechanical effects such as trench excavation and unusual motion can be succinctly explained with a vortex. Meteorological reports of close distance encounters of fiery whirlwinds show features that are consistent with localized combustion within the vortex breakdown region along the axis of the vortex. The vortex fireball theory also explains several reported features of ball lightning, including other anomalous lights that would fit the vortex-burner description presented here. If the vortex fireball theory is the correct interpretation of this fireball phenomenon then the 'ball lightning' nomenclature would be a misnomer. Ball lightning could well represent the missing science associated with atmospheric vortices.

## Notes

[1] The vortex fireball is to be distinguished from a firewhirl, which is a vortex created from a buoyant updraft of hot air generated from a fire.

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