

## RESEARCH ARTICLE

# Are Hessdalen Lights a Reality, an Illusion, or a Mix of the Two?

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**Abstract**—Hessdalen Lights (HLs in the following) are luminous, floating, more or less spherical atmospheric phenomena, with a lifetime of a few seconds to sometimes several minutes. These phenomena have been seen in the Hessdalen Valley in Norway for decades. Unfortunately, a full understanding of these baffling events is still lacking in spite of solid, working scientific projects intended to explain them. This paper tries to improve the situation. It raises the questions of where the energy for the creation of the HLs comes from, and what its nature is: (geo)chemical, electric, or other? We propose a new scenario for the Hessdalen lights. It exploits the recent idea of stable and traversable wormholes whose potential existence is beginning to be recognized in physics. Even though appearing highly speculative, this hypothesis has so far not been explored elsewhere, even though it possibly could supply a full description of the wholeness of the phenomenon. On the other side, even if the probability that an HL could indeed be a wormhole is maybe low, this question should not be dismissed out of hand. These theoretical considerations could help to increase knowledge and understanding of both HLs and wormholes. In this framework, we discuss the stability, energetics, and oversized dimensions of HLs. In physics, the final arbiter is not the theory but the experiment. Thus, some ‘simple’ experiments are suggested (high time-resolution photometry and magnetic field measurements). Eventually, if the process described is real, after mastering it there would be a free and inexhaustible source of energy, a tremendous breakthrough after which we could forget controlled nuclear fusion.

**Keywords:** Hessdalen Lights; wormholes

## INTRODUCTION

Hessdalen lights (HL) and related phenomena reported from other regions of the Earth (and also “big” ball lightning) are certainly a great challenge for the scientific community. Scientific studies of these events began with Project Hessdalen led by E. Strand in the summer of 1983 (<http://www.hessdalen.org>) followed by the EMBLA Project in 1998 (Teodorani, 2004, p. 217). Several explanations have been proposed, but unfortunately most of them are far from explaining the puzzling facts (energetics, sizes, erratic motions, velocities, etc). In spite of decades of intense interest and of the large datasets acquired during many observing campaigns by teams at the Hessdalen and Embla projects, no consensus has been established.

First, it seems unlikely that HLs are simple atmospheric phenomena, given that the sightings do not correlate with meteorological data. We know that ionized gas (nitrogen and oxygen are dominant, with a percentage of other elements such as Sc, Fe, etc.) is involved (Teodorani et al., 2001; Hauge, 2007).<sup>1</sup> However, simple flames issuing from combustible gas (methane, etc.) or burning dusts of metal (scandium, etc.) also are excluded because HLs are insensitive to wind and gravity (most of the time the entities are approximately spherical). On the other hand, theoretical models based on possible geophysical or electrochemical sources existing on the site (Hessdalen Valley) fail to answer important key questions.

The first of these questions is relative to the creation of HLs. At this level, we could appeal to another perplexing phenomenon which seems to be correlated to the HLs, that is, ball lightning (BL in the following). In this case, the process of creation is usually identified with electric discharges occurring in stormy weather. Unfortunately, HLs can appear in clear weather, and the obvious exploitable source of energy feeding the BLs (a lightning strike) is not available for HLs.

On the other hand, the energy densities associated with BLs are mild,<sup>2</sup>  $\sim 10\text{--}100\text{ Jm}^{-3}$  (Boerner, 2020), so “soft” models for BLs, within the framework of classical electrodynamics and/or chemistry, have also been invoked. They are based on chemical reactions (Fischer, 1981; Abrahamson & Dinnis, 2000), on electromagnetic radiation stored in a conducting shell (Endean, 1997; Engholm et al., 1990), or on light

trapped inside a shell of low-density air (Torchigin, 2019). Many authors have subsequently tried to stick the various electromagnetic and/or (geo) chemical models which were seemingly suitable for the BLs to the HLs. Therefore, some rather interesting models have been proposed. For instance, Paiva and Taft (2010) have suggested that HLs are formed by a cluster of macroscopic Coulomb crystals in a dusty plasma produced by the ionization of air and dust by alpha particles during radon decay in the atmosphere. On the other hand, Monari et al. (2013) have hypothesized that the valley's shape, microclimate, or unique geology might also act as a giant battery that powers the lights. However, the energies at stake are much higher (by a factor of 100–1000 for the energy density) than those supplied by ordinary (geo- and/or electro-) chemical reactions which are assumed to be present on the site. Therefore, to create a plasma ball a powerful source has to be found (even for a centimetric plasma ball as will be discussed below). What might be the nature of this source when ordinary chemical or electromagnetic processes are very likely not at its root? So what do we do when “simple” models based on the usual physics do not work? To answer this question, we need to inevitably enter into a world of new concepts supported by more exotic models. Thus it appears that the most recent physics should be involved to boost a domain whose study seems to be suspended today. Bear in mind that the primary goal of any researcher is to widen scientific information, even into unexplored areas.

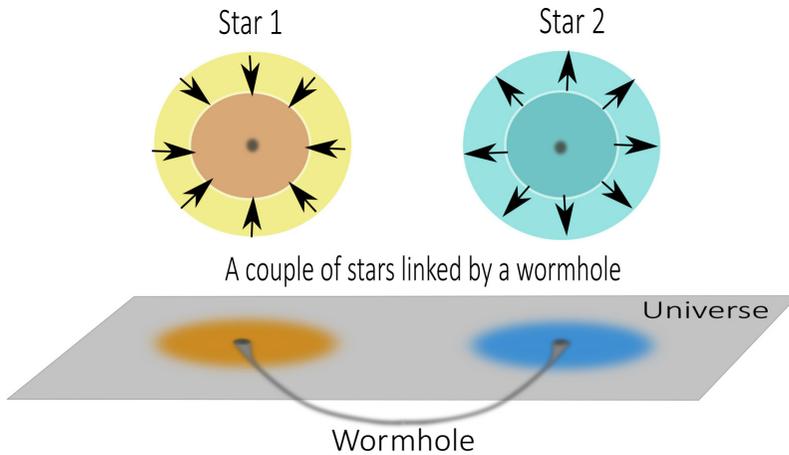
### THE WORMHOLE HYPOTHESIS

Black holes have been invoked for explaining BLs (Rabinowitz, 2001), but the trouble with this idea is that black holes would describe a rectilinear trajectory like a meteorite entering the atmosphere. HLs often exhibit a chaotic (or erratic) trajectory similar to Brownian motion and definitely not a rectilinear trajectory. What is the cause of this rather surprising motion, assuming that this is real? In any case, wormholes, the near relatives of black holes, seem to be better adapted for explaining this very intriguing characteristic. And if black holes have proved their existence, it is very likely that stable (and traversable) wormholes also exist. The value of wormholes in physics is attested to, starting with the seminal paper of Morris and Thorne (1988). In this remarkable paper these authors demonstrate that maybe stable

and traversable wormholes could be somewhat more than simple mathematical curiosities (Morris & Thorne, 1988 ; Morris et al., 1988). Stable and traversable wormholes have received increasing attention ever since as objects that could really exist in the real world; very possibly, at least, as cosmological relics created in the quantum stage, or during the inflationary period of the evolution of the Universe. These primordial wormholes may also initially have captured some magnetic lines of force (Kirillov & Savelova, 2020).

Understanding of the stable and traversable wormholes is in progress, but there remains a great amount of work to do. A good deal of time and effort must be devoted to working out how these strange entities might form, and what might keep them open.<sup>3</sup> Unfortunately, we do not yet possess a theory unifying General Relativity and Quantum Mechanics. Thus, the entire landscape of all the possible types of stable wormholes is largely unknown. Options are wide open and physicists are strongly divided on these questions. Despite this rather uncomfortable situation, the cosmologists have succeeded in proposing a natural (and well-admitted) origin for the wormholes. In its very early (quantum) stage, the Universe should have a foamlike topological structure. Its relics might well survive the cosmological expansion, thus creating a certain distribution of wormholes in the Universe (a kind of porous medium). Moreover, the inflationary stage (Starobinsky, 1980; Guth, 1981; Linde, 1982) should enormously stretch the characteristic scales, pushing the ends of these strange entities farther apart, and eventually making a web of “sleeping” wormholes of all sizes. A rich and complex mixture of silent wormholes could thus exist in the Universe (Kirillov & Savelova, 2011). These tunnels would still be minute in diameter, but the two ends (the mouths) could be millions of kilometers apart (with the only visible features in our three-dimensional space being these two mouths, which are seen as spheres). It is hard to predict how many wormholes there are; but if they follow a Maxwell-Boltzmann distribution (Kirillov & Savelova, 2011) the existence of a wormhole with a millimetric (or metric) throat must certainly be very rare. Moreover, that one of these sleeping wormholes intermittently links two stars, and remains locked in this situation for a short time, has to be an even rarer situation.

At the present time, in view of the difficulties encountered when



**Figure 1.** Schema of stars linked by a wormhole (from Dzhunushaliev et al., 2011).

carrying out the mathematics, only very simple solutions have been imagined. Thus, Dzhunushaliev et al. (2011) imagine that a wormhole (of a metric size) could link a couple of stars. In their model, two twin stars are shown and the wormhole (which can still be seen as an extradimensional channel) links the centers of these stars (Figure 1).<sup>4</sup> In addition, the wormhole instantaneously follows the orbital motion of the two stars. These very special conditions of symmetry are obviously chosen in order to make the problem easily tractable.

However, an extension of this mathematical work is needed, even though the analysis of a situation with a broken symmetry is very likely a hard task. If two stars can be connected by a wormhole as shown by these authors, is it possible to conjecture that a star (the Sun) and one of its planets (the Earth)—de facto a highly asymmetric problem—also are connected by a similar shortcut in space? And in this case what would be the observed phenomenon in the atmosphere of this planet? The question is speculative but it warrants consideration, especially if it makes it possible to advance further our understanding of wormholes. Let us imagine for a moment that HLs have something to do with wormholes.<sup>5</sup>

Before we go any further, two important questions still deserve to be asked:

1. Could a wormhole's mouth be locked in the Sun? In fact the

wormhole's mouth could be found anywhere in space. Most of the time the wormhole's mouth resides in the void, but in this case the other extremity is not fed and remains invisible, and nothing happens. In our scenario one must imagine that, at times (rare), one mouth of the wormhole has been entrapped by the Sun and remains locked in it for a period of time. It is obviously a working hypothesis, but this situation could be achieved following the calculations realized by Dzhunushaliev et al. (2011) about this topic.

2. Why would the second mouth appear "only" at Hessdalen and only intermittently? In fact it is true that Hessdalen is in the area of the world where anomalous light phenomena are found. The big conundrum is that hitherto no one has managed to correlate the phenomena with local meteorology and/or geology, even after forty years of observations! De facto the phenomenon does not seem to be especially linked to Hessdalen Valley. This could be a mere coincidence. Thus, similar events have also been described elsewhere. Apart from fakes, hoaxes, optical illusions, or misidentifications, most of the so-called Unidentified Aerial Phenomena (UAPs), which are recurrent in several places in the world, are possibly Hessdalen-like phenomena not recognized as such (Teodorani, 2014, table 1).

On the other hand are we entirely sure there is not another Hessdalen on the planet, for instance in the middle of the oceans (the majority of the Earth's surface is covered by oceans, or about 71% of the surface of the Earth), or in a vast desert area such as the Antarctic or the Sahara (cold and hot deserts actually make up  $\frac{1}{3}$  of the land's surface area), where there is no one to observe the phenomena? By contrast let us recall that only three percent of the world's land surface is covered with urban areas. Unfortunately in a city the light pollution and skyglow prevent the observation of Hessdalen-type lights (it is admitted that in the United States and Europe 99 percent of the people cannot experience a natural night!). Eventually owing to the air traffic above urbanized regions the Hessdalen phenomena would go completely unnoticed (most of the time a typical Hessdalen light is just an insignificant luminous point in the sky, with the legitimate question: Is it an airplane light or a "true" HL?).

There is moreover another answer to the second question (about the small area covered by the Hessdalen Valley where the phenomena

are seen). We can look at the study of volcanism on Earth, even if the proposed analogy cannot be taken at face value. Why would a small-volume hot spot volcano (as seen at Yellowstone for instance) appear at a well-located point at the Earth's surface and not a few hundreds of kilometers away, and why is this type of event only intermittently active? In addition geologists indeed estimate there are only about 40 to 50 hot spots around the world. The orthodox response suggested today is that a hot spot is the mouth of a mantle plume<sup>6</sup> which rises through the Earth's mantle and which is deeply anchored at the core–mantle boundary.

Likewise let us imagine that the space is a kind of topological porous medium (Kirillov & Turaev, 2007) as is hypothesized in our scenario, of which we distinguish only three spatial dimensions (the smooth surface of the porous medium). The wormhole could then percolate by accident toward a specific point, and for a finite moment, i.e., in the present situation at Hessdalen and not in the nearby valley (bearing in mind that a wormhole of submillimetric size in diameter is obviously much more specifically located than a hot spot volcano of more than 100 km in diameter). This “conduit” in the fabric of space can also temporally (or definitely) disappear, like the mantle plume in the hot spot in volcanism. Maybe there is nothing special at Hessdalen; by the way the events have significantly decreased in recent years, even though the meteorology and the geology of the place have remained unchanged (how can we explain this fact if the phenomenon is specifically related to the location?). It is likely that there will be nothing left to observe at Hessdalen in a few decades. Thus we can even suggest that the same phenomena will one day reappear elsewhere on the Earth's surface with a strong intensity (even though we cannot predict where and when this event will occur, just as we cannot predict the re-awakening of a volcano).

A practical analogy of HL with the so-called problem of the flexible pipe is quite interesting, even though they are different in many respects. The motion of a flexible pipe has been well-studied (Etlender et al., 2007; Xie et al., 2016). As far as we are concerned, with the wormhole problem both radiation and the magnetic field play the role performed by water in a pipe. On the other hand, we can proceed by analogy for the size of the mouth of the wormhole (whose possible cycle of closing and opening regulates for instance the mass or the

radiation flux between the two stars) versus the section thickness of the pipe (which regulates the water fluxes). Eventually we must compare a foreseeable erratic and rapid shifting in the extradimensional space for the wormhole versus the wall motion in the radial direction in real space for the pipe. All these descriptions deserve a deep analysis with the aim of transposing them to the wormhole world and maybe would lead to decades of complex mathematical studies. In spite of the fact that the theory of wormholes is not yet fully developed, the pictorial analogy made above will be useful in the following section.

We know at least that a wormhole has two extremities connected by a “throat.” Let us imagine that one extremity is located somewhere in the earth’s atmosphere, but where is its counterpart? The mouth of a wormhole is usually invisible (as a naked black hole without its accretion disk) unless the other extremity is immersed in a medium that produces a strong radiation field. The only object in the solar system that generates a large radiation field is the interior of the Sun. We can then imagine that the wormhole funnels the radiation field of an interior zone of the Sun from one of its extremities up to the other extremity placed in the earth’s atmosphere (and very possibly also along magnetic field lines) (Figure 2). This suggestion is thus closely based on the model of Dzhunushaliev et al. (2011) where two twin stars are linked together, but with the difference that we suppose that the wormhole is traversable only by radiation and magnetic fields and definitely not through solar matter.<sup>7</sup> Thus an unsuspected connection, other than gravitational or magnetic, would exist between the Sun and the Earth. Even though this connection appears *prima facie* like a remote possibility today, it might reflect reality in the future. Astrophysicists are searching wormholes, far away at the galactic center (Dai & Stojkovic, 2019), whereas these entities may be far closer to home than we think.

To begin with, a first issue arises: What could the diameter of the throat of a wormhole connecting two stars be? Unfortunately, Dzhunushaliev et al. (2011) did not address this important question in their theoretical paper. Likewise what could be the diameter of the throat of a wormhole connecting a star of the solar type and a (telluric) planet? It turns out that HLs studies (see the text that follows) could eventually give an estimate of this diameter, of the order of 0.1 mm for a star–planet wormhole.

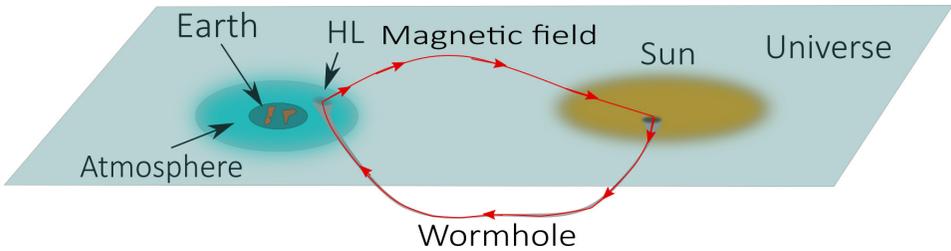


Figure 2. Schema of a wormhole between Earth and the Sun.

On the other hand the mean temperature in the Sun is of the order of  $10^5$  K,<sup>8</sup> and we shall take this value as the “surface” temperature of the (spherical) wormhole’s mouth in the earth’s atmosphere. We can now compare the mouth of the wormhole to a submillimetric star in the earth’s atmosphere. The remarkable idea of comparing an HL to a very small star has been suggested by Teodorani (2014). Note that once the power of an HL (100 kW) and the temperature of the source ( $10^5$  K) are fixed, the radius of the mouth of the wormhole is no longer a free parameter of the model but is automatically fixed by the Stefan–Boltzmann law. In order to avoid any ambiguity we must also specify that the very hot gas surrounding the wormhole cannot be detected by the observer (no more than the wormhole itself which is submillimetric in size). This region which emits a hard UV spectrum is constantly hidden from view by a surrounding shell of dense gas as we shall see below.<sup>9</sup> This shell is optically thick, and radiates in the visible range at temperatures in the continuous range from 5000 to 300 K. The few spectra that we can analyze<sup>10</sup> show features that are a recombination of line spectra of nitrogen and other species (atomic and molecular) directly produced in this shell.

## THE PHOTOIONIZATION MODEL FOR THE HLS

In this part the hypothesis “wormhole” is not essential, a point source of the order of 100 kW is sufficient.<sup>11</sup> The theory of photoionization in gaseous nebulae is indeed well-developed today (see Morisset, 2016, for instance). However a basic statement is sufficient for our purpose here. Also we refer only to seminal papers on this

important topic. On the other hand we have taken a medium composed of pure dinitrogen (by far, dinitrogen is the most abundant gas in the Earth's atmosphere, accounting for about 78.1% by volume of dry air), but the introduction of other gas (dioxygen) would not change the main conclusions of the paper. The recombination lines of nitrogen are prominent in the spectra of HLs (Hauge, 2007). In the following, the species  $N_2$ ,  $N_2^+$ ,  $N$ ,  $N^+$ , and  $N^{++}$  are indexed 1, 2, 3, 4, 5, respectively.

### **The Equations**

The problem has seven variables: The species density  $n_{N^{++}}$ ,  $n_{N^+}$ ,  $n_N$ ,  $n_{N_2^+}$ ,  $n_{N_2}$  ( $m^{-3}$ ), the electronic density  $n_e$  ( $m^{-3}$ ), and the temperature  $T_e$  (K), and seven equations are needed:

- **The neutrality of charge in each volume unit (a plasma is globally neutral)**

$$2n_{N^{++}} + n_{N^+} + n_{N_2^+} = n_e \quad (1)$$

- **The gas equilibrium equation**

The Euler equation for a static spherical ball of gas is

$$-\frac{\partial P}{\partial r} - \frac{GM\rho}{r^2} = 0 \quad (2)$$

where  $P$  is the gas pressure,<sup>12</sup>  $\rho$  is the mass density,  $r$  the radius measured starting from the point source (the mouth's wormhole which is assumed to be here a quasipoint source of energy),  $G$  the gravitational constant, and  $M$  the apparent gravitational mass of the wormhole.

First we begin by the estimation of the pressure gradient in the plasma ball, for a ball filled with plasma with a temperature of at least 2000 K (the minimum threshold for the temperature in a plasma). Taking the particle density in the atmosphere  $n_{atm} \sim 2.5 \cdot 10^{25} m^{-3}$  and a mean mass for the molecules  $\sim 4.8 \cdot 10^{-26} kg$  (dinitrogen or dioxygen), we find numerically for the gradient (with a radius for the plasma ball of the order of 1 m),  $\left| \frac{\partial P}{\partial r} \right| \sim 7 \cdot 10^5 Nm^{-3}$ . Eventually we find for the cor-

responding acceleration field  $g = \frac{GM}{r^2} \sim 6 \cdot 10^5 \text{ m s}^{-2}$ . It is a fully unrealistic value indeed ( $6 \cdot 10^4$  times the acceleration gravity at the surface of the Earth!). The gravitation being a long-range force, the influence of this gravitational field on the environment would be detected at a very large scale. This is obviously not the case. We deduce from this result that the gravity of the star–planet wormhole is necessarily low (contrarily to a black hole, the mouth of a wormhole can appear gravitationally neutral—a kind of massless or sleeping entity).<sup>13</sup> More generally no long-range force, gravitational or electrostatic, can contribute to the stability of a plasma ball such as an HL.<sup>14</sup> The appropriate solution is then

$$\frac{\partial P}{\partial r} \sim 0 \quad (3)$$

and eventually we obtain the pressure equilibrium

$$(n_e + n_{N^{++}} + n_{N^+} + n_N + n_{N_2^+} + n_{N_2})kT_e = n_{N_2atm}kT_{atm} \quad (4)$$

with  $n_{N_2atm} = 2.7 \cdot 10^{25} \text{ m}^{-3}$  and  $T_{atm} = 298 \text{ K}$ . The cohesion of the plasma ball (approximately spherical) is ensured by the ionizing point source.

### — The photoionization-recombination equilibrium equations

$$n_i \int_{\nu_i}^{\infty} d\nu \frac{4\pi J_\nu}{h\nu} \sigma_{1,\nu}(i) = n_e n_{i+1} \alpha(i) \quad (5)$$

where  $J_\nu$  is the mean specific intensity of the radiation field detailed below ( $\frac{4\pi J_\nu}{h\nu}$  supplies the number of photons per unit area per unit time per unit frequency) and  $\sigma_{1,\nu}(i)$  is the photoionization cross section from the fundamental level for the species  $i$  ( $\nu_i$  is the threshold frequency). The total recombination rate coefficients for the transition  $i+1 \rightarrow i$ ,  $\alpha(i)$ , are given by the fitted expression

$$\alpha(i) = 10^{-19} z \frac{at^b}{1 + ct^d} m^3 s^{-1} \tag{6}$$

where the coefficients  $a, b, c, d$  are from table 1 of the paper by P equignot et al. (1991) ( $z$  is the ionic charge,  $z = 1$  for the neutrals), and the normalized temperature  $t = 10^{-4} \frac{T}{Z^2}$ . The molecular recombination coefficients  $\alpha_D(i)$  are taken from Tamadate et al. (2020).

For the photoionization cross sections of the atomic N and its ions, we have chosen a well-known simple law for the species  $i$ , i.e.,

$$\sigma_{1,\nu}(i) = 10^{-22} \left[ \alpha \left( \frac{\nu_i}{\nu} \right)^s + (1 - \alpha) \left( \frac{\nu_i}{\nu} \right)^{s+1} \right] m^2 \tag{7}$$

where  $\alpha$  and  $s$  are coefficients which are supplied in the paper by Henry (1970) and  $\nu_i$  are the threshold wavelengths tabulated in Table 1 in this paper. For the molecular nitrogen  $N_2$ , we have fitted published tabulated values using the downloading link <https://home.strw.leidenuniv.nl/~ewine/photo>. A counterpart curve has been used for the corresponding monocation

The mean specific intensity of the radiation field (Williams, 1968) is

**TABLE 1**  
**Threshold Wavelengths**

Reactions	Energies (eV)	Threshold frequencies (Hz)	Wavelengths (nm)
$N_2 \rightarrow N + N$	9.8	$2.4 \cdot 10^{15}$	$\nu_{D1} = 125$
$N_2^+ \rightarrow N + N^+$	9.8	$2.4 \cdot 10^{15}$	$\nu_{D2} = 125$
$N_2 \rightarrow N_2^+ + e^-$	15.5	$3.8 \cdot 10^{15}$	$\nu_1 = 79$
$N \rightarrow N^+ + e^-$	14.5	$3.5 \cdot 10^{15}$	$\nu_3 = 86$
$N^+ \rightarrow N^{++} + e^-$	29.6	$7.1 \cdot 10^{15}$	$\nu_4 = 43$

$$\begin{aligned}
J_\nu = & \frac{R_s^2}{4r^2} l_\nu \exp(-\tau_\nu) + \frac{(n_3)^2}{n_1} \frac{2h^4}{(2\pi mkT_e)^{\frac{3}{2}}} \frac{v^3}{c^2} \exp\left[\frac{h(v_{D1} - \nu)}{kT_e}\right] + \\
& \frac{n_3 n_4}{n_2} \frac{2h^4}{(2\pi mkT_e)^{\frac{3}{2}}} \frac{v^3}{c^2} \exp\left[\frac{h(v_{D2} - \nu)}{kT_e}\right] + n_e \frac{n_2}{n_1} \frac{2h^4}{(2\pi mkT_e)^{\frac{3}{2}}} \frac{v^3}{c^2} \exp\left[\frac{h(v_1 - \nu)}{kT_e}\right] + \\
& + \sum_{i=3}^4 n_e \frac{n_{i+1}}{n_i} \frac{2h^4}{(2\pi mkT_e)^{\frac{3}{2}}} \frac{v^3}{c^2} \exp\left[\frac{h(v_i - \nu)}{kT_e}\right] \quad (8)
\end{aligned}$$

where the intensity of the source (i.e., the mouth of the wormhole assimilated to a black body) is

$$l_\nu = \frac{2h \frac{v^3}{c^2}}{\exp\left[\frac{h\nu}{kT_{WH}}\right] - 1} \quad (9)$$

The optical depth is given by

$$\begin{aligned}
\tau_\nu(r) = & \int_{r_{WH}}^r dr' [n_1 \sigma_{D1,\nu}(1) + n_2 \sigma_{D1,\nu}(2) \\
& + n_1 \sigma_{1,\nu}(1) + n_2 \sigma_{1,\nu}(2) + n_3 \sigma_{1,\nu}(3) + n_4 \sigma_{1,\nu}(4)] \quad (10)
\end{aligned}$$

### — The temperature equation

$$\begin{aligned}
& kT_e [(n_3)^2 \alpha_D(1) + n_3 n_4 \alpha_D(2) + n_e n_2 \alpha(1) + n_e n_4 \alpha(3) + n_e n_5 \alpha(4)] \\
& = n_1 \int_{\nu_{D1}}^{\infty} d\nu \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_{D1}) \sigma_{D1,\nu}(1) + n_2 \int_{\nu_{D2}}^{\infty} d\nu \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_{D2}) \sigma_{D1,\nu}(2) \\
& + n_1 \int_{\nu_1}^{\infty} d\nu \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_1) \sigma_{1,\nu}(1) + n_2 \int_{\nu_2}^{\infty} d\nu \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_2) \sigma_{1,\nu}(2) \\
& + n_3 \int_{\nu_3}^{\infty} d\nu \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_3) \sigma_{1,\nu}(3) + n_4 \int_{\nu_4}^{\infty} d\nu \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_4) \sigma_{1,\nu}(4) \quad (11)
\end{aligned}$$

**The Results**

The equation system considered above has been normalized and solved by an iterative method at each point of radius  $r$ . MATLAB numerical computing was used throughout the calculations. The results are displayed in Figure 3.

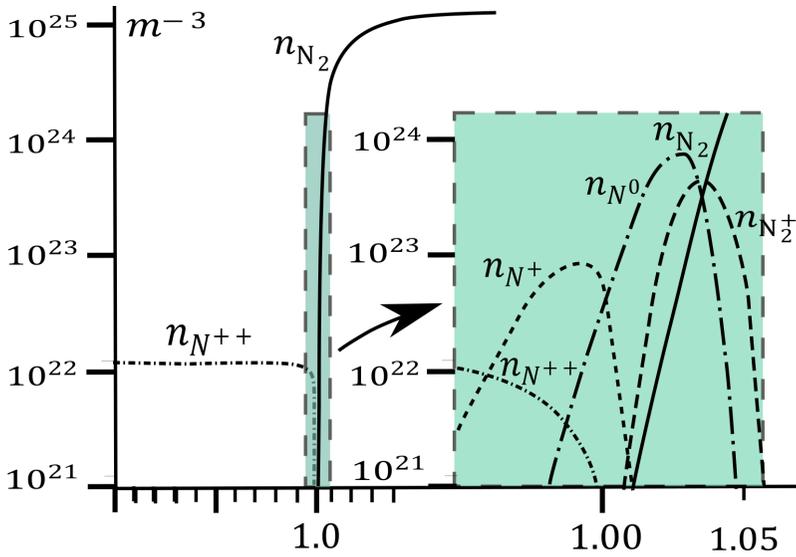


Figure 3. Results of the equations using Matlab.

We can see that HLs are described in the present context by a small quasi hollow ball filled with plasma at a low density (the unit on the abscissa is of the order of 1 cm). In the transition region (thickness < or ~ a millimeter) the density increases by three orders of magnitude and the temperature rapidly drops from  $10^5$  K to 298 K. The surrounding thin shell is optically thick and radiates as a black body in the visible range (with a quasicontinuous spectrum in the recombination lines by giving HL the appearance of an opaque disk). The energy contained in this hot plasma ball is

$$\frac{4\pi}{3}R_{N^{++}}^3(n_{N^{++}} + n_e)(kT_e) \sim 0.5J$$

This seems to be a relatively low energy, which would instantaneously dissipate within  $\sim 10^{-5}$  s without the input of energy from the wormhole (power 100 kW). This energy can increase the temperature of one kilogram of water by only  $10^{-4}$  °C. There is no risk for the observer even at a short distance (nobody has been injured in Hessdalen Valley by an HL, or at least no claim has been made). Nevertheless the energy density which is associated is rather high, of the order of  $500 \text{ kJ m}^{-3}$ . By comparison, let us note, however, that the energy density usually attributed to an “ordinary” (and not exceptional) ball lightning and produced by an electric discharge (for instance a strong lightning impact in stormy weather) is much weaker and of the order of  $10\text{--}100 \text{ Jm}^{-3}$  (Stenhoff, 1999). An HL cannot be generated by a weak electric source (such as a natural battery as proposed by Monari et al., 2013) and lightning strikes are excluded. Other chemical sources are dubious. Another more energetic source must be found, as suggested here.

However, and contrary to expectation, even with a continuous input of energy of 100 kW, the plasma ball is found to be very small given that its radius is of the order of one centimeter! Let us note that this result is independent of the ionizing nature of the point source (a wormhole, a black hole, or any other “exotic” particle). Only the power of the source matters and it is approximately fixed by the observation. A checking by a direct calculation of the radius of the Strömgren sphere, for the reaction  $N^+ \leftrightarrow N^{++} + e^-$ ,  $\nu_{N^+} = 7.1 \cdot 10^{15} \text{ Hz}$  leads much more rapidly to a similar conclusion.

The number of ionizing photons (for the considered reaction) emitted from the mouth of the wormhole is

$$N_{ph} = 4\pi R_{WH}^2 \int_{\nu_{N^+}}^{\infty} dv \frac{l_v}{h\nu} \quad (13)$$

or numerically  $N_{ph} = 1.3 \cdot 10^{22} \rho h s^{-1}$

The electronic density is given by  $(N_2 \rightarrow 2N^{++} + 4e^- \Rightarrow n_{N^{++}} = \frac{n_e}{2})$

$$n_{N^{++}} + n_e = \frac{3}{2} n_e = \frac{n_{atm} T_{atm}}{T_{WH}} \quad (14)$$

let, with  $n_{atm} = 2.7 \cdot 10^{25} m^{-3}$ ,  $n_e \approx 5.4 \cdot 10^{22} m^{-3}$

The Strömngren radius is given by (cf for instance Osterbrock & Ferland, 2005)

$$R_s = \left( \frac{3N_{ph}}{4\pi\alpha_{N^+}n_e^2} \right)^{\frac{1}{3}} \quad (15)$$

Inside the Strömngren sphere the simulations give  $T_e \approx T_{WH}$ . From Equation (1) we find thus  $\alpha_{N^+} \approx 3 \cdot 10^{-19} m^3 s^{-1}$ . Eventually we obtain again

$$R_s \sim 1 \text{ cm}$$

Again we find a diameter of the order of a few centimeters (smaller than a tennis ball).<sup>1</sup> Nevertheless it is a rather deceptive result given that HLs are generally described as much bigger with a diameter of the order of one meter. Obviously, here the energetics is not a pitfall for a star–planet wormhole as it could be with an ordinary chemical source, and wormholes with a “bigger” diameter, for instance of the order of 1 mm, easily could supply a very high power of 10 MW (for a same temperature of  $10^5$  K), but even with such an impressive (but not observed) power, the radius of the HL would be no greater than 5 cm. It appears at last very difficult to fully ionize a cubemeter of air!<sup>15</sup> So is an HL with a diameter of the order of one meter a reality, or an illusion produced by the brain of the observer seeing a bright point light source (with diffraction artifacts that spread the image of a point source on the retina)?

### ***Does a Skyglow Surround the Small Plasma Ball?***

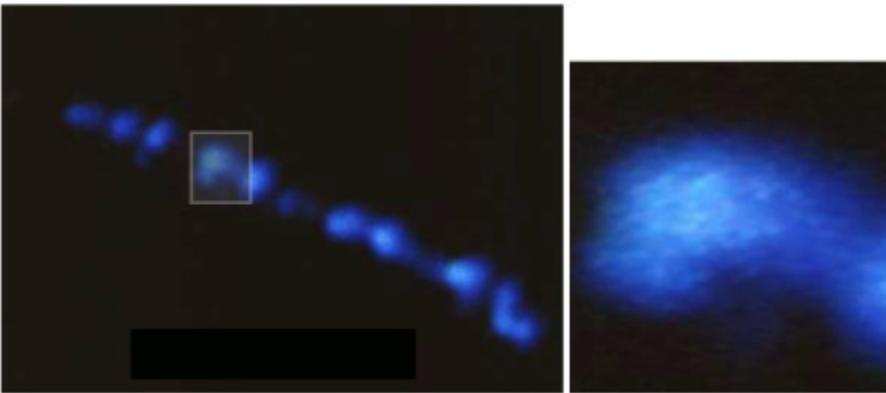
A prosaic scenario could however be supplied to explain the “big” size of HLs. It is well-known that soil dust aerosol is higher under cold climate conditions (as prevailing across Hessdalen Valley during the winter season, a period where the HLs are seen to be more numerous) as a consequence of dry air and weakened precipitations (Petit et al., 1999). Let’s assume a complex mixture of hybrid mineral aerosols is present in the atmosphere of Hessdalen Valley. In order to estimate the

extension of the diffusion zone produced by these aerosols illuminated by the plasma ball, the aerosol optical depth, which is a measure of the amount of light that aerosols scatter and absorb in the atmosphere, must be known. Complex organic aerosols constitute a large portion of these particles (Bzdek et al., 2014),<sup>16</sup> but here we will take spherical microclusters made of pure silicon associated with soil dust.

We can estimate the dust concentration to be of the order of  $1 \mu\text{g m}^{-3}$  in the atmosphere of Hessdalen (the mean dust concentration in the Arctic). Let particles have a mean radius  $r$ . The mass and the radius of a silicon atom are respectively  $4.7 \cdot 10^{-26} \text{ kg}$ ,  $1.11 \cdot 10^{-10} \text{ m}$ . This gives for the particle density (with particles of micrometric size),  $3 \cdot 10^{-14} r^3 \text{ (m}^{-3}\text{)}$ . With an extinction cross section<sup>17</sup> in the visible range  $\sim 2 \times \pi r^2$ , we find for the extension of the diffusion zone surrounding the plasma ball  $\sim 5 \cdot 10^{12} r \text{ (m)}$ . We note that regardless of the size of the particle (micrometric or submicrometric) the medium surrounding the plasma ball is optically thin and therefore no diffuse glow of a metric size is created.<sup>18</sup>

### *The Possibility of a Mixed Explanation*

A closer look at an HL photograph (Figure 4), however, shows a rather inhomogeneous and patchy surface and definitely not a perfect small disk with a sharp circular boundary as often falsely related.



**Figure 4.** Imprint of the wavering trajectory of the HL (taken from the Hessdalen Project, E. Strand). Magnified enlargement on the right side.

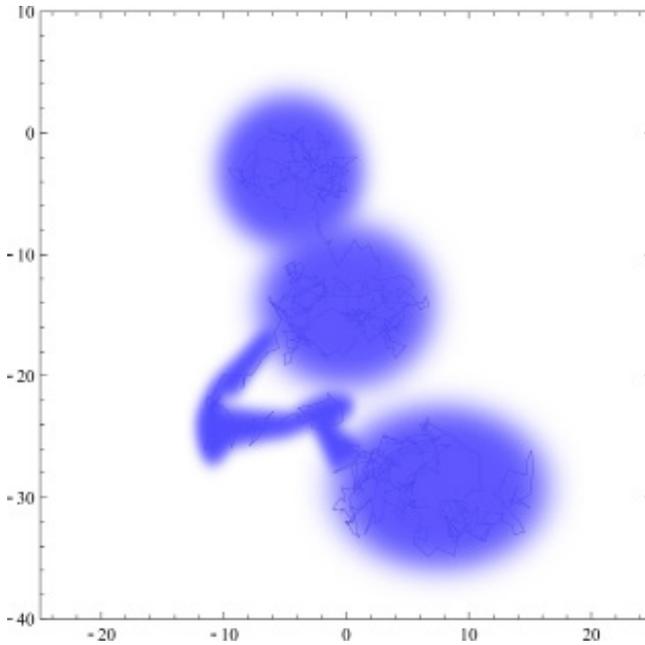
On the contrary, well-individualized grains appear on this photograph and at some moment the “global” ball splits into several small pieces. The HL brightness strongly fluctuates and can even disappear and then a moment later suddenly reappear. This oscillation between appearance and extinction is difficult to explain, invoking for instance a chemical source or a point electric discharge for the HLs. What energy source can produce such strange phenomena?

Maybe a mixing of a real event (visualized by the small grains on the photograph) combined with an optical illusion (i.e., the extended disk) is a way to solve the problem. From the various and enigmatic reports of eyewitnesses, skeptics of HLs (or more generally BLs) often deduce that they are afterimages on the retina due to exposure of the intense flash of light from linear lighting. We know that lightning balls as an optical illusion often have been invoked in the literature (Argyle, 1970; Berger, 1973; Peer et al., 2010; but see also for critics, Bäckér et al., 2007). However, it seems that at least a part of the phenomenon has a physical reality. It is well-known that after seeing a bright light, a persistent afterimage remains in the visual field for several minutes. Sometimes this afterimage is even complex (Taya & Ohinata, 2002) and the effect also similarly affects cameras. More precisely the persistence or recurrence of an image after the stimulus (the physical phenomenon) has been removed can produce on the retina or on a photograph the impression of an extended, diffuse, or granular picture instead of a unique, small, and sharp one.

We continue our investigation by now presenting more specifically two likely scenarios, labeled A and B, even though other possibilities arguably exist.

**Scenario A. A wormhole subject to a very fast Brownian motion on the spot + a “slow” drift?** This is the context in which the wormhole hypothesis appears most useful. We can imagine that the mouth of the wormhole fluctuates in diameter, alternating between a “large opening” (~.1 mm) and closing.<sup>19</sup> The erratic appearance of this mouth in a spatial zone of ~1 m, approximately spherical in shape (Figure 5), can thus give the subjective impression of an extended luminous surface (taking into account the afterimage perception and the light trail, it is well-known that light trails create a sense of speed and energy in the images).

This effect can also easily explain the intriguing fact related by



**Figure 5.** An example of a typical Brownian motion of a quasipoint light source. The resolution imaging device (eye or camera), if low, can strongly blur the trajectory of the primary tiny source.

witnesses: In some cases the HLs have also been perceived as suddenly animated with very rapid velocities, larger than the sound celerity in the air without sonic bang (Strand, 1990). This immediate description is obviously weird in view of the physics. Yet here the explanation is rather simple. When the mouth of the wormhole appears at one place it ionizes its immediate environment to form a plasma ball (more than one centimeter), then this ball collapses and then again reappears elsewhere leaving the illusory percepts of a continuous motion of a well-individualized small plasma ball, even though it is not the same piece of gas which is ionized each time (let us note in support of this claim that the luminous ball seen in Figure 4 appears to be a compact agglomerate of seemingly individualized patches of gas, but having approximately the same size, and this gives the impression that the “primary” HL draws a wavy “S” on the sky background). This is the so-called phi phenomenon which is an illusion of motion that arises when stationary objects (lightbulbs, for instance) are placed side by side and

switched on rapidly one after another (Wertheimer, 1912; Kohler et al., 2008; Steinman et al., 2000). In reality, here the plasma ball is not at all subjected to a superfast translational displacement from one point to another one in space, given that the air is ionized on the spot (but submitted to a succession of cycles, each of them being composed of a rapid expansion of a hot ionized gas,  $\sim 10^{-5}$  s, a stability phase of a few seconds to a few minutes (the primary HL itself), and then a “slow” contraction of a recombined cold gas,  $\sim 3 \cdot 10^{-4}$  s). Thus the plasma gas forming the ball at a given moment does not move in a translational way and this is very likely why no sonic bang is associated with the phenomenon.<sup>20</sup>

As shown in Figure 4, on the magnified view (right side), we distinctly guess the fuzzy imprint of the wavering trajectory (which overlaps itself, but a straight track composed of small well-individualized patches, ending at each extremity with a sudden change of direction that is clearly visible) of the “primary” HL (i.e., the small plasma ball surrounding the wormhole’s mouth and instantaneously produced by ionization). The corresponding path is drawn superimposed on the “global” phenomena (registered by a low-time resolution camera or the eye) in Figure 6. A high time resolution imaging camera system with submicrosecond timing accuracy and very low remanence level should ensure easy confirmation (or refutation) of this statement. On the other hand a time-dependent model also remains to be created to theoretically establish this idea.

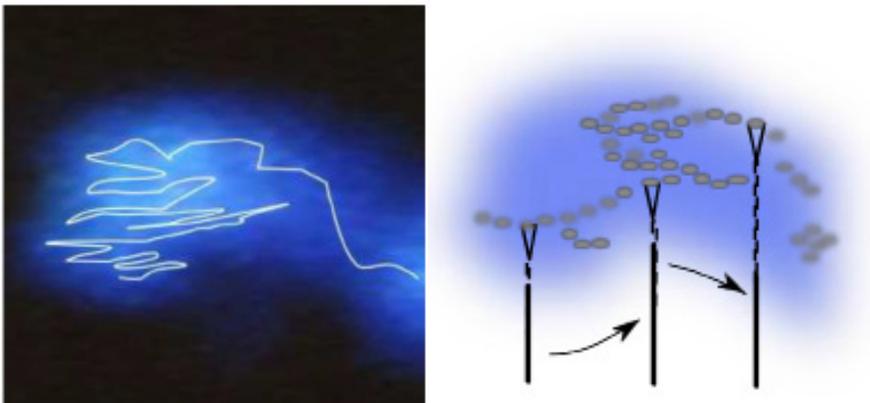


Figure 6. Path of the trajectory from Figure 4 superimposed on the global phenomena.

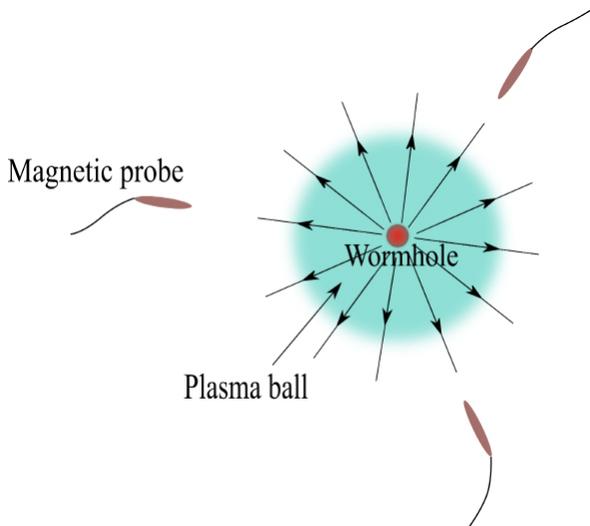
**Scenario B. A wormhole with multiple heads?** Another daring hypothesis would be that the mouth of the wormhole splits into a multitude of very small heads<sup>21</sup> (producing a structure that can be pictured as a kind of “swarm of bees”), for the same total power of ~10–100 kW. The attractive interaction between these heads should naturally produce an extended cohesive spherical ball. This scenario is very different from scenario A where just one head with high-speed motion is present. The resulting effect would then be a metric or decametric in size plasma ball, appearing with a grainy texture, as seen in Figure 4 (enlargement on the right side). The great interest of this second scenario is that the ball could now be divided into two or three components during the interaction, and the result would be a geometric structure, i.e., respectively, a dumbbell or retaining a triangular shape (as in the impressive figure 5c in Teodorani, 2004).

Unfortunately this very interesting possibility has not been examined in the literature on wormholes and it is difficult to say whether it is logically defensible (even though there exists no counterargument against it). But precisely because of this statement we can suggest that the study of HL phenomena is helping to advance knowledge of wormhole physics and vice-versa. Again, capturing an HL phenomenon with a ultra-high-speed camera is highly desirable in order to see how the ball can divide into several parts from one initial unit.

### ***The Magnetic Field***

With an assumed magnetic field of the order of  $10^{-1}$  tesla<sup>22</sup> taken at the mouth of the wormhole, and assuming a decrease as  $r^{-2}$  for a monopolar field in the ball,<sup>23</sup> we obtain  $10^{-9}$  tesla at one meter from the HL. This value is very low (compared to the earth magnetic field  $\sim 5 \cdot 10^{-5}$  tesla). At 10 m this value falls to 10 picotesla, but this is still above the accuracy of the ultrasensitive magnetic sensors,  $\sim 1$  picotesla (Abel et al., 2019).<sup>24</sup> A protocol for measuring the field configuration is sketched in Figure 7. Even though this operation will not particularly be easy to achieve, this would enable us to conclude the presence of a monopolar field<sup>25</sup> and therefore the likely existence of a wormhole at the center of the HLs.

The intensities that are supplied above are, however, minimal but



**Figure 7.** Positioning of three magnetic sensors to measure the magnetic field configuration at the mouth of a wormhole.

could be much higher (cf Note 24). On the other hand, in addition the positioning of the three magnetic sensors as shown in Figure 7 naturally leads to a triangulation of the HL. This crucial experiment could thus contribute to the accurate determination of both the position (its size) and the luminosity of an HL, two key parameters in the understanding of the phenomenon; even though trapping any elusive thing such as an HL between three sensors represents a great challenge. Unfortunately, we must admit that as long as we have not realized this type of experiment, the full understanding of HLs will remain out of range.

## THE CREATION OF A WORMHOLE

Following the scenario described here, to create an HL or a big BL, a wormhole is appealing. However what process could build up a wormhole? The problem seems to have been moved from one area to another and ultimately left unsolved.

Brushing aside this question, we could even say that wormholes have existed since the time of the big bang where these entities were created by quantum fluctuations and then considerably expanded to millimetric or metric size during the inflationary phase. Thus worm-

holes might have been prefabricated by nature at the very beginning of the Universe (Cramer, 2016). Unseen since the dawn of time, these sleeping wormholes are patiently awaiting matter or energy coming into close proximity, to reveal their fantastic nature.

Unfortunately, from an experimental point of view, the situation appears much more complicated with regard to the fact that an “immeasurable energy” seems needed to build a wormhole from nothing. However, the latter question is ill-posed and this requirement of an “immeasurable energy” is possibly a false appearance. A stable wormhole may be easier to create from “nothing” (more exactly not from nothing but in fact from the fabric of space–time) than we usually believe. The goal is asking the right question: What energy is required for burning down a gigantic forest of hundred-year-old oaks? Is the answer a very huge energy? No, just the energy contained in a match (a very small activation energy indeed). Most reckless people are unaware of this simple fact. Maybe the universe is actually full of stable topological defects and is similar to a porous Swiss cheese of which we see only the smooth surface.

In the special case of HLs a strong magnetic disturbance or a magnetically collimated particle flux sourced from the Sun and reaching the polar terrestrial regions (Hessdalen is located in a Nordic high-latitude region) is maybe this small match that triggers a hidden machine in the fabric of space–time producing a longitudinal rip between the Sun and the Earth. Subsequently an extradimensional submillimetric channel (a wormhole) could open up between the Sun and the Earth for a few seconds or even minutes.

Another point still deserves special attention. Let us imagine for a moment that a technology could be derived from this scenario (simply retrieving a primordial stable wormhole and domesticating it—after all, man did not create atoms but has learned how to use them to extract hidden nuclear energy). The exploitation of a centimetric star–planet wormhole located at the center of a simple spherical shell of water of a few meters in size located on this planet could supply a power of 100 MW to its inhabitants (the power of a small nuclear reactor but without radioactive wastes). Will future generations be able to master this revolutionary technology, much more simply than the long-overdue controlled nuclear fusion?

## CONCLUSION

This paper has been devoted to an understanding of Hessdalen lights and “big” ball lightnings a few decimeters or meters in size. If it is well-known that the Earth and the Sun interact through gravity and magnetic fields in usual space, we have shown that it could well be that they also interact in another more subtle extradimensional way. This bold remark could eventually constitute the first expected evidence that stable submillimetric wormholes exist in the universe and furthermore close to home. We end by emphasizing that we are aware that this idea is highly speculative. However, it is located at the crossroads of several topics, such as plasma physics, magnetohydrodynamics, and wormhole theory (the latter still in its infancy). This is a remarkable field for investigation, even if a good deal of work remains to be done to specify exactly the nature and behavior of a star–planet wormhole.

## NOTES

- <sup>1</sup> Let us notice, however, that the spectrochemical analysis and line interpretation are unfortunately questionable in these works, due to a too-low-resolution spectrum and a very low signal-to-noise ratio. Even though very important, these works are just a first step. We know that an accurate identification of the chemical elements is strongly dependent on the spectral resolution level. A high spectral resolution would be highly desirable, although we feel that this type of experiment, realized on transient moving sources, is indeed a huge challenge. Some suitable devices do exist and could be tested. For instance, a slitless echellelike (multiorder) wide field spectograph is able to allow a resolution of the order of  $\frac{\lambda}{\Delta\lambda} = 10^3 - 10^4$  which is at least a factor 10–100 times higher than the spectral resolution typically obtained using a simple transmission grating (see for instance the patent: <https://patents.google.com/patent/US8749781>). The wide field of this kind of disperser allows one to obtain a good quality spectrum even if the light ball is randomly moving (within an acceptably small angular motion), in the case that it is sufficiently luminous.
- <sup>2</sup> Remarkable exceptions have been noted, however (Nikitin et al., 2018), even though some values appear to be overestimated in the latter work.

- <sup>3</sup> In pure (ordinary) General Relativity, static wormholes are unstable. Imposing the stability of static wormholes requires a supplementary ingredient. Several hypotheses were suggested, such as the presence of an exotic negative mass (Morris & Thorne, 1988). However, static and traversable wormholes solutions also have been found in the vacuum of  $R_2$  gravity, a special case of  $F(R)$  theory where the role of exotic matter is played by a modification of general relativity (Duplessis & Easson, 2015), etc. The zoo of stable wormholes is decidedly wide.
- <sup>4</sup> We have reduced the Universe to a two-dimensional space (a plane), so that we can visualize the wormhole in its entirety. Especially the mouths of the wormholes are not circles as shown in Figure 1, but spheres! In our three-dimensional world, locally, a wormhole would appear as a sphere (the core of an HL?).
- <sup>5</sup> Until now all models using conventional physics that have been proposed (Paiva & Taft, 2010; Monari et al., 2013; and many other equivalent or more exotic models), in order to explain the HLs, encounter serious difficulties, and for more than four decades now. From a theoretical point of view we can say that the topic of HLs is at a standstill with standard physics. The challenge is twofold: the energetics and the incredible motions of HLs, characterized by rapid accelerations and abrupt changes of direction.

i. Let us consider first the energetics. In the case of a ball lightning the energy is “easily” supplied by a lightning bolt. It is clear that we can then attempt to treat the question with the help of conventional physics. However, for the HLs no lightning bolt is present and the question is: What is the nature of the energy source of HLs? How is a large energy confined in a small volume (size less than or about equal to 1 m) and, secondly, how does the cohesion of the plasma endure for sometimes several minutes?

ii. The erratic motion of HLs, in turn, seems to defy laws of physics (obviously in appearance only, and we will see that this is not a problem with the wormhole hypothesis).

Nonetheless, it is difficult to understand why no explanation of all these things has been supplied after nearly half a century of studies (Hessdalen and EMBLA projects). Are we reluctant to receive an explanation for HL phenomena in terms of standard physics? This

is why a speculative and unconventional hypothesis (a wormhole), even though daring, deserves our attention, and we must take this opportunity to move things along. In physics the credibility of a hypothesis is not based on whether it is conventional or odd, but upon its falsifiability. Falsifiability is the key concept in the separation of science from pseudoscience. De facto we propose in “The Magnetic Field” section an experiment to test it. A wormhole’s mouth has a characteristic signature, it is clearly identified by its monopolar magnetic field. Is this the case for HLs? We are convinced that it will be a difficult task to extract this information from this unusual and transient phenomenon. However, if this experiment were carried out, and it proved positive, we would have taken a major step toward understanding both HLs and wormholes. This should whet the appetites of experimentalists.

- <sup>6</sup> A mantle plume is a long thin conduit connecting the top of the hot spot (the visible aerial part) to its base, locked at the core-mantle surface.
- <sup>7</sup> The wormhole under consideration is thus an entity “fitted” between the nontraversable wormholes of the type Einstein–Rosen bridge, captured by general relativity (and which serves no purpose in physics) and the “more physical” wormhole analyzed by Dzhunushaliev et al. (2011). We still have an opportunity to investigate a vast and varied field of knowledge between these two limits.
- <sup>8</sup> For this mean temperature, we take a round value near the geometric average of the central temperature ( $10^7$  K) and the surface’s temperature (6000 K).
- <sup>9</sup> If the wormhole’s mouth ( $P = 100$  kW) were located outside the dense earth’s atmosphere (i.e., for instance, located at 100 km in altitude above our head), we could think that its apparent brightness should be the same as a solar-type star (absolute luminosity  $\sim 3.83 \cdot 10^{26}$  W) located at 0.7 light-year, a short distance indeed; as the nearest star to our solar system is 4.3 light-years away. However, the wormhole’s mouth emits in the hard UV range while the Sun emits in the visible range. The hard UV is completely absorbed by the Earth’s atmosphere. Eventually this “star” would not be visible from the ground level.
- <sup>10</sup> Once again let us note that these spectra were recorded with the help of low-resolution spectrographs, in fact basic grating filters

mounted in front of video cameras and SLR cameras (Hauge, 2007). More sophisticated devices are needed to obtain confirmation. High-resolution spectroscopy is indeed of basic importance in this type of research, for not only line identification but also for calculating the number of atoms that contribute to a given excitation level that produces the spectral line of a given chemical element. This would provide a precise measurement of pressure, density and temperature of the atmospheric plasma induced by the exit hole (where only the radiation field passes) of a hypothetical wormhole.

- <sup>11</sup> The content of this paragraph is independent of the nature of the source, a wormhole, or something else (for instance a black hole, an exotic particle made of dark energy, or Rydberg matter, etc.).
- <sup>12</sup> We assume here that the radiation pressure in the ball of ionized gas is negligible with respect to the gas pressure.
- <sup>13</sup> The apparent gravitational mass of a wormhole's mouth seen by an outer observer can be positive, null, or even negative (Cramer et al., 1995). For the other extremity of the wormhole, the inner pressure gradient of the Sun must still be compensated by a negative mass,  $M$ , forming a spherical shell lining the wall of the mouth. This mass creates a repulsive gravity which prevents the solar matter from entering the wormhole. It is easy to show that

$$\left| \frac{M}{r} \right| \sim \frac{M_{\odot}}{R_{\odot}} \left( M_{\odot} \text{ solar mass and } R_{\odot} \text{ solar radius} \right).$$

With  $r \sim 10^{-4}$  m, we find  $M \sim -3 \cdot 10^{27}$  kg. However, we think that the introduction of a huge negative mass is problematic in theory, even though some theoreticians of wormholes admit this possibility (so far negative masses have never been detected in the Universe). Recently, an exploration of the vacuum solutions of pure  $R^2$  gravity uncovered solutions for the stability of wormholes without appeal to elusive negative masses (Duplessis & Easson, 2015). This second path is deemed much more credible.

- <sup>14</sup> A magnetic field could still contribute to the stability of the plasma ball. Nevertheless, taking into account the energetics it would necessarily be very high. In this case we might detect some environmental interferences (for instance on both the electrical systems and the informatics devices, and this field might also have

left magnetic remanence behind in some ferromagnetic materials). De facto magnetic recordings (Teodorani & Strand, 2001, especially figure 5) seem to clearly suggest that a correlation exists between HLs and magnetic pulsating events with a mean amplitude of a few nanoteslas. With these values registered at a distance of 1 km we deduce a magnetic intensity of a few milliteslas in the environment of the HLs (both assuming a decrease of magnetic intensity by  $r^{-2}$  and a radius for the “environment” of the plasma ball of the order of one meter).

In addition, we can still imagine that a strong magnetic field is confined deep inside the plasma ball and is rapidly decreasing toward its surface. We know indeed that a magnetic field with a characteristic monopolar configuration with rapid decrease in intensity can be associated with a wormhole (see the section “The Magnetic Field”).

<sup>15</sup> In addition to the energy problem, the issue of the size is also recurrent for HLs and BLs. Likewise in the laboratory BLs of a diameter larger than a few centimeters seem difficult to produce, as low-energy chemical processes are involved (Paiva et al., 2007). To fully ionize a cubic meter of air at atmospheric pressure, a minimum of 100 MJ are needed.

<sup>16</sup> Let us still note that HLs are seen in extremely dry air and that tiny droplets are excluded. Urban and industrial areas are prolific producers of sulfates, nitrates, black carbon, and other particles, but that is not the case in Hessdalen Valley. It is in a boreal forest, where organic particles such as amines are dominant (Kannosto et al., 2008). The conclusion found for silicon microclusters is easily transposable to these types of particles.

<sup>17</sup> Factor 2 (extinction efficiency) is a mean value for dielectric microscopic or submicroscopic particles (with sizes comparable to the wavelengths of the radiation in the visible range); the extinction efficiency strongly oscillates around this value (Mie Theory).

<sup>18</sup> Let us note that a ball lightning (BL) has been observed with a diameter estimated at 5 m (Cen et al., 2014). This is a rather strange observation. Ordinarily a BL is generated by a cloud-to-ground lightning strike and is of small size (centimetric). The lightning bolt strikes the soil and a plasma of small silicon clusters ( $Si$ ,  $Si_2$ ,  $Si_3$ , ...) is generated (a kind of natural laser ablation). Thus the prominent

lines of the neutral radical  $Si$  ( $\lambda = 478.2, 479.2, 568.4, 594.8, 615.5, 633.1, 655.6, 672.1$  nm; cf the Charlotte Moore's Tables) were clearly identified in the spectrum. If the description is right this transient chemical species (characterized by a very short lifetime) had spread over a distance of 5 m from the impact point of the lightning strike. However the diffusion coefficient in the stable air for an atomic species is of the order of  $10^{-5}$ – $10^{-4}$   $m^2s^{-1}$ . Eventually, for a distance of 5 m we calculate a diffusion time immeasurably much greater than the lifetime of free radicals such as  $Si$  which is very short (without a continual input of energy). The evaluation of the diameter in this observation is thus strongly questionable (the result is without doubt linked to a very approximate evaluation of the distance).

- <sup>19</sup> This wave effect assimilated to a kind of gravitational wave of strong amplitude would deserve special attention by itself, but unfortunately it is not yet fully described in the literature on wormholes.
- <sup>20</sup> When the wormhole's mouth is opening, an ionized ball instantaneously appears around it. A few moments later the wormhole's mouth is closing and the ionized ball instantaneously disappears, leaving a trace in the sky with an afterimage effect (or an image retention for a photographic device). The cycle can renew further from a new position, giving to the observer the false impression of a plasma ball acquiring an incredible (but obviously fictive) acceleration. More precisely, it seems from Figure 4 that two phenomena are superimposed with regard to the behavior of the wormhole, a Brownian turmoil which is extremely rapid and jerky (difficult to display with a low time resolution recording system), and a slow drift.
- <sup>21</sup> Another analogy can also be made with a magnetic field bundle which can be decomposed in a multitude of rope strands, as seen for instance in the Sun's atmosphere.
- <sup>22</sup> This is the mean value attributed to the magnetic field deep in the Sun. The magnetic field lines can funnel up to the mouth of the wormhole where they very rapidly expand.
- <sup>23</sup> Let us note that the mouth of a wormhole has the appearance of a monopolar magnetic field, but it is not a magnetic monopole (a particle) which very likely does not exist in nature.
- <sup>24</sup> Let us note, however, that measurements of magnetic field carried out at a distance of a few kilometers from HLs (Teodorani & Strand, 2001)

seem to supply much higher values, of the order of one nanotesla (i.e.,  $\sim 10^{-3}$  tesla when referred at one meter distance from the HL). This suggests that values as high as  $10^5$  teslas could eventually be reached at the mouth of the wormhole (radius  $\sim 0.1$  mm). In the framework of this interesting scenario a compression of the solar magnetic field ( $10^{-1}$  tesla) by a factor of  $10^6$  would then be produced in the throat of the hypothetical wormhole.

<sup>25</sup> As appropriate a magnetic field line ultimately forms a closed path by passing by the wormhole channel and by looping through the real space between the Earth and the Sun (Figure 2).

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