Journal of
Scientific
Exploration

Anomalistics
and
Frontier
Science

RESEARCH ARTICLE

Vapor Phase Electrochemistry 2: Spherical and Spheroidal Air Plasmas

David J. Turner
condphys@frontiernet.net
ORCID: 0009-0003-9245-1844

Condensation Physics
Romney, WV, USA.

SUBMITTED April 4, 2023
ACCEPTED March 16, 2024
PUBLISHED September 30, 2024

https://doi.org/10.31275/20242943

PLATINUM OPEN ACCESS

HIGHLIGHTS

Rare atmospheric events like lightning balls, earth-lights, and UFOs (now also called UAPs) are probably all plasmas formed by chemical reactions in the air, with the potential to provide carbon-free electrical energy if artificially created.

ABSTRACT

Among the rare meteorological phenomena that exist are long-lived spheroidal air plasmas. Of these, lightning balls are best characterized. Closely related are earth-lights, tornadic lights and Unpredictable Flying Objects (UFOs). Early physicists took all such phenomena to be plasmas and would refer to them as electric fire or fireballs. Many physicists today do not accept that these light emitting objects are plasmas because they neglect a variety of influences that result from *chemical change*. Stability results mainly from entropy production as an ionized, metastable form of nitrous acid, produced at an air plasma surface, refrigerates the surface through its conversion to the stable acid. It is then oxidized to nitric acid in an aerosol form, which restricts the inflow of air to the plasma surface. This can explain the " surface tension" of lightning balls early, as hypothesized by Stakhanov (1979). Studies of earth-lights (Teodorani, 2004) imply that these are plasma balls held together by the same forces as those providing mechanical stability to lightning balls. Studies of flame balls in space support this view. UFOs and earth-lights are structured similarly but the plasma components of UFOs can be held together by far stronger forces. Potentially, air plasmas have important technological implications since they are all powered by extracting and using chemical energy from the air. Crucially, this energy can only be extracted from air whose temperature is below 15^0 C. If air plasmas could be prepared artificially, they would prove invaluable in supplying ample carbon-free electrical energy.

KEYWORDS

Ball lightning; earth-lights; UFOs; air plasmas; tornadoes.

INTRODUCTION

Ball Lightning and UFOs

A few physicists have been interested in the seemingly anomalous properties of ball lightning for over two centuries (Arago, 1855; Flammarion, 1888; Brand, 1971; Singer, 1971; Stakhanov, 1979; Smirnov, 1987), but we are still unable to produce the balls artificially (Stenhoff, 1999). This is despite the fact that two small free-floating plasma balls were produced by accident in the mid-18th century (Priestly, 1781; Cavallo, 1782). The phenomenon possesses so many different characteristics that whole books are needed to describe them. By the 1970s, the wide variety of apparently conflicting evidence was obvious (Singer, 1971; Stakhanov, 1979), and a few physicists concluded that there must be more than one phenomenon. This is now thought unlikely, and by 2002, it seemed clear that the real problem is the number of distinctly different disciplines that are needed to explain all the characteristics (Turner, 2002).

Reconciling all the apparently irreconcilable observations had seemed totally impossible until Stakhanov (1979) offered his tentative and largely qualitative model. It was the earliest model based on electrochemistry. It made use of what little relevant quantitative information was available on the hydration thermodynamics of the two gas phase ions he thought would be present in an air plasma. Before Stakhanov's contributions to understanding the problems there seemed to be very good reasons for doubting the very existence of ball lightning. This was despite much evidence to the contrary.

According to Singer (1971), many scientists, including Kelvin (1872), have concluded that the phenomenon has to be an optical illusion since so many of its claimed attributes clearly violated one or more of the well-established laws of physics. Faraday's conclusions were much less dismissive in that he accepted the empirical evidence but he felt secure in stating that ball lightning cannot possibly be an electrical phenomenon (Faraday, 1839). The simplest way (Turner, 2023) of describing why the conclusions of Faraday were wrong is that it *predated* the formalization of chemical thermodynamics. This was not completed until Gibbs (1878) showed clearly the importance of entropy in all chemical changes.

Stakhanov's (1979) model was based on the idea that, if a plasma containing *hydrated ions* can be held separate from the normal air by some kind of effective surface tension, the lack of buoyancy exhibited in ball lightning reports can be explained by the total weight of the hydrated ions in the plasma. His was the first model that seriously attempted to account for *all of the apparent anomalies* that have long been reported and have continued to confuse physicists. Dozens of these anomalies are known, and Stakhanov's model could account for most of them, including a number of characteristics that no previous model had attempted to explain. However, there were two major limitations. One was that the model could not explain the existence of the most powerful plasma balls that have been reliably reported. The other was that no *explanation* was provided for the *origin* of the "effective surface tension" which is a crucial ingredient of the model. In addition, Stakhanov's choice of one of the ions in the plasma turned out to be incorrect.

A later model, based closely on Stakhanov's, removed all of these limitations by extending the gas phase thermodynamic data *to far higher degrees of hydration* than Stakhanov had considered. An interpolation, between the gas phase hydration data and those for the liquid phase, removed this limitation. The new model (Turner, 1994) explained the apparent surface tension of the balls as a consequence of various chemical and electrochemical changes that seem to be unavoidable *under suitable conditions*. It changed Stakhanov's original picture by showing that the excess weight of a ball is not, as he had assumed, in a spherical volume of lightly hydrated ions; the weight is actually concentrated *at the surface* of a much hotter plasma than his model could explain. This weight of really heavy ion clusters *at the ball's surface* is mainly, though probably never entirely, balanced by the buoyancy of the hot central plasma.

Cooled aerosols need to be produced at the plasma surface, and they restrict the air inflow toward the plasma. In this way, such reported characteristics as bouncing and squeezing through holes smaller than the ball's diameter are explained. Even tendencies to be top-heavy (Stakhanov, 1979) and to be drawn towards hot objects can now be explained - *perfectly naturally though only qualitatively* (Turner, 1998a, 2001, 2002, 2003). One key to the improved model is a relationship for Stakhanov's "effective surface tension" which can be calculated from basic laws of physics together with what seem to be reasonable estimates for the parameters involved (Turner, 2002).

The most obvious relationship comes from an approximate balancing of weight with buoyancy (Turner, 1994). The number of aerosols or droplets surrounding the hot air plasma can be taken as n_a, and their mean radii are all assigned a value of r_a. The radius of the plasma can be taken as r_p, the density of the surrounding aerosols (or droplets) being that of normal water, n_w, while the mean density of the hot plasma can be taken as n_p and that of the ambient air as ña. Then, at equilibrium:

$$n_a \, r_a^3 \, \rho_w = r_p^{\,3} (n_a - n_p)$$

The model also attempted to assess how the chemically induced air inflow and viscosity will influence a ball's stability, but, in this case, the arguments were far less straightforward. This was partly because of an inadequate understanding of the causes for occasional deviations of the balls' shapes from spherical symmetry (Stakhanov, 1979). Nevertheless, it was very clear that reasonable flow rates had no difficulty whatsoever in accounting for the range of "effective surface tensions" that Stakhanov had found were needed.

Later, it was realized that *the most important fact* im-

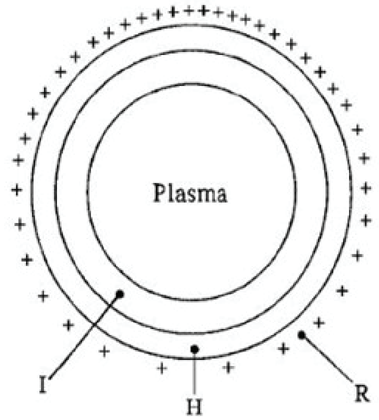

Figure. 1 Schematic Diagram of a Lightning Ball in the Electric Field of a Thunderstorm (not to scale). R is the refrigeration zone, H is the hydration zone and I is the intermediate zone. The ball is held together by an inflow of air but nitrogen oxidation is only possible as long as the refrigeration zone R is present. There are more positive charges on top of the ball than below it due to charge neutralization resulting from conductance in the electric field of the storm.

plied by the above equation (also by another equation - for the pressure difference produced by the droplets) is that it is *always the product* of the droplet sizes and their concentrations that controls one of the forces acting on a plasma ball. The important point is that a local reduction in *either* r_a or n_a will increase the local inflow of air. This means that any such reduction, whether induced by a local flow of current (Turner, 1994), by a local heat source (Turner, 1996a, 2001), or, as we shall see, by the presence of another nearby plasma ball, can produce an unanticipated force of attraction.

Figure 1 is a schematic diagram of a lightning ball according to this model (Turner, 1994). It represents a plasma ball floating in the normal electric field of a thunderstorm. The plasma at the center, once established, acts like a catalyst for the oxidation of nitrogen, first to nitrous acid and then to nitric acid. These reactions extract energy from the air and explain the surprisingly long lives of some plasma balls. We shall see that such balls can combine to form larger and longer-lived assemblages of plasma balls such as earth-lights and unpredictable flying objects (UFOs). The acronym UFO has long been used to stand for Unidentified Flying Objects, but Unpredictable Flying Objects now seems to be a more appropriate name. This acronym has the advantage, over all the more recently used ones, that it has been in constant use for three-quarters of a century (Turner, 2023). The following descriptions of the zones in a lightning ball (some widths greatly exaggerated in the figure) assume that all current interpretations of the relevant observations (Turner, 2002) are correct. No width can currently be quantified because the relevant chemistry cannot be quantified (Turner, 2023).

Figure 2 represents, qualitatively, a radial profile

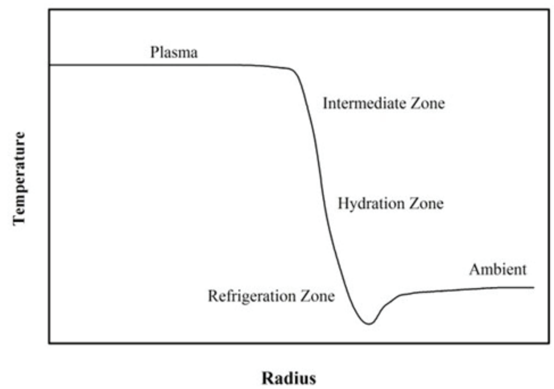

Figure 2. Temperature Profile Near the Surface of a Lightning Ball. No value can be quantified.

of the temperature near the surface of a lightning ball. Plasma temperatures and diameters of lightning balls are known to vary over many orders of magnitude (e.g., Stenhoff, 1999). The rates of the various chemical reactions occurring outside the plasma will also vary greatly. We possess no valid way of describing these rates of reaction because they involve ions in humid air (Turner, 2023). Because we are equally ignorant of the rates of aerosol growth as a function of distance from the plasma, the size distributions of the particles surrounding it are also unknown. All we know about the particles is that they can be either small enough to appear transparent or so large that they prevent any light from passing through them (e.g., Singer, 1971). In principle, their sizes can vary by factors of millions (Turner, 2023). Since ambient air is being drawn into the plasma, there will be gradients in humidity which it is also impossible to quantify.

In the vital refrigeration zone R (now believed to be very thin), endothermic (heat extracting) reactions occur, and aerosols containing nitrous and nitric acid are produced just outside it. In zone I, the intermediate zone, the identities of the very hot plasma ions change, as they cool, in favor of more stable (lower energy content) ions. In zone H, which is probably the widest zone, the most

Table 1. Approximate Temperatures and Key Chemistry near a Plasma Surface

Zone	Plasma	I	H	R	Exterior Air
Temperature	> ~ 450	< ~ 450	450 to ~ 15	< ~ 15	normal range (degrees C)
Significant Chemistry	hot ions	NO^+ and NO^- are formed	hydrated NO^+ changes to $H_3O^+.nH_2O$	molecular NO_2 is formed	HNO_2 is oxidized to aerosols that contain HNO_3

stable ions arriving from I (which are NO^+ and NO_2^-) become increasingly hydrated as they cool further. In this process, the anion remains unchanged (apart from its hydration), but the cation changes to hydrated forms of H_3O^+. An electrical double layer exists between the plasma and the intermediate zone, with an excess of electrons lying toward the edge of the plasma.

Table 1 provides a simplified summary of the various processes that are, according to the basic electrochemical model (Turner, 1998a), occurring near the plasma boundary of a lightning ball. All the processes must be occurring at suitable rates for any plasma, or group of plasmas, to have a long life. The need for them all to proceed at near-optimum rates probably explains why air plasmas are all rare phenomena.

Quantitative Restrictions Concerning the Electrochemical Model of Air Plasmas.

Since the *rates* at which ions react in moist air cannot currently be calculated - assuming that valid conclusions are required - ion *concentrations* cannot be calculated either. This problem results from a sub-discipline of thermodynamics that has never been developed (Turner, 2023). Unfortunately, this is not the only problem that restricts us to qualitative arguments.

The role of aqueous aerosols is clearly vital to the model, but they are very poorly characterized. Mole fractions of any impurities in them can vary widely (by factors of many millions), and they have hardly been explored experimentally at all (Turner, 2023). To make matters worse, where experimental studies on aerosols have been made, there is frequently little agreement on the interpretations of the results. A summary of the problems has recently been provided by Lee et al. (2019). Clearly, any serious attempt to quantify the model is likely to prove misleading. Fortunately, it is possible to glean a little more information on air plasma processes by considering the characteristics of *grouped plasma balls*.

As we shall see later, grouped air plasmas are usually far longer-lived than are lightning balls and single lightning balls have *never* been observed to approach one another close enough to stay in contact. This is because of the positive charges on the outside of each ball. For this reason, the large groups of plasmas observed in earth-lights and UFOs probably need to be produced at the same time. The reason for the longer lives of clustered plasmas is probably that the electrochemical environment established by any single ball, in a group of them, helps stabilize the necessary processes that occur at the surface of all the others. As with normal gas flames, the *ignition* requirements of an air plasma are probably quite different from the requirements for a *long life*. It seems there are close similarities between the two forms of plasma. One obvious difference is that, because of refrigeration at their surfaces, only air plasmas can form into groups of plasma balls.

As is well known, the Earth maintains its negative charge during thunderstorms (e.g., Mason, 1971). Downward-moving negatively charged species, carrying roughly half of this current in the air, move far faster through the plasma than through the air. This is because electrons are carrying the negative current once they are inside the plasma, These electrons then proceed preferentially to neutralize some of the positive charges at the bottom of the ball. This reduces the *number* of charged aerosols below the ball and thus increases the flow of air *into the bottom of it.* An inertial force (a jet engine in reverse) adds to the effective weight of the ball and also explains the phenomenon once called "electrostatic guidance" (Turner, 1994).

Since 1993, a few physicists have acknowledged the merits of this model (see e.g., Anonymous, 1994; Chown, 1993; Corliss, 2001; Matthews, 1994). However, many more seem only to see non-existent weaknesses in it rather than the *real limitations* which result from the absence of any *valid* quantitative theory for ion-ion interactions in compressible fluids (Turner, 1983) and in moist gases (Turner, 1994, 2023). This absence first became clear in failed attempts to quantify the thermodynamic properties of electrolyte solutions in near-critical water and steam (Turner, 1983, 1989, 1990). A problem which would certainly arise in any future attempt to test improved models is sedimentation in the gravitational field of the Earth (also at sharp pipe bends in flowing steam). Some electrolytes, including NaCl, are sufficiently soluble near the critical point of water to permit experimentation (Turner, 1988), but in moist air, the *equilibrium* levels of electrolytes are all so low that comparable experiments would be impossible.

Lightning balls were once fairly commonly witnessed indoors, but such sightings are far less frequent inside modern homes. This is probably because lightning balls are attracted to heat sources (Turner, 1996a, 2001), including those produced by coal or wood fires. The attraction results from smaller, slightly hotter aerosols on one side of the ball. There has long existed an almost unbelievable illustration, from 1886 originally, of a large lightning ball entering a room over what appears to be a burning fire and terrifying the people in the room (Hartwig, 1892). The occurrence is by no means unique (Brand, 1923). Few of the serious books on ball lightning use this image - although recent entries in Wikipedia have shown it. Previous decisions *not* to re-publish it were probably made because the event seemed impossible. Hence most reputable scientists have not wanted to risk using what could be unreliable evidence. However, once the electrochemical model for air plasmas is accepted, the event can be seen as perfectly natural (Turner, 1996a).

Few houses in the developed world are any longer heated using open fires - so the balls now have fewer ways that favor entry into a room. In and near the top of a chimney, above a burning fire, a lightning ball sufficiently close to it will be unavoidably drawn towards the heat from the fire below it because of the fact that the equilibrium *diameters* of aerosol particles will be smaller on the side of a ball that is warmer than on the other side (Turner 1996a, 1998a. 2001). Presumably, similarly produced forces can attract lightning balls in through open windows. Passage, through closed windows, is an entirely different matter, as it seems that several different types of driving forces must be involved in these cases (Turner, 1998b).

Most crucially, the first form of the basic ball lightning model (Turner, 1994) provides a very powerful cooling mechanism at air plasma surfaces (see later). As a consequence of this cooling, very hot plasmas can be contained. Due to the absence of valid ion interaction theories, however, the model is little better than qualitative - although there are a few quantitative elements. A more recent description of the missing science (Turner, 2023) clarifies *why* it is still quite *impossible to quantify* any relevant ion interaction model that could be valid for the surface of an air plasma. It also explains why the situation is unlikely to change soon - unless attitudes to the support of some kinds of very long-term research change completely.

It seems that once well established, a ball's lifetime need only end when the electric double layer at the plasma surface is somehow destroyed. This can occur for a variety of reasons, including contact being made with a well-earthed object, an unobserved change in the electrical state of the air, or encountering a parcel of air whose impurities disrupt the oxidation processes at the ball's surface. In the model being described, a central plasma is obviously *assumed*. However, the fact that an air plasma's presence can explain so many observations supports the basic assumption. Many physicists, who simply cannot believe in any plasma model, seem unable to accept that *only electrochemical models* can explain *every one* of the well-known peculiarities of lightning balls.

Further Clues Concerning the Electrochemical Model of Air Plasmas.

Fortunately, Powell and Finkelstein (1969) were prepared to accept (as have many other physicists) that ball lightning must be a plasma. As a result, they obtained emission spectra from brief globules of plasma that were produced by powerful radio frequency discharges on mixtures of nitrogen and oxygen. Their conclusions were essential components in the first version (Turner, 1994) of the basic electrochemical model for ball lightning.

Dozens of distinct ball lightning characteristics have been described over the centuries and many of them, taken together, certainly do imply that the phenomenon is inconsistent with one or more of the known laws of physics. Descriptions go back many centuries, the earliest one recently found in English records apparently dating from 1195 (Gasper & Tanner, 2022). Most of the apparent anomalies are by now very well defined, but no property, except perhaps size *range* (Turner, 2002), can be explained even semi-quantitatively (Turner, 1998a, 2023).

Partly because of these problems, a number of writers on the subject have been unwilling to accept that any kind of self-contained air plasma can exist. There are usually two justifications claimed for this belief. The first is the objection that Faraday (1839) raised. He simply could not accept that ball lightning could possibly be an electrical phenomenon. This was because all of the evidence available to him implied the inevitability of rapid charge neutralization - but this is *not the case* if the two ions concerned are heavily hydrated (Turner, 1989, 1994, 2023). The second claim is that any *self-supporting* plasma violates the so-called virial theorem (Singer, 1971; Collins, 1978). This theorem completely ignores chemical driving forces so that the argument is totally irrelevant if chemical and electrochemical forces contribute to the stability of the plasma. The mere existence of gas flames, where chemical processes provide containment, now makes this criticism seem absurd.

Probably, however, the main factor that limits our understanding of ball lightning is that it has proved impossible to simulate most of its characteristics under controlled conditions. Over the centuries, there have been numerous preparations of short-lived, roughly spheroidal air plasmas that have been claimed to be simulations of ball lightning, but a lifetime of two seconds is about the longest ever claimed over the last two centuries (Barry, 1980). In fact, there seem to have been only two truly realistic simulations ever, and they were both accidental preparations in the mid-18th century.

After providing detailed descriptions of the two experiments, Priestley (1781) commented on one of them as follows: "Could we repeat this experiment, there would not, I think, be any natural phenomenon, in which the electric fluid is concerned, that we could not imitate at pleasure. This circumstance alone makes it a very interesting object of investigation". See Priestley (1781), Cavallo (1782), or Turner (2002) for the only detailed description of the experiments we possess. Sadly, Priestley's over-optimistic hope is still unfulfilled.

These early experiments had been performed by a physics teacher, John Arden, and a landowner and Fellow of the Royal Society, William Constable. In two *successive* experiments, with very large and very similar Leyden jars, a 2 cm diameter ball of light was formed (somewhere inside each jar) during the electrical charging of the jar. Each ball survived for several seconds, the first having escaped from the top of the jar in which it had formed and then returned to the inside of the jar for a few more seconds, hugging the chain carrying the charging current as it moved. This ball survived long enough for the very strange behavior to cause an exchange of comments between the two men conducting the experiments.

Both balls ended their lives by cracking circular holes through the glass wall of the jars in similar ways to those by which lightning balls occasionally crack holes in glass windows (Grigor'ev, et al., 1992; Turner, 1997a,b). The conversation during the first experiment had been recalled and it was subsequently recorded in a letter to Priestley. Its duration was used, very much later, to estimate that this ball had lasted outside the jar for at least four seconds. The total lifetime would probably have been at least 10 seconds (Turner, 2002). This is far longer than the duration of any other claimed ball lightning simulation, of which I am aware, *and* it simulated *far more characteristics* than any other. The balls both ended their lives by cracking circular holes in the glass walls of the Leyden jars in which they were produced and, in both cases, the holes apparently had diameters indistinguishable from those of the balls themselves. During most modern cases of this kind of window damage, the actual formation of the holes (due to thermal cracking) was not witnessed, but *whenever the hole cracking was actually observed*, the ball and the hole seemed to have had identical diameters (Grigor'ev et al., 1992).

In the case described by Priestley, a need for precise matching of electrical and chemical forces seems the only rational explanation for the fact that two extremely rare events *immediately followed one another but were never repeated*. The implication of this finding is that (very rarely) a lightning ball can start its life in a similar way to that by which a fire starts its life - i.e., with the help of a spark. However, there is little doubt that lightning balls *can also* begin their lives without the involvement of a visible spark (see e.g., Corliss, 1977, 2001; Singer, 1971). Population inversions (Handel & Leitner, 1994) seem crucial in such cases - and possibly always.

One might have expected that the formal similarity between the plasmas of lightning balls and of gas flames would quickly have led to an agreed picture of how the two phenomena are related. In the event, a very slow and circuitous path was taken. The main reason was certainly that the two accidental Leyden jar preparations were soon forgotten - and for a very good reason: the experiments were *never* replicated. Many of the most famous "electricians" of the day, including Franklin and Priestley, had apparently tried repeatedly to duplicate the findings, but al the attempts failed (Cavallo, 1782; Priestley, 1781).

In 1992, I was able to visit the stately home of William Constable, where his collection of scientific curiosities and equipment was being readied for eventual display to the public. All the hardware (except the broken Leyden jars, of course) that he and Arden must have used appear to have survived. As a consequence of help from Alan Clark, at the time Deputy Librarian of the Royal Society, I had been invited to inspect the collection before it went on public display. One important fact became clear from *simply seeing the actual hardware* that had been used: replacement of a broken Leyden jar would have been a very simple matter (with sufficient care) without causing any disturbance to most of the *very thick* brass chain used to connect the "electric machine" to the inner coatings of the Leyden jars.

The heavy chain could easily have produced a spark between its links, but it was unlikely to have provided exactly the same distribution of poorly conducting contacts between its links if it had been moved, even slightly, between the charging operations that produced the two plasma balls. Following the second experiment, the chain was presumably disturbed and the energy in the spark, that resulted from the charging current through the chain, could no longer exactly match the other required conditions. These could have been space charge distributions, air contamination, the absolute electrical potential and/or gas phase inversions of excited state molecules that might have allowed a ball to form. Such inversions are key elements in the ball lightning model of Handel and Leitner (1994), and they might well be crucial ingredients at the birth of most, if not all, lightning balls.

The similarity in size of the two plasma balls witnessed by Arden and Constable seems very significant. It is now known that reported lightning ball sizes can vary over three orders of magnitude (Stenhoff, 1999). Also, it appears to be generally recognized that even if one could predict that a ball would form somewhere in front of an observer, its diameter would be almost totally unpredictable. On rare occasions, multiple balls have been seen escaping from a dark cloud in the sky (Singer, 1971; Turner, 1996b), and they usually seem to be of fairly similar sizes - though just how similar would usually have been difficult to determine.

Air Plasmas and Meteorological Conditions

In this context, a truly extraordinary account of multiple ball production from the clouds (Turner, 1996b) was provided to me as a consequence of one of the witnesses (Keith H. Hill) having read a brief historical account of the development of the electrochemical model that had appeared in the New Scientist (Chown, 1993). Like many of the more informative accounts by witnesses of ball lightning, this one had been remembered vividly over many decades, in fact, from late July 1956. The display had been observed by crew members of a fishing vessel who were encountering a very severe storm in the Great Australian Bight (to the south of the continent).

The cloud height seemed very low (about 300 m), and, as Mr Hill described the event, the clouds consisted of "... a solid dark grey rippled even mass from horizon to horizon. The storm began shortly after sunset with large balls of lightning coming from the cloud base, dropping to the sea in 2 to 3 seconds of activity. These rather large balls seemed to be about one metre diameter occurring every 3 to 10 seconds, to within 100 metres (but fortunately not on our vessel !) to some miles away. The display allowed us to dispense with our compass sighting as so many times the sky was alight." Following later correspondence, Mr. Hill investigated some meteorological records for the relevant day, and it seemed clear that the large air mass involved would have passed over a huge area in the southern Australian desert and then through some very humid environments near to the coast. The exact track could not be determined.

In 2006, an extremely detailed account was provided of the nuclear weapons tests that were performed by British and Australian personnel during the 1950s and 1960s (Carter et al., 2006). The motivation for this work was an assessment of the health risks to the individuals involved, but my interest was purely in the dates of the tests. The important point, from the locations of the sites, is that two of them had been almost certainly under the path of the air mass that was responsible for the unique cloud formations and for the other observations made from that fishing boat in 1956. In the 1990s, Mr Hill had gone as far as he could in finding roughly the regions over which the cloud mass responsible must have passed. At that time, it had not occurred to either of us that the locations of old nuclear test sites might be relevant.

In view of the unique nature of what Mr. Hill and his colleagues had observed, I now believe that my original conclusions about the event (Turner, 1996b) are probably largely irrelevant. They would have been quite different if I had known what was revealed in the study of Carter et al. (2006). In 1996, I tried to explain the unusual form of the clouds and the apparently very similar sizes of the lightning balls as consequences of the pickup (in the desert) of dust particles and the subsequent gradual sorting by size as the cloud moved to the south and then over the very humid coastline to the sea. This sorting may well have occurred but it seems much more relevant that what could have made the event unique was that large quantities of *radioactive materials* had been picked up and transported from one of the sites of the nuclear tests.

In fact, the date of Mr Hill's observations places significant restrictions on which of the sites might have been the source of the ionizing radiation that must surely have produced the exceptionally large number of similarly sized lightning balls. The restrictions apply because one of the test-sites (Emu Field) had been used for a few tests before the main site (at Maralinga) had been prepared. All the tests at Maralinga were dated *after* July 1956. Thus, any radioactive material could only have come from the nearby Emu Field site - or far less likely from very much more remote sites.

Clearly, much speculation is involved in the arguments just provided, but at least they can explain why there seem *never* to have been any records remotely similar to those provided ed by Mr Hill. Assuming the validity of most of the arguments used here, it seems clear that it should be *possible*, in principle at least, to provide formation conditions that are far more reproducible than has been believed to be possible in the past.

Unfortunately, we do not know what all these conditions would have been.

More Recent Evidence

In 2002, the Royal Society published a special "Theme" issue of Phil. Trans. Roy. Soc, on the subject of ball lightning. I, among others, had been asked to contribute to it. As editor, they chose John Abrahamson, who had recently published a brief paper on ball lightning in Nature (Abrahamson & Dinniss, 2000) but who had rather little earlier experience on the subject. In my initial contacts with him, he expressed great enthusiasm for a then recent book on ball lightning (Stenhoff, 1999). This book presents a well-balanced assessment of the very challenging interpretational problems and of the widely divergent views on the nature of ball lightning.

However, it seems Abrahamson subsequently decided to seek advice from two other physicists. Both men were widely acknowledged experts in the field, but, unfortunately, *both* were among the large group of physicists who simply could not accept that ball lightning is a plasma. They were Stanley Singer and Vladimir Bychkov. The coverage of the "Theme" issue clearly reflects their views. Presumably, this was the reason that my contribution (an invited one) was the *only one in the collection* that advocated a plasma model. The decision to ignore all basically electrical models must have been taken despite the fact that several such models offer good, if partial, explanations for some of the well established properties of ball lightning (see Stenhoff, 1999).

Singer, whose 1971 book first convinced me that ball lightning really exists, provided an introduction to the new collection. Unfortunately, it included a comment that was completely inaccurate. It reads as follows: "Ball lightning has been observed by staff in the Cavendish Laboratory, although its head at the time, Professor B. Pippard (1982), was skeptical of the reality of its existence". In fact, in that 1982 paper, he gave a completely objective description of the event and would not have fought so hard as he subsequently did to ensure the publication of my first paper on ball lightning (Turner, 1994) had he not accepted the reality of the phenomenon. Neither would he have provided me with copies of *all* the correspondence that had resulted from his 1982 description of the Cavendish event in Nature and from a subsequent radio interview on the BBC.

Some of the correspondence he provided may explain Singer's mistaken claim in his Introduction to the special "Theme" issue of *Philosophical Transactions of the Royal Society* (Singer, 2002). Presumably, the views of Singer and Bychkov are the reason the editor *added the words* "with comment" to the original title of my paper. These comments were trivial, but the effect seemed to have been to warn readers that the content of the paper should not be taken seriously. My formal work on the subject had ceased a decade earlier when the laboratory at which I had once worked was closed, and I was "offered" early retirement. By 2002, I was working without formal support. I was thus in no position to object to the addition even had I been warned of it - but this was not the case. Similarly strong views to those of Singer and Bychkov may also account for the fact that some recent entries on ball lightning in Wikipedia did not even mention that plasma models exist.

A newer entry there does refer to a few plasma models, but it still makes no mention of electrochemical models - despite listing 101 references to other work and despite the fact that no other models can explain *all* the well-reported characteristics of the phenomenon. It seems that many people prefer to believe in mysteries rather than accept that reasonable (though largely thermodynamic and qualitative) explanations for them exist.

Fortunately, a new *experimental* study provides strong support for important aspects of the improved electrochemical model (Turner, 1998a). This is because nitric and nitrous acid are *both* produced (at very low levels) in water vapour-saturated air when this is irradiated with high-energy UV (Bartlett and Turner, 2024).

The whole subject of UFOs is controversial - but only, it seems, to those who are unfamiliar with recent progress in understanding ball lightning. In an early book on UFOs, Klass (1968) assembled a wide variety of evidence demonstrating a close connection between UFOs and ball lightning. He assumed that both phenomena are plasmas. It now seems clear that Klass's kind of logical, but largely qualitative, arguments can *only* be seen as realistic once it is acknowledged that vapor phase electrochemistry has *never* been brought to a usable state of development (see Turner, 1983, 2001, 2003, 2023). Most physicists who have studied many UFO accounts find that some characteristics of these objects are so anomalous that the possibility of alien visitations must be taken seriously (Vallee, 1965; Hynek, 1972; Sturrock, 1999).

Although such beliefs are understandable, I believe they are mistaken. In my opinion, the most valid criticism of Klass's conclusions is that, since ball lightning is itself poorly understood (so poorly that it has not been reproduced artificially for over 260 years), any claimed similarity between it and UFOs represents no real advance. It seems that attitudes like this have contributed significantly to the inhibition of research on all of the naturally contained air plasma systems that exist. Specialization has not helped either (Smirnov, 2000; Turner, 2001, 2002, 2023). The tracking of aircraft by UFOs, which makes the credibility problem even worse for most people, will be considered elsewhere (Turner, 2024).

Flames and Flame Balls

Eighteenth-century scientists, including Benjamin Franklin and Joseph Priestley, had developed only a very crude understanding of electricity, but they easily identified meteors and lightning balls as electrical phenomena. They usually called them fireballs or globes of fire (Bertholon, 1787), but they sometimes referred to them as "electric fire". It seems that most early investigators made little distinction (apart from duration) between the various forms of plasma that had been observed: fire, lightning balls, what we now call meteors, and fireballs (very long-lived meteors).

Flames are very easy to study compared with lightning balls, but despite centuries of study, there are still many unanswered questions (e.g., Gaydon & Wolfhard, 1970; Wu, et al., 1998; Wu, et al., 1999). The most instructive early experiments with flames were those that employed pre-mixed flames, for example, from Bunsen burners. However, experiments with pre-mixed gases can also be undertaken in a quite different way - if gravity-free experiments are used. Some experiments of this type were designed and conducted specifically to address several outstanding questions (Wu et al., 1999). During one unique set of experiments in an orbiting space Shuttle, two complete surprises were encountered. These surprises are highlighted in the NASA news story, (*A Flame Ball Named Kelly*,' available at https://naturalplasmas.com.) and they will be discussed once some historical aspects of flame study have been briefly described.

During early experiments conducted by "electricians", as these scientists tended to be called at the time, it was discovered that the surfaces of flames are always electrically charged. This is not surprising to us, since we now know that a flame is a plasma and that electrons move much faster than ions. Hence, an electrical double layer is produced at any plasma surface, and such a layer is a *qualitative* prediction at the visible surface of any flame.

Sanduloviciu has long stressed the importance of self organization at a plasma surface in connection with the surfaces of lightning balls (Sanduloviciu, 1991, 1992) and she has subsequently succeeded in producing brief, but remarkably spherical, plasmas in the air (Sanduloviciu & Lozneanu, 2000). However, these balls required an extremely complex combination of fields that seems most unlikely to be provided in Nature.

Since flames require fuel and since the air provides the oxygen to burn it, it seems obvious that chemically induced air inflows (plus electrostatic forces at the plasma surface), when balanced by the thermal energy output from the plasma, can contribute stability to a flame. Laboratory studies on flames quickly led to the discovery that much greater reproducibility of experiments can be achieved by *premixing* the fuel with the oxidant. These flames then revealed how very complicated other aspects of their physics and chemistry really are (Gaydon & Wolfhard, 1970).

There is one very rare kind of feeble flame that has been reported from time to time for well over a century, but it is so rare (and poorly understood) that it almost defies belief, and hardly anyone (including practically all forensic scientists and lawyers) ever takes its possible occurrence seriously. The flames are those involved in the phenomenon of spontaneous human combustion (Randles & Hough, 1992). The only rational explanation for what is (regularly but very rarely) reported seems to be that the flames arising from the bodies observed are a kind of hybrid between a normal flame and a lightning ball (Bauer, 2003; Turner, 2003).

In other words, their stabilities partly result from similar forces to those present in ball lightning. In human combustion cases, some of the required energy could be provided by the oxidation of very small quantities of organic molecules - most plausibly ethanol. The phenomenon is usually associated with excessive alcohol consumption. As with ball lightning, though with much more evidence to go on, we still understand few of the details involved in actually *igniting* the burning process for any flame.

In the 1960s, Barry (1968) prepared some unusual balls of glowing plasma in an attempted simulation of ball lightning. The idea prompting the experiments was that ball lightning is a flame and that an electric spark, resulting from a thunderstorm field, might ignite a localized source of hydrocarbon fuel. Barry assumed that the fuel concentration required might be well below that usually needed for combustion, so these conditions were provided. Some of his experiments employed a large container filled with extremely lean mixtures of propane in air.

When an electric spark was applied between copper electrodes, bright balls were sometimes formed and, when they were, they lasted for up to 2 seconds. The balls were a few cm in diameter, yellow-green in color, and they moved randomly and rapidly about the chamber. The unusual greenish color of the balls was assumed to result from the use of copper to make the spark gap. It is just possible (because three oxidation states for copper are accessible) that copper species in the air can sometimes catalyze specific reaction steps needed in producing a stable gas-plasma interface.

In 2003, NASA published some very unexpected findings with flame balls, which had been obtained on the tragic last flight of the Space Shuttle Columbia. They represented the final experiments in a program of research on low fuel-content flames under so-called "micro-gravity" conditions (Wu et al., 1999). Actually, the gravitational field experienced on a manned spacecraft is usually more like 10^{-4} of normal gravity than 10^{-6} of it, but the name is used nonetheless. The objectives of the experiments were tests of chemical engineering models in an area where there were known to be inadequately answered questions. The most obviously strange observations from these experiments concerned occasional pairs of flame-balls that *spiraled each other* at a fixed separation once the pair had formed.

The experimental approach was, in principle, the same as Barry's since it also used pre-mixed gas components, low fuel content, and spark gap ignition. Preparatory experiments, in this case, had involved brief tests under low gravity conditions in drop towers plus a set of tests on an earlier Shuttle flight. The latter indicated that the balls had lasted considerably longer than predicted. The final results of the program were obtained during the fatal last flight of the Shuttle in 2003. A summary of the findings and a discussion of them can be found in the web-published NASA news story.

The new results confirmed that some of the balls had survived for far longer than had been predicted by the theoretical models. These were based on known rates of chemical reaction, the heat produced by these reactions, the quantities of fuel present, and what was expected of the normal means of heat transport. However, the balls also showed completely unexpected behaviours. Multiple balls were sometimes created and on two occasions a single ball underwent a corkscrew-like spiral motion. This probably occurred when the igniter released a small particle of charged metal of appropriate sign. This then produced the attraction causing the spiral motion. If this explanation of the spiral motions is correct, it reveals serious omissions from the standard models that attempt to explain flame behavior."

When a hydrogen containing fuel is burned, the water released is strongly attracted into the electric fields of any ions present in the double layer at the plasma surface. Any combustion products that have thermodynamic properties similar to metastable nitrous acid (see earlier) can cause refrigeration to take place at this surface. If sufficient electrochemical cooling at the surface is taking place, a local structure rather similar to that of a lightning ball will result, the inflow of gas being restricted by the presence of aerosols - just as in the case of ball lightning. Under the lean fuel conditions being studied, heat losses will be unusually small.

On Earth, heat losses due to convection are significant. In zero gravity, there will be essentially no heat loss due to convection and very little due to conduction. These effects had been allowed for in the models used, so there was no obvious cause for an extended life of some flame balls. In ball lightning, heat escape by conduction is prevented by the inflow of air through a spherical array of aerosols and this inhibits conduction - and convection is prevented because of the *evenly* distributed *inflow* of reactants.

In fact, the author's earliest description of ball lightning referred to this "thermal lagging" as a significant part of a ball's role as a "thermochemical heat pump" powered by the electric field of a thunderstorm (Turner, 1994). In 1994, I had yet to realize that the production of nitric acid can feed additional chemical energy to the ball *so long as* efficient refrigeration at the plasma surface is maintained and no adverse chemical changes occur. The role of nitric acid formation in providing energy was only appreciated later (Turner, 1998a).

If, in the studies of flame balls in space, heat loss by conduction had been overestimated or reaction rate estimates had mistakenly assumed the identity of activities and concentrations, the efficiency of the combustion process could have been underestimated and led to an underestimation of the lifetimes of the flame balls. Some of the *organic ions* unavoidably released during burning may well have been able to refrigerate the plasma surface by processes analogous to those in ball lightning. The unavailability of any relevant thermodynamic data means that this is impossible to prove or disprove. However, since the actual concentration of ions around a flame ball will be minuscule in comparison with any uncharged species present, the concentrations of trace impurities inside a flame ball will greatly exceed those of the ions (as is the case with lightning balls).

If nitrogen was one of the impurities, as was probably unavoidable in even the purest gases obtainable, then metastable nitrous acid would have been escaping from the flame balls, and it, alone, could have refrigerated the plasma surface and made the electrochemistry at its surface closely resemble that of a lightning ball. Most important will have been the unanticipated force attracting air to the plasma surface just as it does with ball lightning (Turner, 1994, 1998a, 2002). If another flame is sufficiently close, the unexpected inward force will resemble that of a jet engine but in reverse (because the gas flow is reversed). Thus, qualitative arguments, similar to those used for ball lightning, seem relevant. In the case of a pair of flame balls under micro-gravity conditions, this unquantifiable force of attraction is certain to be present whenever two balls happen to be produced sufficiently close to one another.

This is because the total concentration of water released in the burning process will be fairly small in view of the lean-burn conditions employed. Hence, the ions present *between* the two balls will compete very effectively with each other for the few free (combustion-produced) water molecules present locally. The attracting force between the balls will result from the increased inflow of air where the charged aerosols are reduced in size, producing inter-ball attraction.

The cause of the inter-ball attraction (reduced sizes of the hydrated ions between the balls) is, of course, very similar to that providing what used to be called the electrostatic guidance of lightning balls (Turner, 1998a, 2002), but it is more similar to their attraction to hot objects (Turner, 2001). It should be recalled that an attracting force on a plasma ball can arise through a reduction in either the size or concentration of the aerosols involved (Turner, 1994). With flame balls, only *size* reductions are likely since no current (apart from the sparking current) was presumably present during the experiments.

The extraordinary corkscrew motions observed in the Shuttle experiments must have resulted from this force of attraction balanced by electrostatic repulsion between the positively charged surfaces of the balls - plus slight gas motion resulting from the creation of any flame balls formed earlier. The unexpectedly long lifetimes of the gravity-free balls can be taken as additional evidence supporting the electrochemical processes that occur in ball lightning. As we shall see later, similar mechanical forces seem to explain the attraction between plasma balls in the much larger structures that are occasionally observed as UFOs.

In the electrochemical model for ball lightning, as with a flame, the central plasma's shape and stability depend on a balance between thermal, electrostatic, gravitational, and chemical forces. These produce electrostatic repulsion between cations at the outer plasma surface, and resistance to the inflow of air by the heavily hydrated ions inevitably formed near the plasma surface. Of course, lightning balls and flame balls display obvious differences, such as the nature of the fuel. In a flame, the fuel can be any substance known to be combustible over a wide range of elevated temperatures, while nitrogen is not normally thought of as a fuel at all. It can only be considered to be a fuel when nitrogen is oxidized *in moist air* by a plasma whose air surface is *below* 15^0 *C* (Turner, 1998a). The difference arises simply because normal burning is sustained by the *energy* released during oxidation while, as we shall see in the next Section, the *essential intermediate* process in nitrogen "burning" is *entropy* driven.

Thermochemical Refrigeration and Energy Supply in Air Plasmas

The electrochemical model for ball lighting (Turner, 1994) is based on the only reliable *quantitative* data that are relevant and available. They are standard state thermodynamic data for the species most likely to be involved in air chemistry (Chase et al., 1985; Wagman et al., 1982) plus data obtained later (Keesee & Castleman, 1986) on the *hydration thermodynamics* of gas phase ions. Unfortunately, the forces between such hydrated ions cannot be calculated validly using any available theory for ion-ion interactions (Turner, 1990, 2023). This fact means that *nothing of value* can be quantified concerning the thermodynamic activities of real ions (at any finite concentration) *or to their rates of reaction*. *Only standard state thermodynamic values are of any practical use at all*. The reasons for this have been re-stated in detail recently (Turner, 2023).

Clearly, this restriction to standard state properties greatly reduces how much quantitative information can be deduced from tabulated data, but by 1994, it had been discovered that the use of *standard state data* (alone) can be surprisingly informative when applied to the problem of ball lightning stability (Turner, 1994). The crucial group of reactions is approximated by the following set of charge neutralization processes:

$$H3O^{+}.nH_2O + NO_2^{-}.nH_2O \rightarrow HNO_2 + (2n+1)\,H_2O \qquad (1)$$

Hydrates of the two stablest known ions likely to be present near the surface of an air plasma are represented as the reactants in Reaction 1. In reality, it is most unlikely that n is the same for both ions. The simplification is necessary because there is no current way of knowing how the thermodynamic activities of the species present are related to their concentrations (Turner, 2023). The estimated thermodynamic properties of Reaction 1 (for standard state conditions at 25^{o}C) are shown in Table 2 (Turner, 1994). The thermodynamics of neutralization for these pairs of ions (referred to here collectively as metastable nitrous acid) resulted in a consistent, though qualitative, explanation for *most of* the strange behaviors associated with ball lightning (Turner, 1994).

ΔH^o, ΔS^o, and ΔG^o, are respectively, the standard enthalpy, entropy, and Gibbs free-energy for the process. They are related by the identity $\Delta G^o = \Delta H^o - T\Delta S^o$. The ΔH^o values can be thought of as the energy that would be released as heat, for each participant in Reaction 1, if each component were to be present in its standard state. This is obviously a hypothetical concept, but what matters most in the present context is the sign and magnitude of the free energy and of the enthalpy. Both energies are large in magnitude for n = 0. On the other hand, for n = 15, the *heat taken in from the surroundings* is even larger than that *released* when n = 0. In the latter case, the enthalpy is forcing the reaction to proceed from left to right, while for n = 15, it is pushing the reaction to the left so that it is *the entropy change* that forces the reaction to occur.

The dependence of the free energies of Reaction 1 on n at higher degrees of hydration is shown in Fig 3. Since what determines whether a reaction will go to the left or the right is the free energy, the ΔG values in Fig.3 show that, for all the listed values of n up to 25, the reaction can proceed to the right because the free energy is negative. As just pointed out, what allows the effect of the unfavorable enthalpy, for, say, n = 15, to be overridden is the positive entropy contribution. A positive entropy is a measure of the extra freedom that the molecules in the system gain when the reaction occurs. The cooling resulting from Reaction 1 resembles that resulting from water evaporation in that both processes have positive enthalpies and positive entropies.

The changes in ΔG^o with n imply that, for n much greater than about 25, *any form of nitrous acid in the gas phase* must be considered a *strong acid* as opposed to the

Table 2. Standard State Thermodynamics for Reaction 1 (from Turner, 1994)

n	0	1	3	5	7	10	15
ΔH^0 / kJ.mol^{-1}	-700	-487	-217	- 11	169	433	872
ΔS^0 / J.mol^{-1}K^{-1}	14	241	687	1174	1640	2332	3521
ΔG^0 / kJ.mol^{-1}	-704	-559	-422	-361	-320	-262	-177

weak one that it is in a normal aqueous solution. The data also show clearly that the change from heating to refrigerating processes occurs over a very limited range of n, so this change is only possible in the very *early stages* of hydration of any freshly produced ions.

These will have been produced by UV irradiation from the plasma. This means that the temperature gradient close to an air plasma will inevitably be very high. This is why lightning balls occasionally crack circular holes in glass windows (Turner, 1997b). The very limited range of hydration numbers that can lead to refrigeration is presumably one of the many possible reasons for the rarity of ball lightning and its close relatives.

It should be noted that the values listed in Table 2 (taken from Turner, 1994) are the results of the original estimates, and, as pointed out at the time, the number of digits displayed implies a considerable overestimate of the precision of the actual measurements. These represented remarkable experimental achievements, but the actual precision of the available data, as tabulated by Keesee and Castleman (1986), is not known.

A far more important limitation is that, because of the absence of any theories that apply to the interactions between ions in a compressible fluid or in moist gas (Turner, 1983, 2003, 2023), nothing can be predicted validly about the actual concentrations of the ionic species that surround an air plasma. This also means that *no reaction rates between the ionic species* can be calculated - at least if meaningful conclusions are required. The stablest *dry* cation formed near an air plasma is NO^+ (Turner, 1994), but this is rapidly converted to H_3O^+ as soon as it encounters water vapor (Puckett & Teague, 1971). This fact supports the importance of Reaction 1 as well as the other main assumptions of the basic electrochemical model for ball lightning (Turner, 1994).

As seen in Fig. 3, if n exceeds about 25, nitrous acid in the vapor phase will become a strong acid in that the two ions cannot annihilate each other's charges (as Faraday assumed they would). There is now some suggestive experimental support for this implication (Bartlett & Turner, 2024). The fact that metastable nitrous acid can be a strong acid in the gas phase is crucial to plasma stability. This is because, as the distance from the plasma increases past the point where n exceeds 15, hydration numbers will increase, and the aerosols will rapidly grow. Lightning balls are sometimes transparent and sometimes very cloudy. A potentially more stable ball might be expected in the latter case. However, even such a ball cannot survive if the *earliest stages* of Reaction 1 are catalyzed in some way so that surface refrigeration becomes impossible.

Reaction 1 alone cannot explain the long lives of many lightning balls (or of their even longer-lived relatives, such as tornadic lights and UFOs). Plasmas surrounded by metastable nitrous acid only possess long lives (in the absence of a thunderstorm field) because of a second overall reaction involving nitrogen oxidation:

$$N_2\,(g) \quad + \quad 2.5\,O_2\,(g) \quad + \quad H_2O\,(g) \rightarrow 2\,HNO_3\,(aq) \qquad (2)$$

Here, the designation (g) means gas phase, and (aq) means aqueous, in the form of aerosols (and/or droplets sometimes) of nitric acid solution. There are three other reactions nominally similar to Reaction 2 - due to the possible presence of water in two phases - but Reaction 2 is the only one that is thermodynamically possible, and even then, it is only possible if the local temperature is less than about 15^0 C (Turner 1998a, 2023). The other three reactions (all of them thermodynamically impossible) are for reactant water as a liquid and for nitric acid product as a gas. Note the reduction in the number of molecules in Reaction 2, which means that an inflow of air toward the plasma is predicted (according to Le Chatelier's principle) whenever this reaction occurs.

An air plasma itself is usually so hot that it contains numerous different ions and radicals that are of sufficiently high energy to produce either nitrous or nitric acid under appropriate conditions. This implies that the plas-

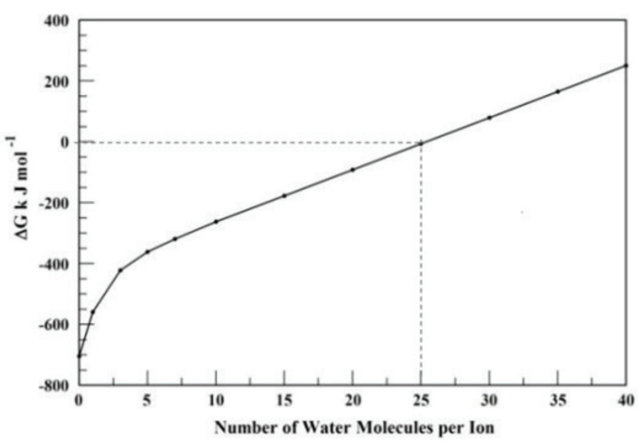

Figure 3. Free Energies of Reaction 1. Note that ΔG changes sign where the number of water molecules in each ion cluster (assumed identical for ions of both charges) is near 25. This means that the reaction is thermodynamically *impossible* when the number of water molecules in each ion cluster is greater than about 25.

ma can act as a catalyst for the formation of nitric acid. In the original formulations of the model (Turner, 1994, 1998a, 2002), it was tacitly assumed that the nitrous acid needed to diffuse out of the plasma. However, it has recently been shown that high-energy UV (that produced by electric charge neutralization within a mercury vapor plasma) can produce both nitrous and nitric acids directly from cool, moist air (Bartlett & Turner, 2024). This implies that *no species needs to diffuse out of the plasma* against the air that is flowing in towards it. Once nitrous acid has been produced outside the plasma, it is easily oxidized to nitric acid by, for example, the ozone that is also produced by UV radiation.

A crucial point in the context of air plasma stability is that if the metastable nitrous acid produced just outside the plasma is *hydrated by very little more than, say, six water molecules*, their subsequent neutralization will significantly cool the air close to the plasma-air boundary. The data in Table 2 also seem important in another way since they imply that refrigeration at the surface of a plasma is *impossible* if the water activity close to the plasma becomes sufficiently high. This fact must surely contribute to the rarity of stable air plasmas since processes occurring further away from the plasma need to limit the water content *at its surface* to a very narrow range. The *hemispherical* air plasmas that can be easily produced by sparks in water-saturated air (Turner, 2023) probably have very short lives because the water content of the air near the plasma is far too high.

Any anion (for example, formed from an organic contaminant) that happens to have similar thermodynamic properties to the nitrite ion could, in principle, behave in a similar way. However, nitrite is the only known gas phase ion, that could be involved at a plasma surface, *whose thermodynamic properties have been measured*. In fact, it seems quite possible that specific organic ions can replace the role of nitrous acid in refrigerating the surface of such feeble plasmas as those that seem to arise in spontaneous human combustion cases (Bauer, 2003; Randles & Hough, 1992; Turner, 2003) and possibly also in stabilizing the surfaces of will-o'-the-wisps.

In an established air plasma, any liquid water reasonably close to a hot plasma will tend to evaporate, whereas, further away from it, it will have a tendency to condense - as long as the local temperature is sufficiently low. In such cases, aerosols and water droplets (all eventually containing nitric acid) located at specific distances from the plasma surface would be in a state of kinetic equilibrium. If the relevant physical and chemical conditions are maintained within correct limits, which means optimal for plasma stability, these steady-state conditions *could* last indefinitely once they have been established. Demonstrably, they *do not* last indefinitely, and this implies that at least some of these conditions are easily lost once they are optimal.

Unfortunately, we still do not know exactly what these conditions are, although one obvious optimization candidate is the water activity close to the plasma - as just seen. It is also unclear to what extent quite different kinds of energy input are needed in the earliest formation stages of some air plasmas. This fact becomes clear once it is accepted that lightning balls can definitely form in the air without the slightest sign of a spark (e.g., Corliss, 1977; Handel & Leitner, 1994 Singer, 1971).

Several of the books by Corliss (including Corliss, 1977, 2001) catalog the behaviors of numerous kinds of unusual natural light phenomena. Some of them seem to be more or less closely related to ball lightning. It seems possible that information from the larger air plasmas might eventually provide valuable hints as to what the optimizing conditions are and how many of them are crucial.

Optimal conditions for forming a stable lightning ball probably include the following: the ranges of mean space-charge-density in the air, the local (possibly time-dependent) electric field, the relative humidity and local humidity gradient plus the nature and concentration of any contaminant molecules and aerosols in the atmosphere (Turner, 1998a, 2002). Generally, we know none of these parameters, and it seems clear, from the rarity of contained air plasmas, that non-ideal values are very much more likely to be present than optimal ones.

The electrochemical model for air plasmas has, to date, relied mainly on ball lightning reports, the particulars of which have been very well documented. The purpose of the material to be discussed next is to seek any relevant clues that might have been revealed through other observations on natural air plasmas: those that have been studied over a far shorter period of time than has ball lightning.

Earth-lights, Earthquake Lights, and UFOs

Unlike ball lightning reports, which have been taken seriously by at least a few physicists for centuries, the reports of unusual flying objects are taken seriously by very few scientists. Fortunately, there exist a number of phenomena whose sizes are usually larger than lightning balls but smaller than most UFOs, and these have proved somewhat easier to study fruitfully than have lightning balls. Earth-lights are among the smallest of the poorly understood natural lights that are sometimes grouped together with UFOs. They have been studied for several decades in the Hessdalen region of Norway by Strand

and his collaborators and observed in several other places fairly regularly (Devereux, 1990; Strand, 1985, 2000; Teodorani & Strand, 1998; Teodorani, 2004; Teodorani, 2011). The Hessdalen studies, although still inconclusive in some ways, are very important.

As we shall see, the uniquely detailed studies at Hessdalen provide vital clues to the close connections that exist between ball lightning and earth-light plasmas. It now seems clear that earth-lights, as well as earthquake lights, volcanic lights and all *real* UFOs, are basically groups of interacting, electrochemically contained, air plasmas. I should try to clarify at this point what "real", in the context of earth-lights, means.

Teodorani (2004) listed 30 places in the world where apparently real earth-lights (strange luminous phenomena) are reported repeatedly. However, nothing like the detailed studies carried out in the Hessdalen valley have been carried out elsewhere. It has long been believed by some scientists that most, if not all, of these phenomena, are consequences of remote lights, such as car headlights, seen as a consequence of the mirage effect known as the Fata Morgana (Pettigrew, 2003). Some of these lights may simply be the result of these effects, but others are certainly not.

The main reason for thinking that some of these phenomena differ from those studied at Hessdalen is that many seem to arise in deserts, whereas the phenomena observed in the Hessdalen Valley all seem to occur under conditions of very high relative humidity (Teodorani, 2004). However, even deserts are not completely free of water vapor, and relative humidities can go up considerably as temperatures fall at night - so the apparent distinction might possibly be irrelevant. Most earth-lights are seen only at night. The original studies of earth-lights in Norway's Hessdalen Valley (Strand, 1985, 2000) concentrated on attempts to correlate visual appearances of the lights with the detection of radio waves, the object being to understand the energy source (or sources) of the plasmas. Seismic strains have long been considered as possible contributors to their energy supply (e.g. Devereux, 1990; Finkelstein & Powell, 1970), and this is presumably one reason they are called earth-lights.

Far fewer observations of earthquake lights have been reported. This is probably because, for obvious reasons, they are rarely seen clearly and never at close range. Nevertheless, in his book on earth-lights, Devereux (1900) refers to several studies of them made by J. S. Derr and M. A. Persinger. Earthquake lights seem to be closely related to UFOs, but unlike the latter phenomena, seismically produced radiation is more likely to be involved in their production. UFOs are commonly observed at heights of several thousand meters, so seismic forces seem unlikely to be effective. Many of the lights in the Hessdalen Valley were observed fairly high in the sky (Teodorani, 2004), but *they* could still be within the range of tectonically generated radio sources.

A number of intriguing observations, most awaiting detailed explanations, have been reported from this valley. Unfortunately, despite the very wide range of electromagnetic frequencies that have been used in investigating the phenomena, few questions have yet been answered definitively (Teodorani, 2004). The earth-lights at Hessdalen are nearly always observed at night. They tend to be larger and longer-lived than most lightning balls. Unlike ball lightning, they *never* appear to be associated with thunderstorms. Also, unlike lightning balls, they normally consist of groups of individual plasma balls, all resembling lightning balls (Teodorani, 2004).

During one four-year period, after an automated observation system had been installed in the valley, the number of balls recorded monthly varied between 4 and 18 over a period of 26 observing months (Teodorani, 2004).

Clearly, the observations were sufficiently numerous to be very instructive. While this situation is, in most respects, much more favorable to observation than are reports of ball lightning; the lights are seldom seen at close range, the valley being a large one. More studies in this valley appear to be highly desirable,

It seems clear that the *large DC fields* experienced during a thunderstorm are *not* required for the formation of these air plasmas. One very important property of plasmas is that they can absorb and emit electromagnetic energy over a very wide range of frequency (Stenhoff, 1999). This is basically why seismic strains have been thought to be possible initiators of earth-lights as well as for their fairly long lives. It should be realized, of course, that the precise needs for *igniting* any kind of plasma need not be the same as those that provide it with a long life. In lighting a gas flame, the chemistry of the spark has nothing to do with the nature of the fuel.

It is still uncertain where the energizing radiation in the Hessdalen valley originates. Piezo-electricity formed from quartz crystals in the ground has been proposed as have cosmic rays or solar wind particles decomposing in the air (Teodorani, 2004). If cosmic ray showers represent the crucial source of *ignition*, all the initial component balls of an earth-light might well be created as fairly close neighbors. And if, as seems likely, UFOs possess similar structures to earth-lights, they might well be born inside a single large cloud high in the air. It is clear that electrical energy does not need to be supplied continuously to an air plasma because nitric acid production can supply all the needed energy *once a plasma ball exists* (Turner, 1998a).

In the context of plasma stability, the most important observations on the Hessdalen lights probably come from photographic records made unusually close to a few of the lights. These permitted detailed examinations of their shapes and colours. The images were obtained with high resolution digital cameras - still and video.

Teodorani (2004) has provided a detailed summary of some of the findings but mainly concentrating on newer results - including those obtained during his group's visits to Hessdalen from Italy. Most of the detailed imaging was obtained during three joint Italian-Norwegian observing campaigns known as EMBLA. Most of the individuals studying the phenomena were either physicists or electrical engineers.

Unfortunately, it seems necessary, at this point, to comment on the very common (and perfectly understandable) tendency of scientists and others to ignore observations they do not understand. Ever since science has been considered a profession, a reasonable number of scientists have believed in the existence of ball lightning. This seems to be far less true concerning the existence of UFOs and sometimes even of earth-lights. Scientists who refuse to accept anything they have not seen with their own eyes can have so much faith in the laws they were taught that they refuse to believe there are significant gaps in our knowledge. But there are (Turner, 2023).

Some researchers even manipulate totally irrelevant facts to "prove" their points just as effectively as can politicians. In both cases, the reason is the same: they are utterly convinced they are correct. Presumably, some physicists feel justified in acting like this because of their unshakable faith that all the needed laws of physics are available - but this is not true in systems like those being discussed (Turner, 2023). For such people, evidence is usually explained away as a hoax - or simply ignored. The literature is full of similar dogmatism concerning earth-lights (Devereux, 1990). In such matters, dedicated disbelievers can go to extreme lengths to "prove" that the observed lights were really caused by some manmade light even after triangulation using photography has shown this to be quite impossible. The need to mention these facts is that ill-informed comments of this kind (plus even worse ideas) are readily accessible from some of the websites that discuss the Hessdalen phenomena and similar ones.

The more recent collaboration at Hessdalen was mainly between the Østfold University College in Norway and the Radio Astronomy Institute in Bologna, but other individuals have also been involved. In the present context, the photographic evidence was particularly revealing. In a few cases, triangulation, using images from well-separated cameras, allowed output optical powers to be calculated. One recorded light measured 19 kW of visible light (Teodorani, 2004). Structurally, the most important observations (several of which were recorded with video cameras) were assemblages of half a dozen or so white or multicolored balls, from which occasionally, a single ball would shoot away. Also, a few groups of multicolored balls were examined in detail, using image processing methods so as to provide light-intensity profiles for the individual balls that make up the more complex objects.

A few of the strongly colored balls were examined spectroscopically. All appeared to have smooth spectral emission profiles with broad peaks resembling those of light emitting diodes (LEDs). It was found that, as the emission intensity increased or decreased the spectral *shapes* were unaltered. Teodorani speculated that the spectra might result from mold spores drawn into the plasma and burnt. The suggestion was that such spores, on burning, produce a large quantity of almost mono-disperse nano-crystals of semiconductors (quantum dots).

Such nano-crystals can yield very bright colors when excited by UV radiation, and such radiation is inevitably produced by charge neutralization inside a plasma. A reasonable assumption is that only relatively low power balls are colored, while the white ones are much more powerful. This suggestion seems to be supported by the existing evidence on ball lightning. A more quantitative study might, in the future, be possible on this matter.

Many studies have shown that quantum dots can be produced efficiently by processing appropriate mixtures

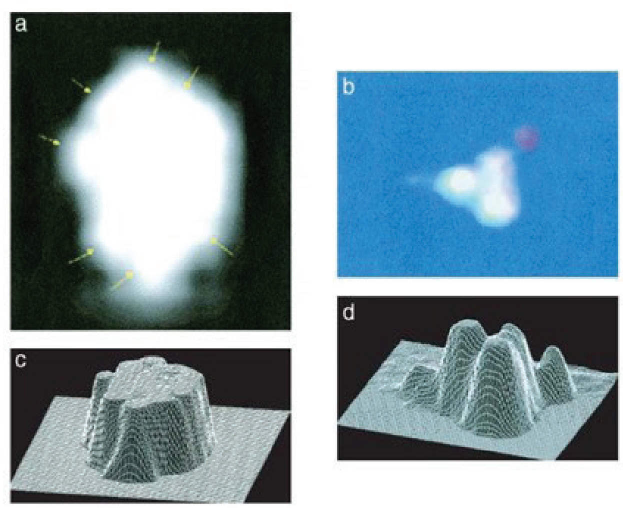

Figure.4. Processed Images for Two Earth-Lights. The top figures are the actual images and the bottom two are those processed by the methods described by Teodorani (2004). The left image was obtained by summing 30 sequential frames from a video-camera. The image on the right was obtained as a still photograph and the luminosity was estimated to be about 100 kW.

of chemicals inside plasmas (e.g. Mangolini et al., 2005; Sankaran et al., 2005). It seems that fungal spores can provide ideal mixtures that provide bright colors. Teodorani suggested that a search for the fungi possibly responsible was desirable. This would obviously require tests of whether burning their spores in a plasma does actually produce quantum dots. Such studies should prove very instructive - especially if spore counts at different seasons of the year could also be measured and compared with data on the brightly colored balls. The identities and properties of the various suspended mold spores could presumably be significantly different at different seasons of the year.

The forces that hold a group of spherical plasma balls together in an earth-light seem to have an origin that is closely related to those that provide structural stability in lightning balls. As shown earlier, apparently similar forces can also draw pairs of flame-balls together (under gravity-free conditions). *The forces holding multiple balls together in an earth-light* seem not always to be very large and they are balanced by electrostatic repulsion. The air inflow *between* the individual balls, in a stable assemblage of plasma balls, will be more restricted than it is *into the outward-facing* parts of the balls. Thus, they can be easily drawn together *if initially formed sufficiently close to each other*. The aerosols *between* the individual balls will be smaller than elsewhere because of the extra competition for hydration - causing mutual attraction between the balls.

Teodorani (2004) discussed several different aspects of the unusual structures and behaviours of earth-lights. One is a commonly observed change in size of such lights. Figure 5 (Fig. 6a in Teodorani's paper) shows a selection of low resolution video frames of an earth-light growing in size and then shrinking. Teodorani was able to demonstrate that the simple *expansion* of a *single* plasma sphere seems *never* to be observed.

Instead, there is a sudden appearance of "satellite spheres" around the original ball. He also provides single shots from video images showing the ejection from large white light-balls of small green ones (sometimes appearing rather yellow on a printed page). At least on the basis of the data collected so far at Hessdalen, it seems that the ejected balls are *always* green. As Teodorani points out, this seems to suggest an important role for trace chemical contaminants in the air.

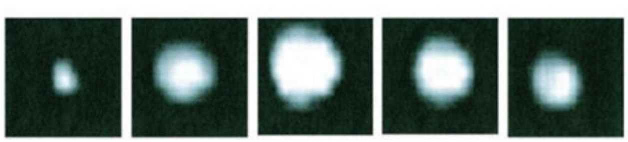

Figure 5. Selected Video Images Showing Changes in Size for a Stationary Earth-Light. The light was situated on a hill top and was visible for a total of 60 video frames.

Variations in radiant optical power of the Hessdalen lights tend to be characterized by a pulsation rate, either regular or irregular, whose period is normally less than one second. Teodorani (2004) observed that there would be "several cycles of pulsation, ranging from 1 second up to 3 minutes or more, in alternating 'on' and 'off' phases, each lasting some seconds. 'On' phases most often had a duration of 5 seconds". Occasionally, a few effectively invisible plasma balls were present. When a light phenomenon lasted longer than 3 minutes or so, the "radiant power tended to stabilize at a high value with a much lower-amplitude pulsation".

Figure 6 shows 21 fairly evenly spaced shots from a video record of a typical event that lasted about 3 minutes. One interesting characteristic of a few of the earth-lights observed by Strand and Teodorani in the Hessdalen Valley is that they can sometimes be invisible at optical frequencies *although detectable in the infra-red*.

Possibly the entry of a specific impurity into such a ball causes it to become visible. Presumably these balls are of fairly low energy before one or more key impurities enter the system or the local electrical state changes.

One obvious possibility is that specific insects are drawn into the *outside of one* component ball and that their presence interferes with the local refrigeration processes, thus making some balls (the green ones) sightly less robust than others. The possible consequences of such changes will be referred to shortly. On the evidence available so far, what seems clear is that small balls positioned within a few meters of the main cluster can be either white, red, or blue, but those in the range between 50 and 100 m from the main structure are always green.

These arguments imply that creating an earth-light should be little more surprising than that of a lightning ball. However, it is not obvious why lightning balls never cluster into earth-lights. Their *location at birth* (normally far from cosmic rays or sources of tectonic forces) might well be responsible. It seems significant that lightning balls, once created, never seem to transform into earth-lights. Possibly, a complete explanation would require a *valid quantitative theory* for ion-ion interactions in moist air. However, we know that this does not exist and that it is unlikely to do so in the near future (Turner, 2023).

Once the apparent family resemblance between lightning balls and earth-lights is accepted, earth-light growth, splitting, pulsation, and the overall shape-changes all seem moderately easy to understand. It seems clear that an earth-light is basically an assembly of mutually attracting air plasma balls whose output of light can change

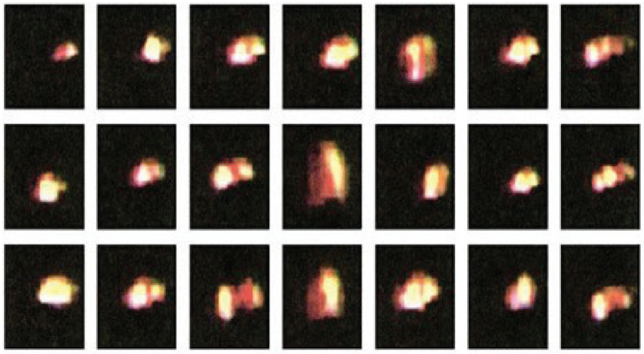

Figure 6. Selected Video Images Showing Changes of Shape of an Earth-Light. Only the brightest frames were selected. The light was blinking and its total duration was about 3 minutes.

very rapidly as species of different chemical identity are drawn into the component balls. It should be born in mind that most lightning balls are so much shorter-lived than most earth-lights that changes in colour or brightness are rarely recorded. They are, however, described occasionally (Stakhanov, 1979). From a few measured sizes of earth-lights (via multiple photographs of the same light source), it seems that their large *overall* size can result from both the *number* of component balls and the *individual ball sizes*. All *individual* plasma ball sizes seem to be established at birth (Turner, 2002). They never appear to change size once they have formed.

Extreme temporal variations in light intensity were found to be common with the lights at Hessdalen. Such changes are rarely observed with lightning balls. The difference may be due to the fact that lightning balls seem *never* to be observed very close to one another. Hence, normally, once a lightning ball has ceased to exist and emit UV radiation (perhaps because of the entry of some specific chemical), it can no longer induce nitrogen oxy-acid formation locally, and the self-re-enforcing chemistry ceases. On the other hand, if several plasma balls are present, as in an earth-light, there can still be ample UV locally to assist the refrigeration/oxidation processes - so long as these regions are favorable in other necessary ways (whatever they may be). If this explanation is correct, a possible implication is that igniting a lightning ball and igniting an earth-light require somewhat different conditions. Unfortunately, this does not immediately suggest what these conditions are in either case.

There are several possible reasons for size differences in individual lightning balls. These sizes are consistent with a reasonable initial growth mechanism that is very fast and, in part, is determined by the dust content of the air (Turner, 2002). The calculations imply that very large balls *only* form in rather clean air. However, hardly any of the required input parameters for even this calculation can be defined reliably, and none at all that could provide a credible estimate of a size range for an *assembly* of plasma balls such as an earth-light or UFO.

A noteworthy reported difference between the three types of air plasma is that lightning balls are almost always observed as individual objects while UFOs and earth-lights always seem to consist of multiple balls. The component balls of UFOs normally seem to be in such very close contact that, as seen in the next Section, they often appear to be single metallic-looking structures that can sometimes be decorated with bright lights.

Multiple lightning balls are occasionally seen escaping from dense clouds, but they apparently have no tendency whatsoever to attract one another. It is extremely rare for multiple lightning balls to be seen near the ground although there was one reported exception in 1897 when two ladies reported seeing a group of balls (of various delicate colors) floating around and apparently always evading their grasp (Anonymous, 1930; Corliss, 2001). Not the slightest tendency for mutual attraction was observed in this case. This is probably because of the long range of the forces of repulsion compared with the short-range influence of the inertial forces.

Some Unique Characteristics of UFOs

There is ample evidence for the existence of atmospheric phenomena that are, in many respects, remarkably similar to ball lightning but are very much larger and longer lived. As pointed out earlier, Klass (1968) stressed these similarities. The full range of diameters attributed to ball lightning is between 2.10^{-2} and 2 m (Stenhoff, 1999). However, some authors (e.g., Corliss 1977, 2001) do not distinguish between ball lightning and less common atmospheric plasmas such as Unpredictable Flying Objects or UFOs. These objects have often been reported to have a linear dimension of 20 m or more, but they are usually seen at far greater distances (in such cases predominantly by aircraft pilots) than are normal lightning balls. Hence, the range of their sizes is less reliably defined.

In addition, UFOs can be reported with *significantly different shapes,* while free-floating lightning balls are always close to spherical (except when squeezing through holes smaller than their normal diameter or when they are bouncing or rotating very fast). Few ball lightning witnesses think of reporting their experiences unless they hear broadcast accounts by some eminent physicist, read about a new ball lightning model, or learn of specific requests for new accounts. Unfortunately, many people who have seen UFOs appear to be severely inhibited about reporting their observations. It seems there can be very real risks of ridicule whenever UFO experiences are described (Hynek, 1972).

Clearly, as is the case with ball lightning, all the evidence for the existence and characteristics of UFOs comes from eyewitness testimony. Thus, it is necessary to comment on some of the adverse consequences that this fact has had on the whole question of belief in the existence of naturally contained air plasmas. The occasional hoax is one obvious difficulty, but hoaxes are usually fairly easy to identify.

There seem to be three far more important problems concerning UFOs. One is the ease with which reliable sightings can be misinterpreted or, particularly by those in authority, simply ignored (Haines, 1994; Hynek, 1972; Kean, 2010). Another problem is a general belief among many physicists that long-lived air plasmas simply cannot possibly exist. The third is the high degree of specialization in science (Turner, 2002, 2023). This has long proved essential if progress is to be made, but it unavoidably leaves all scientists, however objective, ignorant of a truly enormous number of empirical facts. Thorough collections of such facts are *only* feasible in the space provided by a book.

As indicated earlier, several good books on ball lightning have been written, nearly all of them by well-respected physicists. Recent books on ball lightning make reference to thousands of scientific papers on the subject, many of them published by scientists of repute in well-respected journals. The situation regarding UFOs could hardly be more different. The literature on UFOs is also very large, but the fraction of it that is scientifically valuable has always tended to be small (Hynek, 1972). Among the reasons that ball lightning reports are easier to believe than those of UFOs are the following facts: lightning balls are almost always small, rarely being large enough for anyone to think of the cloudy ones as containing even a baby. Also, they are usually fairly transparent. Thus, alien visitors are *never* invoked or even implied in efforts to explain lightning balls.

UFOs are even more unfamiliar objects than lightning balls to most people. Even though rather few individuals have seen a lightning ball themselves, many people seem to know of someone who has, even if it is only through the memory of an elderly relative or a friend. However, there are much more important differences between the two phenomena than this. UFOs are sometimes quite large enough to hold one or more men, and they are usually characterized by strongly reflecting surfaces. A very large number of fairly small plasma balls will emit copious quantities of UV, the output of each ball helping to stabilize its neighbors. This will produce large quantities of aerosols and barely visible droplets (Bartlett & Turner, 2024). In quantity, these can *resemble* metallic surfaces by making them capable of reflecting light from the Sun or Moon. Also, UFOs frequently display illuminated bright patches that are often interpreted as windows.

Book publishers can hardly be blamed for seeing the advantages of sensationalism over the likely boredom of scientific disputes concerning speculations on poorly understood phenomena. Nevertheless, there exist enough detailed descriptions of UFOs and their strange behaviors to clarify their clear similarities to and differences from lightning balls.

Some experienced investigators of UFOs (e.g., Vallee, 1965, 1999) prefer to call them Unexplained Aerial Objects (UAOs) - because the objects will normally have been *identified,* and they are just as likely to be stationary as moving. Others (e.g., Teodorani, 2011) prefer to use a similar acronym but substitute the word "Object" with "Phenomenon." This is presumably because the relationship between the objects and their energy sources is considered one of the most important problems - as it certainly is.

The long-used term UFO is used here mainly because of its familiarity but also because it is an acronym for Unpredictable Flying Objects. Unpredictable Aerial Phenomenon is, in some ways, a more appropriate term, but the objects can fly. It is the *unpredictability* in their behavior that is so strange (Haines, 1994). It has to be admitted that, for those like Strand (1985) and Teodorani (2004) whose interests were mainly in earth-lights, flying is not a word that readily comes to mind since they *usually* remain reasonably stationary - although there are exceptions.

Among the most numerous and mutually consistent reports of UFOs are those provided by pilots (Chester, 2007; Haines, 1994; Hynek, 1972; Kean, 2010; Smith, 1997). These reports frequently describe apparently deliberate tracking of an aircraft by one UFO or a group of them, as well as rapid changes in direction. Although often seen at considerable distances from the observers, the descriptions are surprisingly consistent - even in their seemingly most bizarre movements (Haines, 1994). UFO tracking of aircraft and mutual UFO motions, resulting from long, thin plasmas between them, will be discussed in a future publication.

One of the most respected experts on UFOs was J. Allen Hynek, an astronomer who was originally asked, by the US Air Force, simply to eliminate from its records all those UFO reports that were likely to be misidentifications of astronomical objects. Eventually, however, he spent over 20 years examining all the records held by the Air Force as well as many other descriptions provided by private citizens and policemen from observations at ground level. His general approach has been followed by several later investigators of the subject.

The ground-level reports can be almost as strange as the reports of pilots. Both kinds occasionally describe sudden bursts of acceleration to speeds much faster than are likely to be achievable by any fighter aircraft (though not faster than the speeds of molecules in gases). In close encounters, witnesses can sense high temperatures on their skin, more rarely actual burning, and at longer ranges it is frequently observed that a UFO has burnt a patch of vegetation while it was close to it. More often than not, if the UFO approaches a moving car at close range, the ignition system malfunctions, and the car stops. The car cannot then be started until the UFO has flown away (Hynek, 1972). It is well known that plasmas can emit radiation over a huge range of frequency (Stenhoff, 1999), so that many observations are readily explicable if the objects are plasmas.

Also, when electrochemical influences are invoked, we can see that the structure and characteristics of UFOs are easily explained as assemblages of single plasma balls that differ in no significant way from lightning balls. One of the most basic problems in understanding UFOs (as well as lightning balls) is that no one has ever been able to prepare *very long-lived* air plasmas that have been *held in place* for long enough to study their full emission spectra in great detail. The only real evidence on this matter is that of Powell and Finkelstein (1969) which was discussed earlier. However, the absence of such evidence does not justify doubting those characteristics of UFOs that could simply be consequences of electromagnetic radiation.

The literature on both ball lightning and UFOs is large, and it demonstrates that viewpoints on both subjects are very diverse. This seems inevitable. Not only do the accounts seem difficult to reconcile with the known laws of physics, but viewpoints inevitably reflect what we already happen to know. Various aspects of the serious problems associated with over-specialization, as it relates to air plasma study, have been raised elsewhere (Turner, 2002, 2003, 2023). Clearly, if relevant valid theories do not exist, all that remains for advancing our knowledge are qualitative arguments. Attention here mostly concerns further evidence that the structures of air plasmas can be stabilized by their interactions with other air plasmas.

In 1999, the solar physicist Peter Sturrock was persuaded by a visiting physicist and UFO expert, Jacques Vallee, to organize a three-day presentation on the subject of UFOs. This was followed, a few weeks later, by a three-day panel discussion among the audience of eminent physicists who (some with difficulty) had been persuaded to attend. They had agreed to attend both meetings even though none had any particular interest in the phenomena. It seems that the most encouraging statement these physicists were prepared to make after the event was this: "Whenever there are unexplained observations, there is the possibility that scientists will learn something new by studying these observations." (Sturrock, 1999).

Vallee had been collecting data on UFOs for many years and has written several books on the subject. At Sturrock's formal meeting, specific examples of the kind of evidence available were provided - one involving a helicopter being so extraordinary as to be almost unbelievable. In all the specific cases described, either multiple witness reports or physical evidence (such as confirmed photographs or, radar records or both) were used. Many of the observations threw light on such points as physical appearance (shape and reflectivity), huge power ranges displayed, and (somewhat smaller) ranges in size. Unsurprisingly, no hopes were raised for research funds to study UFOs through the normal science funding agencies. In any case, it is difficult to suggest what could be done apart from observing earth-lights more thoroughly - for example, by setting up more autonomous recording stations similar to those at Hessdalen. Really adequate levels of support for such studies seem unlikely as long as basic gaps in science remain unrecognized and as long as there are plenty of more easily studied research projects to occupy the attention of scientists (Turner, 2023). However, as mentioned earlier, more studies like those at Hessdalen should prove extremely valuable.

In the present context, it is only necessary to refer to one particularly dramatic occurrence described in Sturrock's (1999) collection. One reason for choosing this example is its possible relationship to the kinds of plasma lights that are, from time to time, reported inside and above tornado funnels (Vonnegut, 1960; Vonnegut & Weyer 1966; Corliss 1977, 2001). Studies of tornadic lights, though their existence is apparently still not accepted by all meteorologists, have occasionally been published in reputable journals, and obtaining support to study these lights might prove possible in the future.

The specific UFO report that seems most relevant to tornadic lights was described by Zeidman (1999) in Sturrock's book. The UFO was witnessed in Mansfield, Ohio. There were nine eyewitnesses to the event which occurred in 1973. Four of the witnesses were army helicopter crew members and five watched from a car.

Some in the latter group eventually left their car to watch as the UFO closed in on the helicopter. This was almost directly above them at the time the two objects were at their closest. Allowing for blocked views, some fairly small differences in estimates of size by the crew, and slightly differing estimates of timings, the accounts agree remarkably well. The initial sightings, by the helicopter pilots, closely resembled the kind of UFO report where a conventional aircraft was tracked.

The encounter occurred at night, and the object was first seen as a red light pacing the helicopter on the eastern horizon. Minutes later, it was clearly moving towards the helicopter, and eventually, it approached a distance probably best estimated as 20 to 30 m. By then, it was above and slightly in front of the helicopter. The object appeared to be metallic, and the best estimate of its length was 30 m (Zeidman, 1999). Most of the crew initially saw a well-defined red light in front of the approaching squat, cigar-shaped object. A white light was also seen at the rear of the UFO - but only by the ground-based observers.

As the object closed in on the helicopter, it slowed down and then rapidly changed its direction so as to remain above the helicopter. After this, it parallelled the latter's path (still in front of the helicopter) for about 250 m, and then it returned to its previous bearing. While the UFO was closest to the helicopter, radio communication became impossible, and the magnetic compass was observed to rotate slowly. (The latter observations have been reported on occasion when pilots have close encounters with UFOs). During this period also, a beam of green light shone strongly into the cabin of the helicopter making everything inside appear bright green. According to the witnesses on the ground, there was already a dull green light below the object that brightened significantly (for at least ten seconds) while it was closest to the helicopter. The green light seems (for geometric reasons) to have been impossible to notice from inside the helicopter until the object had moved to a position above it, at which time it suddenly became much brighter.

A point agreed on by all the observers was that, until the UFO was above the helicopter, the brightest light was the red one at the front of the object. This would be consistent with the motion of the UFO being driven by an inflow of air where there is least resistance to it (and presumably, the escaping light would be brightest). During the period of closest approach, the green light increased its brightness dramatically. The apparent opening up of the ball supplying the green light implies a charge neutralization process at the ball's surface similar to that which used to be referred to as the electrostatic guidance of lightning balls (see earlier).

It should be remarked that a simple DC field may not be the only kind that could have led to charge neutralization below the green ball and, thus, an increase in the attracting force between the two objects. If an alternating field was present, possibly in addition to a DC field, a charge neutralization process would occur on the side facing the source of the current - i.e., the helicopter. A force of repulsion, during the opposite phase of the current, need not have been effective if interactions with the many other plasma balls behind it partly neutralized its effects.

The observations of most relevance here were reported by the pilot and co-pilot of the helicopter at the time of closest approach. The pilot had gradually lowered the helicopter from its original height in order to avoid the approaching UFO. Finally he moved the relevant lever to achieve the maximum possible rate of descent.

Despite this, the helicopter was found, shortly after the object departed, to be higher than the crew thought remotely possible and still *rising* at a rate of 1,000 feet (300 m) per minute while *the lever was still set for the maximum rate of descent*. It seems obvious that the UFO had been responsible for the dramatic increase in the helicopter's height. The inflow of air, to the plasmas that lifted the helicopter, must have been considerable.

Once it is accepted that tornadic lights could be similar to this particular UFO, the powerful lifting abilities of tornadoes and the well-known atmospheric pressure drops below them (Meteorological Office, 1978; Roberts, 1982) would seem to be assisted by essentially the same processes in both phenomena. Presumably the lifting forces routinely used in tornado models, which arise from rising parcels of humid air, would still be present in the presence of the plasma lifting processes. It is not obvious to me that the former kind of lifting force can be predicted sufficiently precisely to rule out an *additional plasma assisted* role in most tornadoes.

As we have seen, most descriptions of UFOs by pilots suggest that they are very much larger objects than Earthlights and also are far more robust (see e.g., Haines, 1994; Hynek, 1972; Smith, 1997; Sturrock, 1999). The evidence available confirms that there are two distinct reasons for this size differences: individual component balls can be larger and the *number* of clustered balls is often very much larger in UFOs than in earth-lights.

The first effect is consistent with such UFOs usually having formed at cloud level (most likely inside clouds) in regions where *solid* condensation nuclei happen to be fairly scarce (see Turner, 2002). Large UFOs can certainly travel extremely fast, so their formation high in the atmosphere could easily be responsible for the occasional reports of the sudden appearance of similarly large objects near ground level. If they travel from cloud level to Earth as rapidly as they sometimes do, their chances of being seen are obviously lower than if they were only moving at a few hundred km/hr^{-1}. They are thus statistically unlikely to be seen moving from the clouds, and it may be significant that the actual *births* of UFOs seem *never to have been witnessed,* whereas the births of lightning balls and earth-lights are witnessed fairly commonly.

The second effect (increased number of balls) is consistent with the fact that the high-energy UV produced by very energetic plasma balls can produce new aerosols that are associated with local refrigeration (Bartlett & Turner, 2024). Such processes can presumably support the formation of new plasma balls nearby (as observed at Hessdalen).

In any comparison of UFOs with earth-lights, the latter appear to have a relatively non-rigid structure that holds the individual balls together for most of the time - as the result of air inflow through the (relatively) water-starved regions *between* the balls. A reduced water content there will inevitably be produced as the result of strong local competition for water vapor by the ions that face neighboring balls. The evidence for orbiting of pairs of flame-balls, represents a simpler version of this mechanism.

Such mechanisms probably provide a partial explanation for the shapes and properties of all assemblages of air plasmas. A stable geometry, once generated in *less energetic* balls (e.g., in earth-lights), can be easily disrupted by some perturbation. This might be the entry of a large insect through the outer surface of an outer ball, causing the separation of the ball from the other balls. There is no obvious mechanism that can easily cause a ball so ejected to return to its original clump of plasma balls - another *optimally placed opening* in the ejected ball being required for this to happen. This could be why the apparently weaker green balls in the Hessdalen Valley are ejected and then stay briefly in fixed positions, 50 to 100 m distant from their original clump (Teodorani, 2004).

A comment on the possible internal structure of UFOs is warranted here. We have no direct evidence on this matter. However, reasonable arguments seem appropriate. There seems no doubt that at least one layer of plasma balls always surrounds a UFO, and a second layer may also be possible. However, it is more likely that most of the interior consists of one huge plasma ball. The possibility that plasma balls *can* combine (under very unusual circumstances) may be supported by the fact that the *reverse process* is occasionally observed with ball lighting.

A clear example was that illustrated in an observation described by Mattétal (1895). This was made by a man who was watching a severe thunderstorm from an upper-story window and had a clear view of the roof of a house road across the road, During this observation, a single large sphere of plasma formed above the roof of the house opposite. This occurred on top of an iron rod. The ball suddenly released itself from the rod and split into three, similarly sized, smaller balls. These balls rolled down the roof in the form of typical lightning balls and disappeared when they contacted the gutter. There is no obvious reason why the reverse of such a process, through re-minimization of the surface energy, could not take place *inside* a large UFO where they would be held together by the inward directed forces from the outer balls.

If the electrochemical processes occurring at all the surfaces of air plasma clusters are proceeding very effectively (as is to be expected in very powerful UFOs), the reductions in air pressure between the outer balls could be so large that the balls *never separate*. The normally very stable structures of UFOs are known to split up in only about *6% of sightings* - based on 225 cases (Haines, 1994). The far smaller database on the splitting of earth-lights has only been established for a few years, but splitting seems to be considerably more common in earth-lights than it is for UFOs. If earth-light splitting really is more common than UFO splitting, the differences could simply result from differences in the efficiency of the electrochemical processes that hold the plasmas together.

Supercell Storms

The account of the UFO witnessed in Mansfield and described by Zeidman (1999) was unusually clear and reliable. This is because its description by those in the helicopter was supported by independent witnesses on the ground and because all nine witnesses were unusually close to the UFO when it interacted with the helicopter. There can be little doubt that similar UFOs exist and that they would behave in similar ways if the circumstances were similar. The main significance of this fact to meteorology is that if objects with properties resembling this UFO exist *behind the very thick clouds* of many supercells, they could be responsible for the rare reports of tornadic lights that seem to be associated with supercell storms.

The name "supercell" describes a convective storm system in which complex airflow patterns can become established in a kinetically stable state. It seems that the formation of supercells inhibits the thunderstorm cell replacement processes that otherwise link normal thunderstorm cells together (Browning & Foote, 1976).

Severe storms that produce very large hail are usually of this type. Supercells can exist for several hours and may produce very damaging hail and sometimes spawn tornadoes (e.g., Browning & Ludlam, 1962). By the late 1960s, many characteristics of tornadic storms had been identified and tentatively explained using the concept of a supercell. This was well before any detailed testing of the concept had proved possible.

In 1972, an extensive set of observations permitted an unusually detailed study of a powerful supercell storm that started in Wyoming and ended in Kansas (Browning & Foote, 1976). The largest hailstones fell near the town of Fleming, Colorado, and the storm was named after this town. The total track length of the storm was roughly 450 km. However, the portion of the track within the range of the ground radar installations employed in the study was all that was studied in detail. In fact, tornadoes were observed in this storm, but not until it had moved beyond the areas being monitored. Despite this, the study proved unusually instructive.

The Fleming storm was a typical super-cell storm in that it produced large hail to the left of its eastward path. Radar observations were made continuously from four fixed locations and from four aircraft flying close to and through the storm. The high-resolution monitoring of this storm provided an unprecedented amount of detail in *three* dimensions. High resolution was required because the objective was better *to understand hailstone production* - as opposed to the more usual objective of severe storm study, which is, of course, improved prediction. Far larger scale (but far less detailed) models are used in tornado prediction.

The authors introduced their detailed study of this storm by pointing out that one characteristic of many supercell storms, in both the USA and Europe, is the existence of a distinctively shaped volume well hidden inside the clouds. They refer to this as a weak-echo vault (Browning & Foote, 1976). The term refers to a feature of the radar echoes (from the hail and rain) that is associated with these storms. Most of the fast-rising air in a supercell storm passes through these vaults, and hailstone embryos are produced near a feature that Browning and Foote (1976) refer to as the embryo curtain. This is close to where the air's upward flow is greatest - just inside a characteristic portion of the vault wall. The term vault will be used here in preference to the alternative name more frequently used these days (e.g. Snyder et al. 2013), which is a bounded weak echo region or BWER.

The results of Browning and Foote (1976) show that, from near the curtain wall of rising precipitation, the growing embryos are at first carried up and down, eventually forming very large hailstones and gradually moving more horizontally than vertically. When they grow too large to be retained by the inward air flow, they fall out of the storm. In the northern hemisphere, this is always on the left of the eastward-moving storms. The general picture of the storms (though not the hailstone motions) has, since 1976, been confirmed by many others (e.g., Markowski, 2002; Nelson, 1983). If very large hailstones, ejected during these storms, are collected and sliced, they display characteristic bands of differing textures (see e.g., Mason, 1971).

The hailstones whose nitrate distributions were reported in the first paper of this series (Turner, 2023) were of this type. In this case, the supercell responsible for forming the hailstones was called the La Plata storm since La Plata, MD. was where most damage was experienced. When anion dependencies on radius within the hailstones were obtained for three very large hailstones, enormously varying (orders of magnitude) concentrations of chloride and sulfate were found as a function of radius. However, nitrate concentrations only varied slightly - being essentially independent of radius. The only obvious way that such unchanging nitrate analyses could be explained is repeated passage of the hailstones close to a plasma (or plasmas), producing nitric acid within them on every visit.

Many observations on other supercell storms are well-established empirical facts but attempts to obtain *realistic* flow patterns within the storms have failed to produce generally accepted conclusions. Unsurprisingly, all tornado models have implicitly assumed that *hydrodynamic sinks for the air inside them are absent*. If an air plasma were to be present, however, it would inevitably act as a sink for the water vapor and some of the air by transforming moist air into nitric acid-containing hailstones and then expelling them.

This possibility seems to be routinely ignored in models despite the fact that *tornadic lights* have been reported occasionally for over a century (Vonnegut, 1960; Vonnegut & Weyer, 1966). The collection of accounts in the latter study provides convincing evidence that tornadoes are, in some way, electric phenomena and, it seems (Dessens, 1965) that (at least in French tornadoes and not infrequently then) "...the bottom of the tornado 'vomits' balls of fire". These observations all refer to individual tornadoes, rather than the supercells in which they can be produced, but electrical effects seem clearly to be present - just as Vonnegut claimed.

Possibly, large assemblages of air plasmas inside supercells can sometimes lead to the ejection of individual small plasma balls that can enter the top of a tornado funnel and then either remain in a fixed position or, rarely, move down it. The mechanism for movement against a flow of air would be the same as that which explains several other unusual properties of lightning balls, that is, a local reduction in the size of the aerosols that surround the balls in a comparatively dry wind.

On a much larger scale, the presence of hidden plasmas could explain why there is so little consistency in different interpretations of the flow patterns in various more recent storms that have been studied and modeled. Typically, the vault of a supercell is roughly cone-shaped but with the point replaced by a wide arched roof. In the case studied by Browning and Foote (1976), the main curtain of precipitation began about 4 km above the ground, and the vault extended to a height of about 10 km. The observations implied that hailstone embryos were forming in or near the curtain and growing elsewhere in the cloud. *Inside the vault*, the hailstone production was found to be *extremely inefficient* as measured by radar. This was because only a few large hailstones were present instead of the many much smaller particles that provided the radar echoes elsewhere.

The modeling that attempted to explain the Fleming storm results (Browning & Foote, 1976) was particularly instructive because the motions of clumps of large hailstones were used to define the detailed internal airflow. When these flows were combined with measured wind velocities elsewhere, the patterns resulting appeared to be extraordinarily complex. It seems very likely that if suitably situated air plasmas (acting as sinks for the air) had been incorporated into the models, far more reasonable flow patterns would have been derived.

Presumably, the presence of one or more embedded air plasmas contributed to the larger-scale wind flows, which were, as always, inwards (toward the vault). The presence of hot plasmas would, of course, explain the absence of small hailstones within the vault. Radiant heat would have constantly evaporated any very small ice particles and allowed only large hailstones to grow.

In fact, the observed *motions* of one group of what were taken to be very large hailstones (Browning & Foote, 1976) seem to confirm the above suggestion. The authors referred to these groups of hailstones as radar "hot spots" deep inside the vault. Tracking the paths taken by a few of these grouped objects revealed some very unusual motions. Assuming, with Browning and Foote, that the "hot spots" were groups of large hailstones traveling with the wind, the path of one group, in particular, seemed truly extraordinary. This "hot spot" took a roughly horizontal curved path that had a large velocity component *towards the axis of the low echo vault,* after which it appeared to be heading towards the walls of the vault (see Fig. 16 of Browning and Foote, 1976).

Without the very strange wind motions hypothesized in the authors' model, this motion would have seemed impossible. On the other hand, if appropriately placed sinks for the air had been allowed for, the paths of the hailstones might well have been seen as perfectly natural. The raw data on which the work of Browning and Foote was based may still be available. If it is, a re-analysis of the findings that allows for plasmas in different positions could prove very instructive.

Weak echo vaults similar to the one inside the Fleming storm are sometimes reported in less destructive thunderstorm systems than this, but it seems their structures normally fade away as each storm cell weakens and is replaced in power by the next one of the system. Many studies of hailstone-producing storms have been conducted since the Browning and Foote (1976) investigation (e.g. Nelson, 1983; Wurman, Straka, and Rasmussen,1996; Marquis et al., 2012). The *less detailed* empirical evidence from them usually seems very similar to their findings. However, the various models used to explain the results often lead to divergent conclusions. This situation looks suspiciously similar to the long history of failed attempts to explain the peculiar properties of ball lightning.

Population Inversions

Two decades ago (Turner, 2002), it was argued that a major reason for our limited understanding of ball lightning is that its various characteristics are unavoidably studied by scientists from widely differing disciplines. There are a few characteristics of lightning balls which have only been mentioned briefly so far. Probably the most important of these concern the unavoidable consequences of population inversions (Handel & Leitner, 1994). The earlier statements made here were directly related only to ball lightning but they would also be expected to apply equally to earth-lights and UFOs.

A population inversion of some kind seems *essential* in all those cases where no mechanism for forming sparks seems likely. There exist a significant number of observations of this kind. One specific manifestation of population inversions seems needed to explain the passage of lightning balls through glass windows *without any apparent damage to the glass* (Turner, 1997b). It is not clear, from the very limited information available, whether this phenomenon is more or less common than are cases where a ball cracks circular holes in the glass. If the glass of a window is undamaged when a lightning ball passes through it, energy from the ball must obviously have been transmitted through the glass. As Handel and Leitner (1994) point out, a population inversion seems the only possible way through which this process could be accomplished.

As Table 1 implies, many different processes occur at different distances from any natural air plasma. They can produce aerosols whose sizes vary widely. Population inversions are likely to be very common in at least some of the hydrated ions present outside a plasma ball. This is because energy level differences in all the clusters of water molecules are very small indeed. Hence, energy level inversions are particularly easy to accomplish in aerosols. Their presence could presumably account for many of the reported interactions between air plasmas and electromagnetic waves of widely differing frequencies.

Power Obtainable Safely from an Air Plasma

One of the characteristics of air plasmas that have not been considered so far is the wide range of *energy density* for the phenomenon that has been attributed to them. Unfortunately, the range provided for this property is only meaningful if it is *assumed* that the balls are created following a *single* supply of energy. If this is not the case, the important property is the *power* of the plasma which is a quite different property. However, since most lightning balls only last a few seconds, a rough idea of the range of power in these small plasma balls can be obtained by neglecting this fact and simply using the apparent energy density as a proxy for the power an air plasma can deliver. Such an approach was implicitly adopted by Barry (1980), who showed that the effective energy density (assuming a once-off energy input) can be huge, varying between 0.4 and $2.8.10^5$ J.cm $^{-3}$.

From numerous descriptions in the literature of damage (or lack of it) attributed to lightning balls (and from the much smaller database on UFOs), it seems that the *power* associated with UFOs and tornadic plasmas could vary over similar ranges of power (e.g., Corliss, 1997, 2001). Doubts over whether or not ball lightning is fed by some external energy source were of great concern to nearly all pre-1994 investigators of ball lightning. This question, to which a simple and credible answer was first provided in 1998 (Turner, 1998a), illustrates clearly the problems that arise when *chemical* contributions to the stability and lifetime of all air plasmas are neglected.

Earth lights and UFOs are hardly ever associated with severe weather, so until 1998, it must have seemed obvious to most physicists that UFOs, at least, could not possibly be natural phenomena.

That the energy content and power of an assembly of air plasmas can be considerable is demonstrated by the case of the helicopter that was raised high into the air by a UFO near Mansfield, Ohio (see earlier). In this case, it is clear that it is the power and not the energy content of an air plasma that is important. Part of the reason for referring to these facts here is that they are relevant to the possibility that air plasmas might eventually provide a complete solution to the problem of global warming (assuming it is not too late already). If this development were to prove possible, the fuel used (nitrogen) would produce mainly very dilute nitric acid (Bartlett & Turner, 2024).

There would be no point in trying to extract chemical energy from the air if it could not be accomplished safely. The only safe approach would appear to be to ensure, at least initially, that only single air plasmas could form. If there were to be a risk that new lightning balls could be created from an initial one, this could present a serious problem. However, there does not appear to be a single record of one lightning ball spontaneously creating another one, and, as discussed earlier, the reason for this seems understandable. A minor safety consideration is keeping a single ball in a fixed position. This seems to be easily achieved by providing an array of earthed metal points or rings below the plasma (Turner, 1998a).

CONCLUSIONS

The various kinds of evidence assembled here leave little doubt that many kinds of electrochemically contained air plasmas exist on Earth and that all of them have been observed repeatedly. They include: ball lightning, earth-lights, tornadic lights, and UFOs. However, all the phenomena are extremely rare. The most obvious reason for their rarity seems to be that the long-term stability of the plasmas depends on the presence of several different kinds of force that need to operate cooperatively and possibly at different times after at least one of the necessary forces has already been optimized Our total lack of progress toward the preparation of air plasmas under controlled conditions is another serious problem. It can be hoped that this difficulty will be minimized in the future since we now seem to have a fairly good idea of how exactly these air plasmas differ. Recent successes in obtaining video images of UFOs are encouraging, but there are already many hundreds of witnessed accounts of UFOs and over ten thousand accounts of the strange properties of ball lightning. Rather, little new information seems likely to be obtainable quickly unless drones can be used to approach earth-lights and tornadic lights more closely than is currently possible.

The missing science of vapor phase electrochemistry (Turner, 2023) means that normal models involving chemical kinetics can only lead to misleading conclusions (because we cannot derive chemical activities from chemical concentrations). Thus, it is quite impossible to produce any valid *quantitative* model that involves chemical kinetics and can address the stability problem. Fortunately, some progress seems possible without the need for detailed modeling of the chemistry involved. Since the containment of an air plasma seems to depend on a near-optimal distribution of aerosols in a temperature gradient, modeling without using invalid kinetic assumptions should prove possible.

Experimentally, there seem to be at least two ways to learn significantly more about naturally contained air plasmas. One would involve new, more detailed studies of thunderstorm supercells similar to that of Browning and Foote (1976). The second would involve detailed observation of the kinds of plasma that exist and can be located reasonably predictably. The most obvious path would involve more studies of earth-lights similar to those conducted at Hessdalen. A recent proposal (Teodorani, 2024) for new, more detailed studies like these has been outlined. A more radical proposal would be to send drones like those proposed, but fitted with heat seeking devices and video-cameras into tornado-producing supercells.

Such studies might put us on a path to reversing the global warming problem - because of the chemical energy contained in the air which air plasmas do, occasionally, extract. Such developments should hopefully eliminate the need to burn fossil fuels - at least for the production of electricity.

The most economical approach to starting such a research program could involve three steps. First, it would be wise to determine whether *all large hailstones* created in supercells display nitrate concentrations whose distributions within the hailstones are fairly independent of radial position - as was the case with the hailstones from the La Plata storm (Turner, 2023). Secondly, drones fitted with heat-seeking sensors and video cameras could be used to search for air plasmas inside some tornadic supercells. Thirdly, devices for measuring the scattering of electromagnetic radiation near plasma surfaces could be added to the heat-seeking drones in the hope of obtaining more detailed guidance on the distribution of aerosols around natural air plasmas.

Since there has long been funding available for the study of flames, and because of the apparently revealing behavior of flame balls in space, more studies of flame balls under gravity-free conditions could prove valuable. However, such studies would only be really worthwhile if the flame balls were to be *modeled* in a way that accepts the importance of electrostatic fields at air plasma surfaces. Predictions of any reaction rates that involve ions would not be useful until a satisfactory way of obtaining thermodynamic activities from component concentrations is available. This seems likely to be impossible in the foreseeable future (Turner, 2023).

REFERENCES

Abrahamson, J., & Dinniss, J. (2000). Ball lightning caused by oxidation of nanoparticle networks from normal lightning strikes on soil. *Nature, 403*, 519–21. https://doi.org/10.1038/35000525

Anonymous. (1930). Historic natural events. *Nature, 126*, 262. https://doi.org/10.1038/126262a0

Anonymous. (1994). Ball lightning formation. *Whitaker's Almanac*, 1994, 1184. J. Whitaker & Sons, London.

Arago, F. (1855). Meteorological essays. Longman, Brown, Green and Longmans.

Barry, J. D. (1968). Laboratory ball lightning. *Journal of Atmospheric and Terrestrial Physics, 30*, 313-317. https://doi.org/10.1016/0021-9169(68)90087-1

Barry, J. D. (1980). *Ball lightning and bead lightning*. Plenum Press, New York. https://doi.org/10.1007/978-1-4757-1710-5

Bartlett, V., & Turner, D. J. (in press). Vapour phase electrochemistry 3. Preparation of metastable nitrous acid. *Journal of Scientific Exploration*.

Bauer, H. (2003). Editorial. *Journal of Scientific Exploration, 17*, 387-388.

Bertholon, P. (1787). *De l'électricité des météores*. Bernuset.

Brand, W. (1971) *Ball lightning* (Translation, B. Benny, NASA TT F-13228) in *Problems in cosmic physics, Vol. II & III,* H.Grand, (original work published in German, 1923)

Browning, K. A., & Ludlam, F. H. (1962). Airflow in convective storms. *Quarterly Journal of the Royal Meteorological Society, 88*, 117-135. https://doi.org/10.1002/qj.49708837602

Browning, K. A., & Foote, G. B. (1976). Airflow and hail growth in supercell storms and some implications for hail suppression. *Quarterly Journal of the Royal Meteorological Society, 102*, 499-533. https://doi.org/10.1002/qj.49710243303

Carter, M., Robotham, F., Wise, K., Williams, G., & Crouch, P. (2006). Australian participants in British nuclear tests in Australia. *Vol 1: Dosimetry*. Department of Veterans' Affairs, Canberra. ISBN 1 920720 38 3.

Cavallo, T. (1782). *A complete treatise on electricity in theory and practice*. Dilly and Brown, London.

Chester, K. (2007). *Strange company: Military encounters with UFOs in WWII*. Anomalist Books.

Chase, M. W., Davies, C. A., Downey, J. R., Frurip, D. J., McDonald, R. A., & Syverud, A. N. (1985). JANAF thermochemical tables (3rd ed.). *Journal of Physical and Chemical Reference Data, 14* (Suppl. 1).

Chown, M. (1993). Fire and water: A recipe for ball lightning. *New Scientist, 137* (20 March), 18.

Collins, G. W., II. (1978). *The virial theorem in astrophysics*. Pachart Corp.

Corliss, W. R. (1977). *Handbook of unusual natural phenomena*. Sourcebook Project.

Corliss, W. R. (2001). *Remarkable luminous phenomena in nature*. Sourcebook Project.

Dessens, J., (1965). *Journal de Recherches Atmospheriques*, 2, 91-96.

Devereux, P. (1990). *Earth lights revelation*. Blandford Press.

Faraday, M. (1839). *Experimental researches in electricity (Vol. 1)*. Bernard Quaritch. https://doi.org/10.1098/

rstl.1839.0002

Finkelstein, D., & Powell, J. (1970). Earthquake lightning. *Nature, 228*, 759-760. https://doi.org/10.1038/228759a0

Flammarion, C. (1888). *L'Atmosphère*. Librairie Hachette.

Gasper, G. E. M., & Tanner, B. K. (2022). A marvellous sign and a fiery globe: A medieval English report of ball lightning. *Weather*. https://doi.org/10.1002/wea.4144

Gaydon, A. G., & Wolfhard, H. G. (1970). *Flames: Their structure, radiation, and temperature*. Chapman and Hall Ltd.

Gibbs, J. W. (1878). On the equilibrium of heterogeneous substances. *Transactions of the Connecticut Academy of Arts and Sciences, 3*, 108–248, 343–524.

Grigor'ev, A. I., Grigor'eva, I. D., & Shiryaeava, S. O. (1992). Ball lightning penetration into closed rooms: 43 eyewitness accounts. *Journal of Scientific Exploration, 6*, 261-279.

Haines, R. F. (1994). *Project Delta: A study of multiple UFO*. L. D. A. Press.

Handel, P. H., & Leitner, J-F. (1994). Development of the maser-caviton ball lightning theory. *Journal of Geophysical Research, 99*, 10,689-10,691.

Hartwig, G. (1892). *The aerial world* (p. 267). Longmans, Green and Co., London.

Hynek, J. A. (1972). *The UFO experience: A scientific inquiry*. Henry Regnery Co.

Kean, L. (2010). *UFOs, generals, pilots and government officials go on the record*. Three Rivers Press.

Keesee, R. G., & Castleman, A. W., Jr. (1986). Thermochemical data on gas-phase ion-molecule association and clustering reactions. *Journal of Physical and Chemical Reference Data, 15*, 1011-1071. https://doi.org/10.1063/1.555757

Kelvin, Lord. (1872). Atmospheric electricity. Royal Institution lecture, May 13. *Reprints of papers on electricity and magnetism* (pp. 226-228). Macmillan and Co., London.

Klass, P. J. (1968). *UFOs - Identified*. Random House.

Lee, J. K., Samanta, D., Nam, H. G., & Zare, R. N. (2019). Micrometer-sized water droplets induce spontaneous reduction. *Journal of the American Chemical Society, 141*, 10585-10589. https://doi.org/10.1021/jacs.9b03227

Mangolini, L., Thimsen, E., & Kortshagen, U. (2005). High-yield plasma synthesis of luminescent silicon nanocrystals. *Nano Letters, 5*, 655–659. https://doi.org/10.1021/nl050066y

Markowski, P. M. (2002). Hook echoes and rear flank downdrafts: A review. *Monthly Weather Review, 130*, 852-876.

Marquis, J., Richarson, Y., Markowski, P., Dowell, D., & Wurman, J. (2012). Tornado maintenance investigated with high-resolution Dual-Doppler and EnKF analysis. *Monthly Weather Review, 140*, 3-27. https://doi.org/10.1175/MWR-D-11-00025.1

Mason, B. J. (1971). *The physics of clouds* (2nd ed.). Clarendon Press.

Mattétal, M. (1895). Curiosités de la foudre. *Nature (Paris), 23*, 407.

Matthews, R. (1994). Great balls of fire theory explodes myth. *Sunday Telegraph*, June 12.

Meteorological Office. (1978). *A course in elementary meteorology*. H.M. Stationary Office, London.

Nelson, S. P. (1983). The influence of storm flow structure on hail growth. *Journal of the Atmospheric Sciences, 40*, 1965-1983. https://doi.org/10.1175/1520-0469(1983)040<1965:TIOSFS>2.0.CO;2

Pettigrew, J. D. (2003). The Min Min light and the Fata Morgana. *Clinical and Experimental Optometry, 86*, 109-120. https://doi.org/10.1111/j.1444-0938.2003.tb03069.x

Pippard, B. (1982). Ball of fire? *Nature, 298*, 702. https://doi.org/10.1038/298702b0

Powell, J. R., & Finkelstein, D. (1969). Structure of ball lightning. *Advances in Geophysics, 13*, 141-189. https://doi.org/10.1016/S0065-2687(08)60510-5

Priestley, J. (1781). Experiments and observations relating to various branches of natural philosophy with a concentration on the observations on the air (Vol. 2, pp. 379-383). J. Johnson, London, U.K.

Puckett, L. J., & Teague, M. W. (1971). Production of H3O+. nH2O from NO+ precursor in NO-H2O gas mixtures. *Journal of Chemical Physics, 54*, 2564-2572. https://doi.org/10.1063/1.1675213

Randles, J., & Hough, P. (1992). *Spontaneous human combustion*. Dorset Press.

Roberts, C. W. (1982). *Meteorology*. Thomas Reed Publications Ltd.

Sanduloviciu, M. (1991). On ball lightning phenomenology. In S. Kuhn, K. Schöpf, & R. Schrittwieser (Eds.), *Current research on fusion, laboratory, and astrophysical plasmas* (pp. 235-240). World Scientific, Hackensack, NJ.

Sanduloviciu, M. (1992). The ball lightning as a globular double layer resulting after a self-organization process. In R. W. Schrittwieser (Ed.), *Double layers and other nonlinear potential structures in plasmas* (pp. 268-272). World Scientific, Hackensack, NJ.

Sanduloviciu, M., & Lozneanu, E. (2000). Ball lightning as a self-organization phenomenon. *Journal of Geophysical Research, 105*, 4719-4727. https://doi.org/10.1029/

1999JD900987

Sankaran, R. M., Holunga, D., Flagan, R. C., & Giapis, K. P. (2005). Synthesis of blue luminescent Si nanoparticles using atmospheric-pressure microdischarges. *Nano Letters, 5*, 537–541. https://doi.org/10.1021/nl0480060

Singer, S. (1971). *The nature of ball lightning*. Plenum Press, New York. https://doi.org/10.1007/978-1-4684-1866-8

Singer, S. (2002). Ball lightning - the scientific effort. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 360*, 5-9. https://doi.org/10.1098/rsta.2001.0916

Smirnov, B. M. (1987). The properties and nature of ball lightning. *Physics Reports, 152*, 177–226. https://doi.org/10.1016/0370-1573(87)90142-6

Smirnov, B. M. (2000). Advances in ball lightning studies. *Journal of Meteorology UK, 25*, 308-318.

Smith, W. (1997). *On pilots and UFOs*. Unicat Project.

Snyder, J. C., Bluestein, H. B., Venkatesh, V., & Frasier, S. J. (2013). Observations of polarimetric signatures in supercells by an X-band mobile Doppler radar. *Monthly Weather Review, 141*, 3-29. https://doi.org/10.1175/MWR-D-12-00068.1

Stakhanov, I. P. (1979). *The physical nature of ball lightning* (in Russian). Atomizdat, Moscow. (English Translation: Central Electricity Generating Board Translation CE 8244).

Stenhoff, M. (1999). *Ball lightning: An unsolved problem in atmospheric physics*. Kluwer Academic/Plenum.

Strand, E. P. (1985). Project Hessdalen 1984 - Final technical report. Project Hessdalen Articles and Reports. http://hessdalen.hiof.no/reports/hpreport84.shtml

Strand, E. P. (2000). Project Hessdalen. Project Hessdalen Articles and Reports. http://hessdalen.hiof.no/reports/Hessdal-article2000.shtml

Sturrock, P. A. (Ed.). (1999). *The UFO enigma: A new review of the physical evidence*. Warner Books.

Teodorani, M. (2004). A long-term scientific survey of the Hessdalen phenomenon. *Journal of Scientific Exploration, 18*, 217-251.

Teodorani, M. (2011). Interview. http://www.unexplained-mysteries.com/column.php?id=200292

Teodorani, M. (2024). Investigating UAP events using astronomical techniques. *LiminaT, 1*, 40-54. https://doi.org/10.59661/001c.92684

Teodorani, M., & Strand, E. P. (1998). Experimental methods for studying the Hessdalen phenomenon in the light of the proposed theories: A comparative overview. ØIH Rapport, 1998(5), 1-93. Høgskolen I Østfold, Norway. https://doi.org/10.1039/f19888402683

Turner, D. J. (1983). Electrolyte solutions near the critical point of water: A review and proposal for studies under microgravity conditions. In *Proceedings of the Fourth European Symposium: Materials Sciences Under Microgravity* (ESA SP-191, pp. 393-400). European Space Agency, Paris.

Turner, D. J. (1988). Salt solutions in high pressure steam: Some preliminary studies on the influence of gravity. *Journal of the Chemical Society, Faraday Transactions 1, 84*, 2683-2695.

Turner, D. J. (1989). On the existence of iodide-borate complexes in saturated steam. In M. Pichal & O. Sifner (Eds.), *Proceedings of the Second Safety of Nuclear Installations (CSNI) Workshop on Iodine Chemistry in Reactor Safety* (pp. 135-150). AECL-9923/CSNI-149, Toronto, Canada.

Turner, D. J. (1990). Ions in steam. In M. Pichal & O. Sifner (Eds.), *Proceedings of the 11th International Conference on the Properties of Steam* (pp. 439-451). Hemisphere Publishing Corp., New York, N.Y.

Turner, D. J. (1994). The structure and stability of ball lightning. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 347*, 83-111. https://doi.org/10.1098/rsta.1994.0040

Turner, D. J. (1996a). Some characteristic properties of ball lightning. *Journal of Meteorology UK, 21*, 325-338.

Turner, D. J. (1996b). Reproducibility in the formation of lightning balls. *Journal of Meteorology UK, 21*, 397-399.

Turner, D. J. (1997a). The interaction of ball lightning with glass window panes. *Journal of Meteorology UK, 22*, 52-64.

Turner, D. J. (1997b). Ball lightning through window glass? *Journal of Meteorology UK, 22*, 219-221.

Turner, D. J. (1998a). Ball lightning and other meteorological phenomena. *Physics Reports, 293*, 1-60. https://doi.org/10.1016/S0370-1573(97)00043-4

Turner, D. J. (1998b). Ball lightning and window panes. *Journal of Meteorology UK, 23*, 236-238.

Turner, D. J. (2001). Explaining ball lightning. *Journal of Meteorology UK, 26*, 101-104.

Turner, D. J. (2002). The fragmented science of ball lightning. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 360*, 107-152. https://doi.org/10.1098/rsta.2001.0921

Turner, D. J. (2003). The missing science of ball lightning. *Journal of Scientific Exploration, 17*, 435-496.

Turner, D. J. (2023). Vapor phase electrochemistry 1: The missing science. *Journal of Scientific Exploration, 37*, 390-428. https://doi.org/10.31275/20232707

Turner, D. J. (in preparation). Vapor phase electrochemistry 4: Cylindrical air plasmas.

Vallee, J. (1965). *Anatomy of a phenomenon*. Henry Regnery.

Vallee, J. (1999). Estimates of optical power output for six cases of unexplained aerial objects. In P. A. Sturrock (Ed.), *The UFO enigma: A new review of the physical evidence* (pp. 216-233). Warner Books, New York.

Vonnegut, B. (1960). Electrical theory of tornadoes. *Journal of Geophysical Research, 65*, 203-212. https://doi.org/10.1029/JZ065i001p00203

Vonnegut, B., & Weyer, J. R. (1966). Luminous phenomena in nocturnal tornadoes. *Science, 153*, 1213-1220. https://doi.org/10.1126/science.153.3741.1213

Wagman, D. D., et al. (1982). The NBS tables of chemical thermodynamic properties. *Journal of Physical and Chemical Reference Data, 11* (Suppl. 2).

Wu, M-S., Liu, J-B., & Ronney, P. D. (1998). Numerical simulation of diluent effects on flame balls. In *Proceedings of the Twenty-Seventh Symposium (International) on Combustion* (pp. 2543-2550). Combustion Institute, Pittsburgh. https://doi.org/10.1016/S0082-0784(98)80106-9

Wu, M. S., Ronney, P. D., Colantonio, R., & VanZandt, D. (1999). Detailed numerical simulation of flame ball structure and dynamics. *Combustion and Flame, 116*, 387-397. https://doi.org/10.1016/S0010-2180(97)00356-8

Wurman, J., Straka, J. M., & Rasmussen, E. N. (1996). Fine-scale Doppler radar observations of tornadoes. *Science, 272*, 1774-1777. https://doi.org/10.1126/science.272.5269.1774

Zeidman, J. (1999). The Mansfield, Ohio case. In P. A. Sturrock (Ed.), *The UFO enigma: A new review of the physical evidence* (pp. 298-372). Warner Books.