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A Long-Term Scientific Survey of the Hessdalen Phenomenon

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Abstract—The balls of light which appear in the Hessdalen valley in Norway are exemplary of anomalous atmospheric luminous phenomena that occur frequently at some locations on Earth. The recurrence of the phenomenon and the existence of an instrumented observation station makes this area an ideal research site. The apparent correlation of luminous phenomena with magnetic perturbations, radio emission, and radar tracks, found by Norwegian researchers, led some Italian physicists and engineers of the EMBLA Project to reanalyze the Norwegian data. The second step was three explorative, instrumented, field-study expeditions. The behavior of the phenomenon was monitored with optical, radio, and radar techniques. The global picture of the phenomenon obtained so far shows that the phenomenon's radiant power varies, reaching values up to 19 kW. These changes are caused by sudden surface variations of the illuminated area owing to the appearance of clusters of light balls that behave in a thermally self-regulated way. Apparent characteristics consistent with a solid are strongly suspected from the study of distributions of radiant power. Other anomalous characteristics include the capability to eject smaller light balls, some unidentified frequency shift in the VLF range, and possible deposition of metallic particles. A self-consistent definitive theory of the phenomenon's nature and origin in all its aspects cannot be constructed yet quantitatively, but some of the observations can be explained by an electrochemical model for the ball-lightning phenomenon. The importance is stressed of using more sophisticated instrumentation in the future.

Keywords: atmospheric anomaly—Hessdalen lights—plasma physics—ball lightning—astrophysical techniques—theory

Introduction

The "Hessdalen Lights" reported in the Hessdalen valley in Central Norway represent a prototype of atmospheric luminous phenomena. In general they consist of light balls of many forms and colors, characterized by pulsations, often erratic movements, occasional long duration, and intense emission of energy. Their dimensions range from decimeters up to 30 m. These lights are reported both in the sky and close to the ground. Because the lights characteristically reoccur in the Hessdalen area, the phenomenon is very suitable for systematic instrumented observational investigations. In 1984 a Norwegian organization (*Project Hessdalen*, led by engineer Erling Strand) carried out a 36-day observational campaign in which some instruments were intensively used: radar, magnetometer, radio-spectrum analyzer, seismograph, cameras (some of them equipped with dispersion gratings), Geiger counter, infrared viewer, and laser (Strand, 1985; 2000). This initiative demonstrated for the first time that the phenomenon is measurable. The magnetometer, radio-spectrum analyzer, and radar furnished the most reliable results. In a few cases, the gratings gave a very low-dispersion spectrum, from which it was possible to establish that it was a continuum with no lines. Moreover, many good photographs of the light phenomenon were obtained. 53 visually witnessed occurrences of the phenomenon were accurately reported with precise times and classified by their strangeness and quality indexes (Hynek, 1972). Probably the most important result was that the luminous events often tended to occur at the same time as magnetic perturbations (see Fig. 1; Strand, 1985; Teodorani & Strand, 2001). During that campaign, it was also demonstrated that these lights often produce a strong radar signature with a peculiar behavior. Once a bright light was radar-tracked moving at 8500 m/s (the radar was working at $\lambda = 3$ cm). On another occasion, a light phenomenon under constant visual observation showed up on radar only on every second sweep of the radar dish. In most cases when radar was recording a track, no visual or photographic observation was reported (Strand, 1985; Teodorani & Strand, 2001). Sometimes sudden unidentified oscillating radio spikes in the High Frequency (HF) range were recorded at the same time as light events (Strand, 1985; Teodorani & Strand, 2001). One night, the observers aimed the laser beam (633 nm; power $= 0.4 \div 0.76$ mW, type: Ne-He) at two blinking lights that appeared one after the other over the course of one hour. Several attempts were made to get a reaction. The lights "responded" almost always by changing their flashing sequence from a regular flashing mode to a regular double-flashing mode and returning to a regular flashing mode after the laser beam was moved away (Strand, 1985, 2000).

In 1994, the mystery of Hessdalen-like light balls was thoroughly examined during an international physics workshop (Strand, 1994, 2000). Many theories and observational techniques and strategies were presented. Of most importance, the entire group of scientists accepted the phenomenon as a subject that deserves careful analysis using physical-science protocols. The increased interest has led to subsequent developments of this research.

Since the summer of 1998, under the guidance of Erling Strand and Bjørn Gitle Hauge, now assistant professors of Østfold University College in Sarpsborg (Norway), a real-time automated observatory, the Automatic Measurement Station (AMS) (Strand, 2001), has been operational in the Hessdalen valley. The station is equipped with automatic wide-angle and zoom videocameras able to monitor the phenomenon in real time, a radar transponder, and a magnetometer. During the 5 years of its operation, the AMS has furnished reliable statistics on the lights. The phenomenon tends to be recorded more often in the winter and between the hours of 10.00 pm and 01.00 am (Teodorani &

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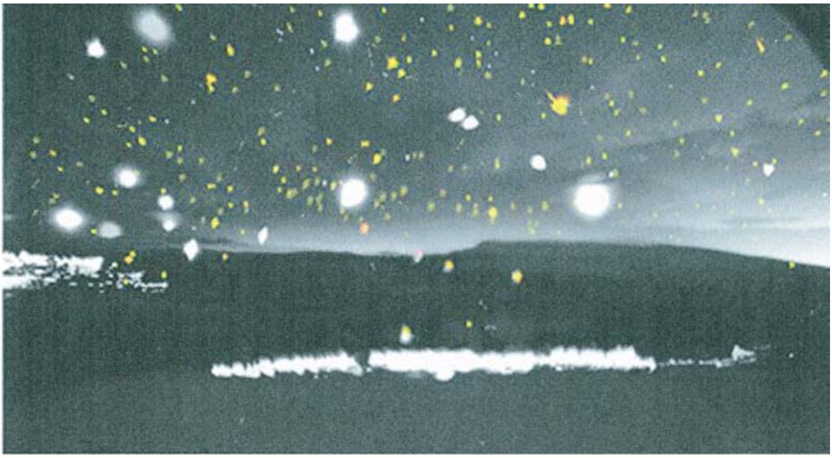

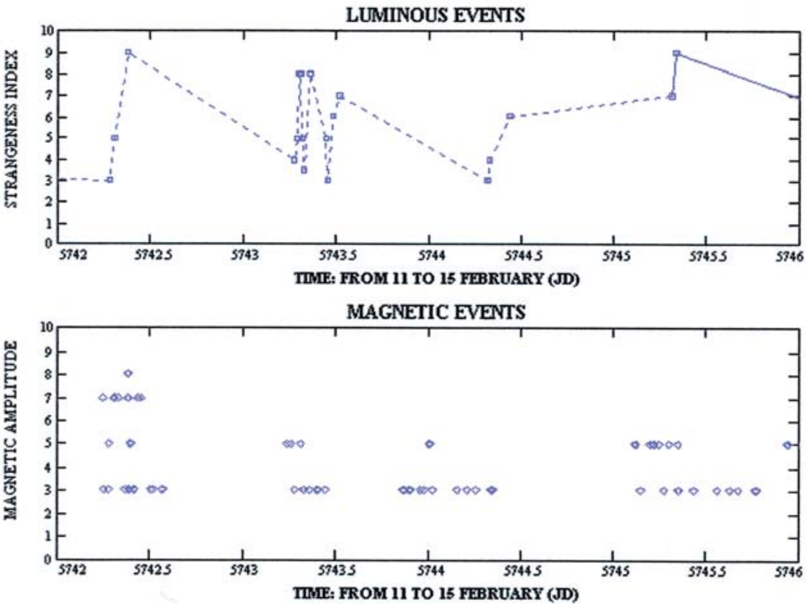

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Fig. 1. a: Spatial distribution of luminous events in Hessdalen obtained by the author by using data acquired from the Automatic Measurement Station in the years 1998, 1999, 2000, 2001 (the 15 bigger lights are due to the Moon in different periods of the year and phases). Artificial lights have been eliminated after their identification was done. The data from 2002 and 2003 are not included as they are incomplete. b: Luminous events (strangeness index) and magnetic events (magnetic amplitude) in Hessdalen, obtained by the author from data acquired during the Norwegian campaign in 1984. The time-axis is in Julian Date (JD: a continuous count of days and fractions since noon Universal Time on January 1, 4713 BCE). The JD must be intended as the number in the graph preceded by 244. All the reported light phenomena occurred at night. The magnetic events were recorded mostly at night and at daytime in few cases.

Strand 2001, see Figs. 1, 2). During these times, humidity very often reaches values of 80–90%, as later recorded (often but not systematically) during our field missions. Records of daylight phenomena are extremely rare. Light phenomena appear anywhere low in the sky and close to the ground without following any preferential trajectory (Teodorani et al., 2000; see Fig. 1a). However, these statistics, which were very useful in establishing that this phenomenon was not caused by any known artificial sources, did not lead to an understanding of the origin or the nature of the phenomenon. A detailed analytical protocol using a variety of instruments was called for. This was attempted by three joint Italian-Norwegian explorative field missions under *Project EMBLA*, which was created in 1995 after several meetings in Italy at the Radioastronomy Institute (IRA) of the Italian National Research Council (CNR). The following scientists and electrical engineers participated in the organizational meetings: Stelio Montebugnoli, Jader Monari, Marco Poloni, Andrea Cremonini, the author (astrophysicist) of IRA-CNR, Erling Strand, Bjørn Gitle Hauge of Østfold University College and their students, VLF expert Flavio Gori of NASA Inspire, and physicist Gloria Nobili of the Physics Department in Bologna. These participants have alternated their presence in Hessdalen during the three missions.

The data acquired by Project Hessdalen in 1984 were analyzed just after the 1994 workshop (see Fig. 1) (Teodorani & Strand, 2001). The analysis confirmed the phenomenological picture deduced by Norwegian researchers. Moreover, in the course of such a post-analysis, a correlation was found between daily solar activity (sunspot number) and some of the measured parameters of the phenomenon (in particular, magnetic perturbations). This preliminary finding suggested that high-energy particles of solar origin colliding with the terrestrial atmosphere might trigger the phenomenon, especially during geomagnetic storms. Geomagnetic storms had been recorded by a field magnetometer in 1984 (Strand, 1985). A more recent analysis, carried out on a very complete observational data-base (Automatic Measurement Station (AMS) data: 1998–2001, see Fig. 2) (Strand, 2001), yielded no correlation between luminous events and monthly and yearly solar activity (Teodorani & Nobili 2002). However, only the sunspot number was considered as a parameter. Further analyses will be carried out by using the solar flux in X-rays and radio waves. Nevertheless, the lack of a correlation so far, assessed by sunspot number, seems significant for medium and long time-scales. Even if the solar correlation study is not yet complete, at present it is not considered a prime factor in the study of the intrinsic physical nature and structure of the Hessdalen light balls.

Instrumentation used in the EMBLA Missions

In August 2000 (EMBLA 2000), the Norwegian AMS station in Hessdalen was equipped for about a month with an additional platform of automated radio

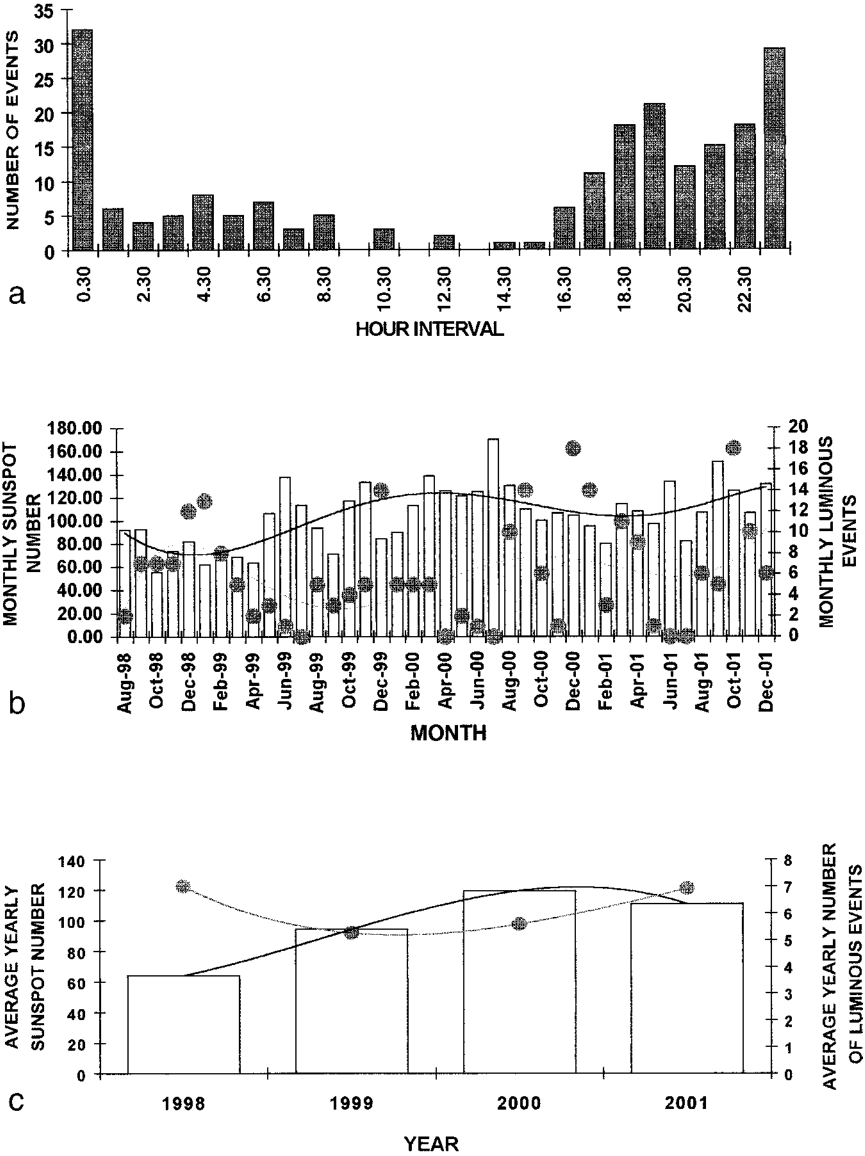

Fig. 2. Temporal statistics of luminous events in Hessdalen obtained by the author by using data acquired from the Automatic Measurement Station in the years 1998, 1999, 2000, 2001. The data from 2002 and 2003 are not included as they are incomplete. a: Hourly number of luminous events (for instance: number 10.30 means interval between 10.00 and 11.00). b: Monthly number of luminous events (circles) and monthly solar activity (bars: sunspot number). c: Yearly number of luminous events (circles) and monthly solar activity (bars: sunspot number).

instruments (Teodorani et al., 2000) designed by the technologists of the Istituto di Radioastronomia (CNR). The following were deployed:

a) VLF-ELF (Very Low Frequency–Extra Low Frequency) correlation receiver and spectrometer connected to two loop antennas. These were sensitive to a magnetic field in the 1 KHz–14 KHz range. This instrumentation furnished some interesting results.
b) VLF *Inspire* receiver and spectrometer connected to a dipole antenna. They were sensitive to an electric field in the 1 KHz–100 KHz range. This instrumentation furnished no relevant results.
c) Two spectrometers (*Sentinel 2* and *Sentinel 5*, constituting two separate computers) connected to a 1420 MHz receiver (not tunable), which furnished respectively a frequency range of 5 MHz at 10 Hz resolution (high resolution mode) and of 10 MHz at 10 KHz resolution (low resolution mode), both centered at 1420 MHz. The receiver had an omnidirectional "ground plane" antenna. (The 1420 MHz frequency is currently used in astrophysical and SETI studies.) This instrumentation might turn out to be important if the phenomena produce electromagnetic emission in this specific microwave range. In any case, this instrumentation, owing to its specific design based on the technology of multi-channel spectrum analyzers (normally used for the SETI project), were capable of recording radio emission in this range at extremely high resolution and sensitivity. This instrumentation furnished no results.
d) Wide-band antenna connected to an Hewlett-Packard spectrum analyzer scanning from 0.1 GHz–1.8 GHz. This instrumentation furnished no results.

All these instruments were computer-controlled and data, recorded automatically and continuously, were stored on CD-ROMs.

The choice of the VLF and VLF-ELF instruments was mostly based on the need to monitor the very-low-frequency electromagnetic field, which was never studied before but whose effects on the human bioelectric activity have been strongly suspected for about two decades (Strand, 2000). The choice of the 1420 MHz spectrometer was due to the need to explore some part of the microwave field which had never been investigated before. It was not an instrument specifically designed to study these phenomena, but it was the only microwave instrument available at that time. Both kinds of instruments should have filled the gap left by previous radio measurements (Strand, 1985), where only the range 100 KHz–1200 MHz was covered.

The EMBLA 2000 personnel were also equipped with the following additional portable facilities: an amateur videocamera, a reflex camera (35–70 mm zoom) mounted on tripod, an image intensifier / IR viewer, binoculars, a fast optical detector, a mini X-ray detector, and a Geiger counter. Moreover, krypton and xenon power torches (flashlights), mini-lasers, and a compass were used to signal the positions of different groups of observers. Not all the facilities were used successfully: the videocamera, reflex camera, binoculars, and image intensifier were the most effective.

In August 2001 (EMBLA 2001), the investigation was mostly devoted to the optical side of this research (Teodorani et al., 2001), using:

a) Meade Comet Tracker reflector telescope (f = 549 mm).
b) StarlightXpress SXL-8 CCD camera.
c) Rainbow Optics (ROS) low-resolution spectrographic grating (200 lines/mm).
d) Canon XM-1 professional digital videocamera (560 × 560 pixels).
e) Yashica 107 Multiprogram reflex camera (35–70 mm zoom) mounted on tripod.

The same portable facilities were also available as those used during the previous mission.

Because of the very high humidity in the Hessdalen area, the system of telescope+CCD camera+grating could be used only seldom, with scarce results. Most of the successful observations were made with both the Canon and Yashica cameras and yielded many photographs and videoframes. Moreover, after deciding to connect the spectrographic grating directly to the CCD videocamera, some spectra of the phenomenon were obtained with a sufficient signal-to-noise (S/N) ratio, but with very low resolution.

In August 2002 (EMBLA 2002) there was a new Italian mission to Hessdalen (Teodorani & Nobili, 2002), consisting of two groups: an engineering group and a physics group. The groups collaborated in some aspects of the investigation. The engineering group mainly dedicated its efforts to using a low-power pulsed radar (power = 40 W, frequency = 439.3 MHz), designed by them (CNR-IRA) (Montebugnoli et al., 2002). The radar, which recorded some transient tracks that rarely corresponded to optical counterparts, was permanently installed at Aspåskjölen, pointing south, where the Hessdalen lights had been seen most often during previous years. The physics group, whose results are presented here in detail, was mainly devoted to four activities:

1) Acquisition of photographs of the lights using three different reflex cameras. A Praktica BX-20, equipped with a 135–270 mm lens, was used both for imaging and spectroscopy. A Yashica 107 Multiprogram, equipped with a 35–70 mm zoom lens, was constantly used for imaging at a focal length of 70 mm. A twin reflex Rollei, with a 35 mm lens, was used for panoramic imaging. In all cases, Kodak 100 ASA Ektachrome slide film was used. This choice of a reasonably fast, small-grained film was dictated by the lack of a high-resolution digital camera.
2) Acquisition of spectra using a spectrographic grating of the same type used during the previous year; it was permanently attached to the lens of the 135–270 mm camera. This configuration furnished a spectral resolution in the range $\lambda/\delta\lambda = 10^2$–$10^3$, 5 times greater than with the videocamera used in the previous mission.

3) Measurement of the radiation field using a Geiger counter in selected places.
4) Collection of samples from ground known to have been approached by the lights, for subsequent laboratory analysis.

The same portable facilities were again used, and in addition two short-range custom-built EM detectors (for measuring electric and magnetic fields) and an acoustic detector which, however, furnished no results. Ground and powder samples were analyzed at the SACMI Imola laboratories using SEM electronic microscopy, optical microscopy, plasma spectrometry, and X-ray diffraction.

Visual observation of luminous phenomena was carried out mostly from the Aspåskjölen site (also called "Vista Point"). Other locations such as Finnsåhögda mountain, Elsjøen, not far from the Öyungen lake (6 Km from Hessdalen), the Öyungen lake itself, and the AMS station, were also chosen as observation points.

Photographs and video frames were processed using sequentially the following software facilities: *Ulead Media Studio* and *DV Studio* for video-frame pre-processing, *Adobe Photoshop 5.5* and *Paint Shop Pro 7* for image resizing, interpolation and enhancement, and *Iris 3.6* and *Matlab 5* for image exposure profile modelling and photometry calculations. Optical spectra were processed using sequentially *Adobe Photoshop 5.5, Iris 3.6* and *Visual Spec 2.0.2* software; the spectra were first enhanced and then calibrated in wavelength using known spectra of streetlights (in particular, high-pressure sodium vapor lamps and their identified lines) as reference spectra. A list of spectral lines of the most important chemical elements was used as well. VLF data were processed by *Spectrogram* and *Autosignal* software. Analytical plots were subsequently done using *Mathcad 5* and *Microsoft Excel 2000* software.

Phenomenological picture and discussion

The three EMBLA missions did not find the external causes that trigger the phenomenon. Nevertheless, some (often interconnected) aspects of the optical behavior of the lights were discovered, even if so far no globally self-consistent model, able to connect the data coming from all of the investigated wavelength windows, is yet available. Precise photometric and spectroscopic descriptions were obtained. VLF Radio investigations showed some recurrent behavior not recorded during previous Norwegian investigations. Laboratory analysis of ground samples showed, for the first time, intriguing hints regarding some possibly released substances. What is known so far about the Hessdalen phenomenon cannot yet furnish a definitive, quantitative theory but it does provide some important clues on possible physical mechanisms. Still, some phenomenological aspects have been defined precisely, as described and discussed in the following sections.

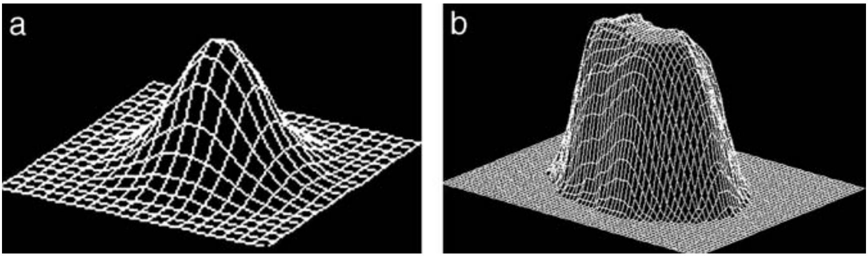

Fig. 3. Light distribution (Intensity Distribution) in the cases of: a: a typical plasma, b: a typical Hessdalen phenomenon. The three dimensions of the plot are x, y and z. The first two define the area of the image, the last one defines the count level (relative intensity).

Uniformly illuminated solid-like light balls

On the basis of the three-dimensional analysis of the Intensity Distribution (ID) (see: ''Introduction to Imaging,'' http://www.astro.ubc.ca/courses/astr405/imaging_lab_proc.html#psf) of the lights, obtained from photo and video frames, it appeared that the radiant power is due to a heated substance. Nevertheless the light phenomenon, in both a photometric and spectroscopic sense, does not have the characteristics typical of a classic plasma of free electrons and ions (Teodorani & Nobili, 2002). When the atmospheric transparency was low, which was most of the time, and when the orbs were low over the horizon, the ID profile was very similar to that of an image of a heated, glowing plasma, i.e., a Gaussian shape with exponential wings. However, further analysis showed that the Gaussian shape was purely an atmospheric effect which produces a ''seeing profile'' with an ID characterized by exponential wings, such as when luminous point-like objects (e.g., stars) are observed through thick atmospheric layers. When the atmosphere was clear, with no fog, the ID profile of the image was nearly flat on top with steep sides. This ID shape is what one would expect for the image of an approximately spherical and solid-like object that radiates the same in all directions (uniform luminosity; see Fig. 3).

An ''Abrahamson ball lightning'' (Abrahamson & Dinniss, 2000) would seem to be one possible natural phenomenon which, at least in some aspects, might produce a light distribution of that kind. In such a case luminosity is produced by a heated non-plasma spheroid constituted of silicon nano-particles extracted from the ground by very strong electric discharges. Such a light ball, which is not a plasma but rather a concentration of heated, chained nanoparticles deposited on a surface, might simulate a uniformly illuminated solid object. A possible occurrence of silicon spectral lines was suspected in the spectra acquired during the 2002 mission[1] (see Fig. 4: spectral peak at 5100 °K), but, unfortunately, the available spectral resolution was too low to resolve such lines (Teodorani & Nobili, 2002). However, the Abrahamson model specifically involves lightning electric discharges from the atmosphere; and such discharges were never recorded in Hessdalen during our observations. Alternatively, one

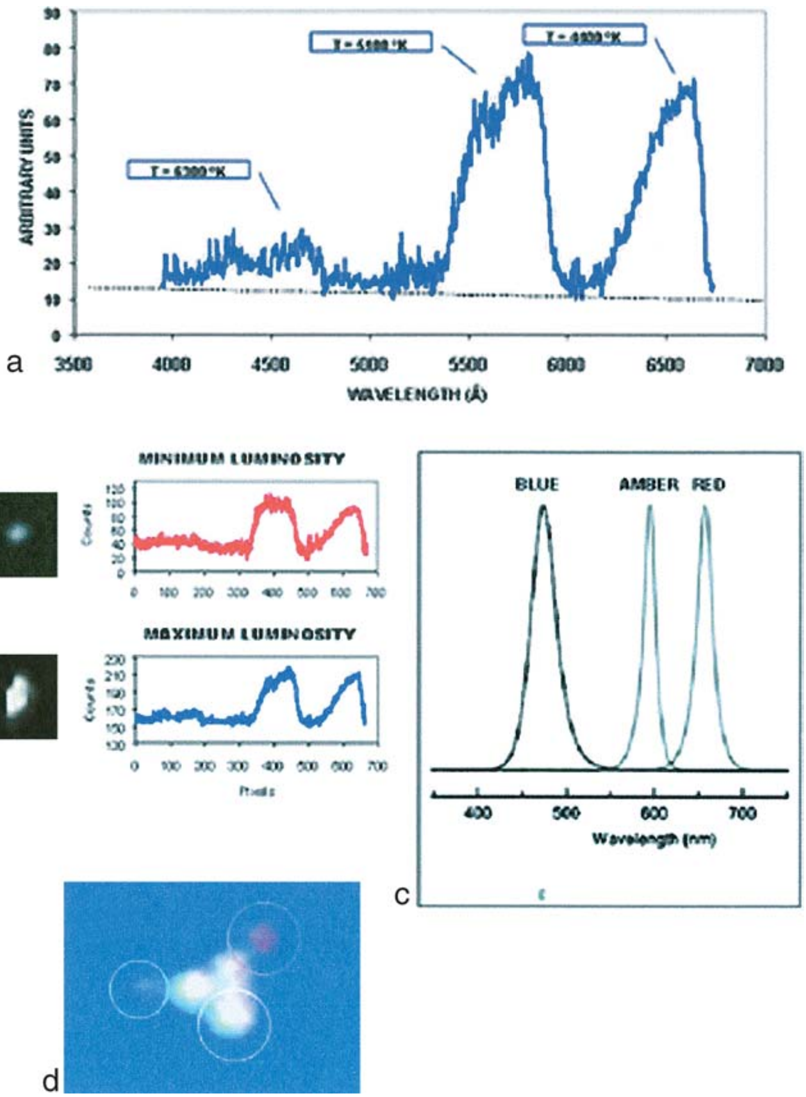

Fig. 4. a: Spectrum of a Hessdalen light phenomenon obtained with a ROS grating connected to a Praktica BX-20 reflex camera equipped with a 270 mm lens, using a Kodak Ektachrome 100 ASA film. The dotted line indicates the level of noise. The three peaks are indicated with the relative temperatures which are derived from the *Wien* law (Lang, 1998). b: Comparison of 2 spectra taken at minimum and maximum luminosity of the light phenomenon, where no variations are recorded in the peaks amplitude and position. The wavelength range of the spectra in pixel shown here goes from 4000 to 7000 Å. c: Simulation of a composite spectrum produced by three differently colored LED lights (blue, amber, red) having the same intensity. d: The three different colors (blue, white and red), with different intensities, recorded photographically from one Hessdalen light phenomenon.

might suggest that in the specific Hessdalen area, where light phenomena are seen very often some meters over the ground, an electric triggering mechanism might be produced by the existing high abundance of quartz, copper, and iron underground. When quartz is subject to tectonic stress, it generates piezo-electricity (Derr, 1986; Freund, 2003; Lockner et al., 1983; Zou, 1995), while copper is an ideal electricity conductor and consequently might be an electrical amplifier of the phenomenon. But, realistically, unless great heat or the presence of huge electron concentrations or both are locally present in the area, no amount of powering by piezo-electricity can reduce silica to the silicon that the model requires. Therefore the Abrahamson model, even if it can explain successfully the observed luminosity profiles, cannot be considered to explain Hessdalen-like phenomena or earth lights in general; it cannot explain the external electric cause that generates these light balls.

The model best able to account for the solid-like ID shape of the lights is probably Turner's electrochemical model of ball lightning (Turner, 1998, 2003). According to this theory, the center of the light phenomenon is a plasma whose temperature is controlled by the input of in-flowing air. In particular, aerosols, enlarged by chemical reactions at the edge of the plasma, can promote the storage of energy within it and maintain electric charge at its surface. This maintains a sharp division between the hot plasma and the cooler air surrounding it (Turner, 1994). A lightning ball of this kind acts as a thermochemical heat-pump capable of powering itself for relatively long periods (up to three minutes) by using chemical energy, electrical energy, or both. A thermochemical refrigeration effect, produced by the evaporation of all the present hydrate water and consequent cooling of the local environment, can provide an established light ball with its structure and stability. A specific consequence of this is that the ball is self-regulating in size (Turner, 1994) and, having a heated plasma in close proximity to a refrigerated region, there can be a very sharp temperature gradient at the surface of the ball (Turner, 1997). Powerful exothermic hydration processes just inside the surface of the plasma ensure that heat is supplied there. On Turner's model, a powerful air-plasma ball will inevitably have a sharply defined edge at its outer surface. This well defined shape matches the ID obtained from most of the Hessdalen phenomena. Thus the apparently "solid" nature of the recorded light emission may be the consequence of a thermo-chemical effect. So far as the triggering of these light balls is concerned, piezo-electricity seems the most probable cause: after the plasma-ball initiation, most of the energy is sustained thermochemically, unlike the precise and limiting conditions required for initiation on the Abrahamson model.

On the other hand, if we assume that light balls are actually uniformly illuminated solid objects and not ball lightning, one might interpret the spectra obtained (see Fig. 4a–d) in a different way. The observed narrow peaks[1] (typically $\Delta\lambda = 400–500$ Å) mostly coincide with those produced by three kinds of LED (Light Emitting Diodes) illumination systems[2] (see Fig. 4c). LEDs are based on semi-conducting elements. The peak at 4400 °K resembles that of a red

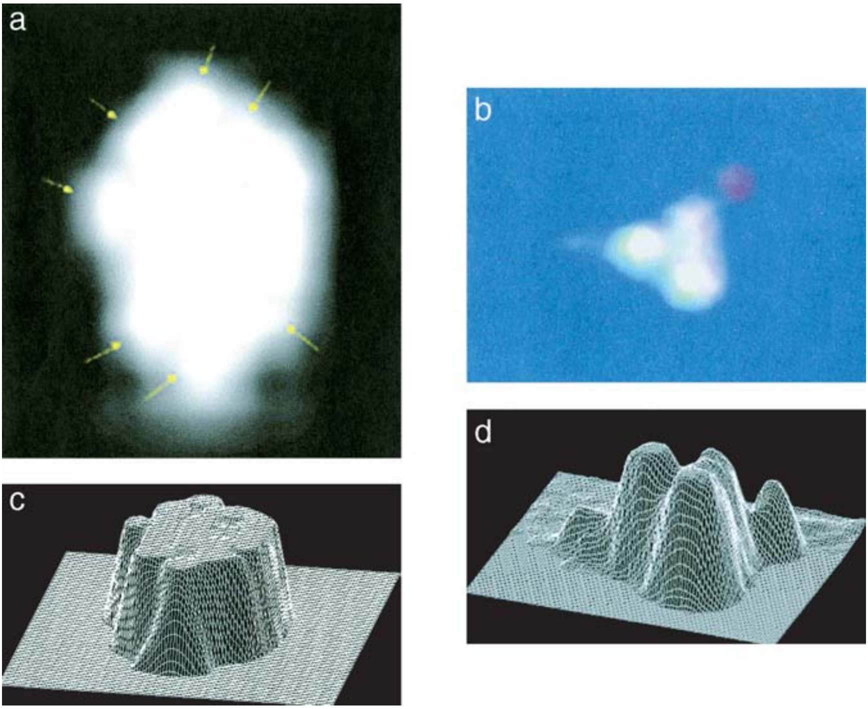

Fig. 5. a, b: Formations of light clusters. b, c: Their corresponding 3-D light-distribution. a: This picture of a light event was obtained by summing up 30 sequential frames (1/30 sec) acquired with a professional videocamera. b: This picture of another light event was obtained after processing a conventional photograph taken using a Praktica BX-20 reflex camera equipped with a 270 mm lens, and a 100 ASA film. The light balls are white (high intensity, center), red (high intensity, above right) and blue (low intensity, left) colored. The absolute luminosity of this cluster of light balls has been estimated to be about 19 kW.

LED light of the types QDDH68002, L3882, L-793SRC-E and QDDH66002; the peak at 5100 °K is slightly red-shifted with respect to the one produced by an amber-yellow[3] LED light of the types HLMP-DL32, LY5436; and the (weak) peak at 6300 °K is resembled by a blue LED Light of the type HLMP-CB31. Under this interpretation, the Hessdalen lights may be the combination of three different LED-like lights; for example, in Figs. 4d and 5b, the three colors are effectively present: high-intensity white and red, and low-intensity blue.

A full confirmation of the identification of possibly crowded spectral lines of naturally occurrring substances, as opposed to LED (artificial) spectral peaks, awaits the deployment of high-resolution spectroscopic techniques,[4] properly adapted to this kind of light source, which will become available in the near future. The existence of "lamp-like solid objects" as an alternative explanation of both the observed brightness distribution and the acquired spectra cannot yet be excluded. Natural processes could also be responsible for this "LED-like" spectrum. Normally the structure of nano-crystallites or quantum dots is artificially controlled by appropriate preparation procedures (Nirmal et al., 1993). In the specific Hessdalen case or elsewhere, a possible spontaneous production of almost mono-disperse quantum dots might come from mold spores, as the main semi-conducting elements, decomposed by the central plasma of the light ball. This hypothesis must be investigated very carefully, before invoking an artificial cause of the Hessdalen lights. In particular, an in-depth chemical and physical analysis of the molds growing in the Hessdalen valley should be carried out to search for traces of potentially semi-conducting elements. This could explain successfully not only the recorded LED-like spectrum but also the existence of balls of distinctly different colors as seen in Fig 5.

Thermally self-regulated clusters of light balls

The light balls show apparently "non-thermodynamic" characteristics (Teodorani et al., 2001, Teodorani & Nobili, 2002). If the illuminated matter were a classical thermal plasma, two main after-effects would be predicted: a) gradual cooling due to adiabatic expansion (no energy exchange with the surroundings during expansion) or explosion after a very short time (as in the case of some ball-lightning reports), or b) colorimetric decay with a fast transition from blue or white to red and final disappearance (Fryberger, 1997). These effects are not seen at all in the Hessdalen phenomenon. This is just what is expected for ball lightning under Turner's model: the thermochemical "lagging" provided by ion hydration, combined with a continuous input of energy and the inward pressure, require neither adiabatic expansion nor fading of the plasma. Some of our observations at Hessdalen suggest that ball lightning and earth lights may be two variants of a common basic structure (Turner, 2003).

What is visually observed from afar (typically: 2–10 Km) is a sharp increase in size of an apparently uniform white-colored light. By resizing and enhancing the acquired photo and video frames, it has been possible to demonstrate that this is caused by the sudden appearance of "satellite spheres" around a central luminous core (see Fig. 5); there is not the expansion of a single orb but a sudden clustering of orbs around a common nucleus. White and (rarer) red balls with the same size often co-exist (see Fig. 5). The non-standard plasma-like behavior of the Hessdalen lights is also evident from a sequence of video frames that show the sudden increase of the radius of a cluster of light balls that were known to be fixed in position and distance. The brightness increases linearly with image size[5] (see Fig. 6), which is very different behavior than that expected from a plasma object that is rapidly expanding and consequently cooling.

For a conventional plasma, the Stefan-Boltzmann law (Lang, 1998) gives the absolute luminosity as $P_{ABS} = 4\ \pi\ R^2\ \sigma\ T_E{}^4$ (where R is the radius of the luminous phenomenon, $\sigma = 5.6697 \times 10^{-8}$ J s^{-1} m^{-2} K^{-4} is the Stefan-Boltzmann constant, T_E is the effective temperature). If the ball is assumed to be a plasma that expands adiabatically, then the temperature should drop when the

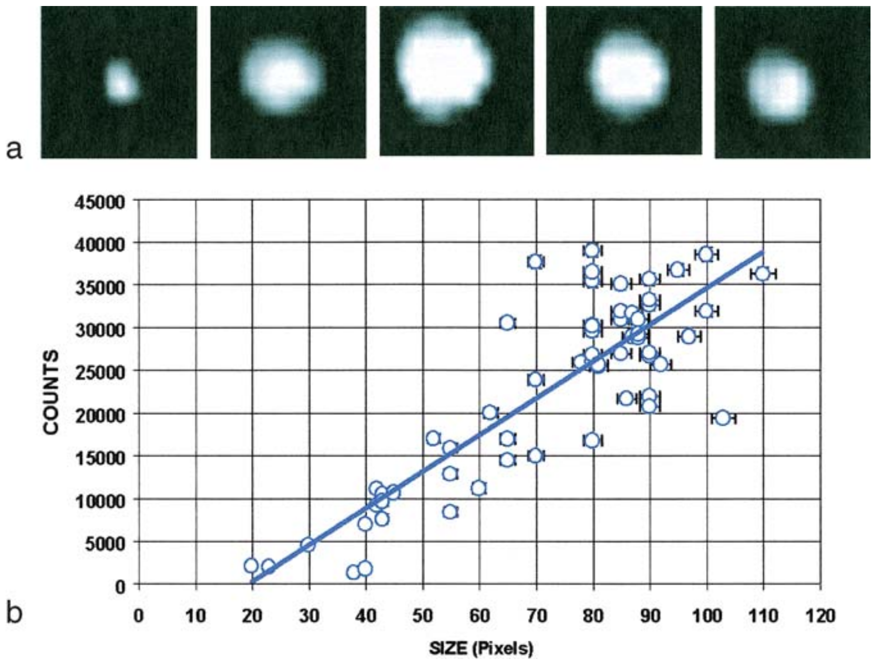

Fig. 6. a: Selected low-resolution video frames of a time-sequence of luminous events. b: The dimension–brightness correlation derived from the analysis of 60 video frames of a given light event which was standing still over the top of a hill. The obtained counts result from the total apparent brightness measured by using a circle which integrates all the image area of each frame.

volume of the ball increases. If the plasma is approximated as an "ideal gas" the adiabatic expansion obeys the law, $TV^{\gamma-1} =$ a constant, where $\gamma > 1$. Therefore, if V increases, T decreases proportionally. Thus the radiant power increases in proportion R^2 but decreases as $(1/V)^{4\gamma-1}$, i.e. $(1/R^3)^{4\gamma-1}$, in other words the power decreases as $(1/R)^{12\gamma-10}$—adiabatic increases in size should be accompanied by less total radiated power and, hence, lower image brightness.

The observed behavior of the light balls is different from this prediction. They radiate more power as they increase in size. Furthermore, white balls (very hot, if a plasma) can coexist with red ones (very cool, if a plasma) of the same size, again violating the predicted behavior of a conventional plasma. The observed behavior of these light balls suggests a self-regulating mechanism that keeps the temperature, and hence radiant power, constant in spite of changes in size. The constancy of the temperature can be deduced by comparing two time-sequential spectra (see Fig. 4b), where the three observed peaks do not change either in amplitude (relative to continuum) or in wavelength as the light ball passes from a maximum to a minimum of light. In such a case the only change consists in a lower luminosity, producing spectra with a lower signal-to-noise ratio.

The appearance of "satellite spheres," composing a cluster around a main

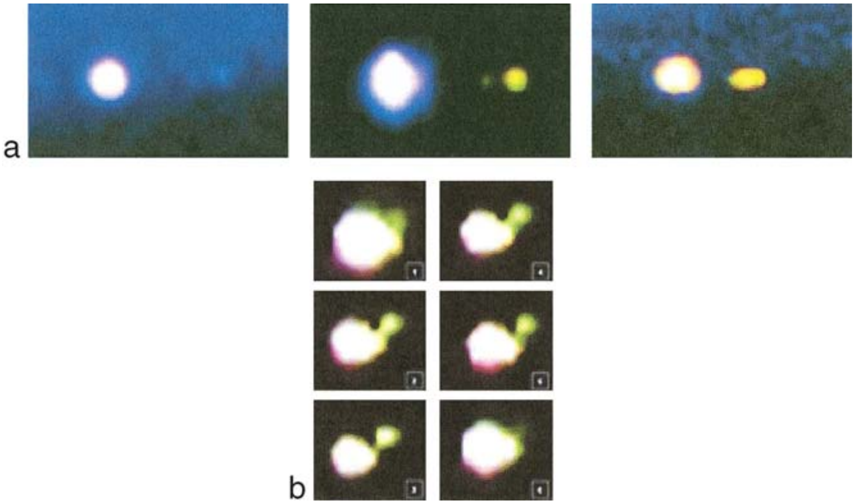

Fig. 7. a: Three photographic examples of ejection of a small green light ball from a larger white light ball. b: One selected video sequence of the same kind of events (total duration ~1 second).

nuclear region, is similar to the commonly reported splitting apart of a lightning ball into one or more smaller balls. Turner's model explains this behavior as a re-minimization of the effective surface energy with the formation of new condensation nuclei (Turner, 2003).

Nevertheless, the production of balls of distinctly different color, recorded at Hessdalen (see Figs. 5, 7), differs from standard (commonly reported) ball-lightning behavior; that may be a distinguishing mark of earth lights, as the Hessdalen phenomenon is usually assumed to be. If so, then the color of the light balls might be produced by quantum dots from mold spores or the like: the atmosphere is full of natural aerosols whose nature varies with locality. As in Turner's model where air is swept into free-floating air-plasma, so here perhaps a cloud of spores are swept into just one side of the plasma, causing the separation of differently colored co-existing light balls.

Plasma confined magnetically to produce self-contained light balls (Stenhoff, 1999) cannot account for the observed characteristics. There is no need to invoke confining magnetic fields, central forces (other than chemical ones) or gravitational collapse, all of which have been proposed as models for ball lightning. The observed light phenomenon can be more realistically described by the electrochemistry of air plasma surfaces, as discussed above.

Strongly and rapidly variable light phenomena

The light phenomenon is strongly variable in radiant power and is characterized by an irregular or semi-regular pulsation at a rate (interval between two maxima) that is normally less than one second (ascertained from

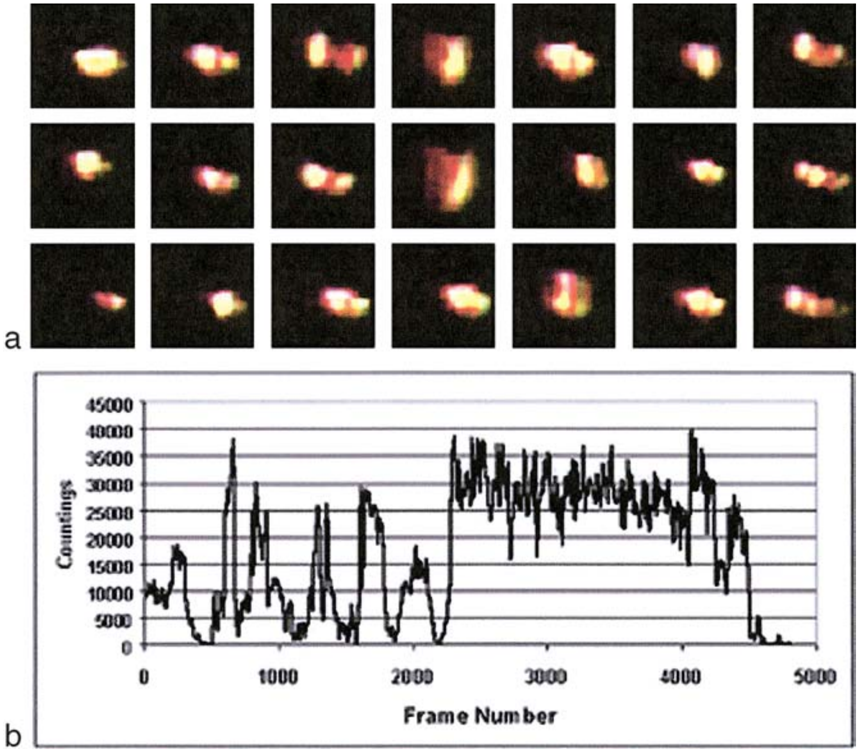

Fig. 8. a: Aspect of the phenomenon at maximum luminosity from high-resolution video frames of a blinking event. b: Light-variations of the same luminous event, whose total duration was of about 3 minutes. Time is represented by frame number.

a sequence of video frames, see Figs. 7, 8). During the three EMBLA operations, the duration of a light event was typically characterized by 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 frequently had a duration of 5 seconds. In the cases where the light phenomenon lasted longer (3 minutes or more), radiant power tended to stabilize at a high value with a much lower-amplitude pulsation (see Fig. 8). In all cases the light phenomenon turns off abruptly, as if by a switch. As emphasized in a previous section, it has been definitively ascertained that the radiant power increase is only due to the increase of the radius of the illuminated surface (Teodorani et al., 2001; Teodorani & Nobili, 2002). This occurs all of a sudden and is due not to the expansion of a single light ball but to the appearance of a cluster of light balls around a central core. This core apparently behaves like a "seed." When observed visually from far away, the cluster of lights appears like a non-resolved slightly extended light source (similar to a planet, like Venus, but much more luminous), but after a proper enhancement of photo and video frames it shows very well resolved characteristics of multiplicity (see Fig. 5). The alternation of sudden increases and decreases of the number of light balls of the cluster is the main cause for the drastic variations of luminosity of the light phenomenon as a whole.

The strong variability of the Hessdalen lights seems to be a peculiarity of earth lights. There is not yet any solid demonstration of such behavior by ball lightning (Stenhoff, 1999). Nevertheless, the mechanism by which such a variability occurs, namely the sudden appearance of satellite light balls around a common nucleus, can be related to the re-minimization of the effective surface energy predicted by Turner's model (Turner, 2003).

Concerning the ''on'' and ''off'' periods of the observed lights, there are hints from some aspects of ball-lightning behavior. Some analogues of ball lightning do not have luminous centers (Turner, 1998) and the visible light emitted from these phenomena is feeble. If the Hessdalen lights alternate between ''on'' and ''off'' phases, it may mean that they are too feeble to be seen in their ''off'' periods. If so, then the ''on'' periods presumably result from periodic increases in piezo-electric activity, or from cosmic-ray showers with their associated release of electrical energy.

Ejection of mini light balls

In many cases, the ejection of smaller light balls is shown under computer enhancement of both video frames and photographs (see Fig. 7). Within our limited data-set, the color of the ejecting ball is always white, while the ejected mini ball is always green (Teodorani et al., 2001, Teodorani & Nobili, 2002). The ejection can happen in a second or less. Video frames with a time-resolution of 1/30 sec show the process as almost instantaneous. Photos show no motion but a clearly distinguished green, smaller light ball standing still at a distance of about 100 m from the larger, white light ball. It is possible that the ejection process has a close connection with the formation of light clusters. The secondary orbs tend in their turn to be surrounded by new spherical orbs to form a new cluster. This mechanism, of unknown origin, is reminiscent of cellular multiplication.

The empirical evidence is that the small balls which can be ejected to a large distance (of the order of 50–100 m) from the large white colored nucleus tend to be green colored, while the small balls which appear to be very close (distance of the order of 2–5 m) to a cluster nucleus tend to be white (high intensity) or red (high intensity) and blue (low intensity) colored. Again the reason for the different colors, which are apparently related to distance from the nuclear region, remains unknown. Both dynamic processes (clustering and apparent ejection) are likely due to the minimization of the effective surface tension, and the transfer of energy to the new ball is probably an electromagnetic phenomenon (Handel, 1997).

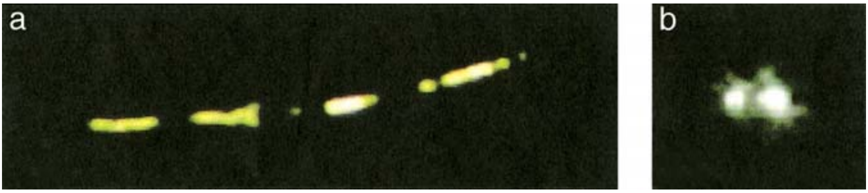

Fig. 9. a: Trajectory of a photographed luminous phenomenon which shows a pulsating behavior. b: Infrared video frame (by Marsha Adams) of a red pulsating light phenomenon which shows a linear motion.

High radiant power

By applying photometric techniques to the photos, on one occasion it was possible to estimate an order of magnitude of the energy produced by the light phenomenon (Teodorani & Nobili, 2002), a typical cluster of multi-colored balls (see Fig. 5) that brightened in a single event and then turned off without turning on again. A duration of 5 seconds was assumed, which was the average of many observations of the same target in the same position. The values of the optical energy of the single components of the cluster were summed to obtain an integrated value. The absolute radiant power P, which can be known only if the distance is known, was derived by assuming that it radiates isotropically. The distance was estimated at 9 Km by triangulation (personal communication from Marsha Adams, 2002), radar measurements by the engineering group (Montebugnoli et al., 2002), and high-resolution topographic maps. A 3-D reconstruction of the map of the area, done in a further phase by geophysical researchers, further confirmed the distance estimates[6]. The cluster-like phenomenon yielded a radiated power of about 19 kW ± about 30%. Similar calculations were carried out on images produced by the well-known streetlights in Hessdalen, whose straight-line distance is known to be about 6 Km; that gave—as expected—a magnitude smaller by a factor of 60 than that of the absolute radiant power of the light phenomenon. For comparison, the radiant power of a Hessdalen light is more than 10 times greater than that of a typical helicopter searchlight. A description of the procedure used to obtain the P value of the Hessdalen light-cluster is presented in Appendix 1.

Jerky kinematic behavior

The motion of most of the Hessdalen light balls is not continuous but jerky. This happens very often close to the ground. The lights turn on and off at a particular point and then sometimes turn on at another point very far away (up to 1 Km or so). This kinematic behavior, which normally produces a dotted luminous trajectory (see Fig. 9), appears very clearly in long-exposure photographs. Some white orbs, which are mostly seen in the sky, behave in a slightly different way. They turn on suddenly, move linearly, slowly and gradually by making a short path towards the observer, have a sudden outburst of light and

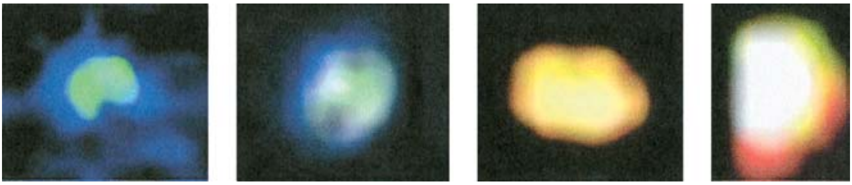

Fig. 10. Three photographic examples of symmetric luminous objects in Hessdalen (*from left*). One video frame of a rectangular luminous object (*on the right*).

disappear abruptly (Teodorani et al., 2000, 2002). Some other orbs are even more uncharacteristic, moving linearly low in the sky and often characterized by long-duration, regularly pulsating, double red lights (Teodorani & Nobili, 2002). In such a case there is no vanishing but only a gradual descent towards the forest.

Both gradual and abrupt changes in motion are predicted by the most recent models of ball lightning. Turner (1998) attributes these kinematic characteristics to asymmetries in the layer of droplets of the light balls, which can be caused by changes in either the chemical or electrical state.

Geometric and symmetric shapes

Approximately 5% of the sightings during the three EMBLA missions were characterized by light phenomena of geometric or symmetric shape (see Fig. 10). Such shapes can form in two ways: a) the more standard light balls join together in a sort of geometrical arrangement, often triangular (see Fig. 5), which tends to dissipate over a period of 5–30 seconds; b) some very-low-brightness objects, often with translucent characteristics and of constant brightness, appear suddenly low in the sky or very close to the trees showing intrinsically geometric shapes, mostly triangular or ellipsoidal (Teodorani et al., 2000; Teodorani et al., 2001; Teodorani & Nobili, 2002). Rectangular shapes have been recorded as well (see Figs. 5, 10): in this case radiant power was very high and the top of the ID was saturated. The reason for these shapes is totally unknown. The rectangular shapes (recorded on 1/30 sec video frames), in particular, are not simply a result of videocamera pixilation effects, since the same kind of shape is recorded by conventional photographs. In a specific case, the rectangular shape is much smoothed owing to fast motions of satellite-spheres around the rectangular core during a long-time exposure (Teodorani et al., 2001).

Some rectangular light phenomena consisted of a central area around which some satellite light balls were very closely distributed (see Fig. 5). Apart from the rectangular shape, seen only in those specific cases, such kind of phenomenon, which was anyway occurring very rarely, resembled the more standard clustering and blinking behavior of the more common light balls.

It must be remembered that 95% of the remaining phenomena, which we can define as the "standard phenomena," showed time variability at a very high

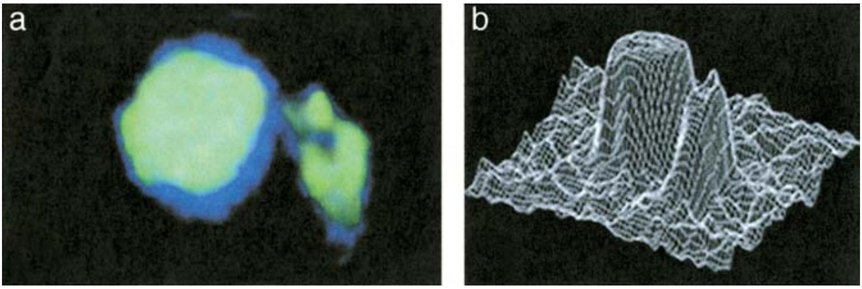

Fig. 11. a: A flashing light which appeared suddenly at a distance of about 100 m far from the observer, as recorded from a long-exposure photograph. b: Light distribution.

level of brightness, clustering behavior, no geometric shape or particular symmetries, and no constancy of brightness at low levels.

The geometric shape found in a minority of light phenomena cannot be explained by any available ball-lightning theory, and the picture is highly complicated by the fact that some of these shapes (in particular, the rectangular one) are just the nucleus of a cluster of lights producing a blinking light phenomenon. On the other hand, the apparently geometric symmetries shown by the mutual position of light balls could be due to mere chance.

Flash-like lights and possible Earth-sky physical interactions

The entire Hessdalen valley seems to be somehow highly electrified. Everywhere, both in the sky and close to the ground, flashes of light appear with durations of fractions of a second. Flashes are mostly orb-shaped, but sometimes very elongated shapes have been recorded as well. Some of them have been photographed using very long exposures towards directions where no streetlights or roads were present (see Fig. 11). In several cases these particular light phenomena approached observers at a distance ranging approximately from 3 (personal communication by Bjørn Gitle Hauge, 2002) to 100 m, showing an intrinsic radiant power ranging from 10 to 300 W and dimensions as small as 10 cm. The presence in the valley of copper mines suggests that, assuming the lights are powered electrically, sub-surface metals may amplify any currents initially produced by piezo-electricity or the impact of cosmic rays. Some of the lights seem to be associated with radio emissions (Gori, 2001; Zou, 1995) from low-energy plasmas which are possibly produced as after-effects of tectonic strain. These would be manifested only in specific locations on Earth where piezo-electric and electromagnetic effects can combine. The Hessdalen area is likely to be one of these geophysically peculiar locations owing to the richness of quartz, copper and iron underground. In this context it is hypothesized that the constantly changing high-energy cosmic-ray cascade might inject some additional energy into the pre-existing low-energy plasma. The effect of this process would be to raise the electrons of a low-energy plasma to a much higher quantum state via photo-excitation and photo-ionization, shifting the emissions from the radio range to the optical. In such a case a very short-lived ball of light would become visible in the form of a flash. The ongoing random changes in cosmic-ray cascade could produce corresponding changes in light intensity, flash-like appearance and disappearance. This process could continue until the high-energy cosmic-ray cascade momentarily ceases and the light disappears. This is but one hypothesis (by the author) that must be verified using proper instrumentation such as Cerenkov detectors and VLF-ULF and UHF spectrometers. It is not known if any physical link between flash-like lights (also called: "micro-radiation") and the long-lasting light balls exists, but it seems that the frequency of these flashes increases just a little before and after the manifestation of the long-lasting light balls.

Low-luminosity emission

We lacked an infrared detector, but with night-vision systems (NVS) we were able to observe phenomena that were extremely weak when seen with the naked eye but that showed high brightness with the NVS. Such a device is able to intensify the optical light at long range (of the order of kilometers) and to give an infrared image in the very short range (of the order of 50 m). In some cases when the light phenomenon disappeared totally from sight, at the same position in which the phenomenon was previously located we were able to see a very intense and quite stable emission that lasted many minutes (Teodorani et al., 2001). This duration was longer by at least a factor of 10 than the typical optical duration of the light events. This important information, which unfortunately does not come from recorded data (such as infrared photographs) but from our eyewitness using the NVS, suggests that what we have conventionally called "off" phases of the Hessdalen lights might be only "low-luminosity" phases. It is worth noting that similar low-luminosity phenomena were photographically recorded on infrared-film in Pensacola, Florida (Maccabee, 1991: http://brumac.8k.com/GulfBreeze/Bubba/GBBUBBA.html).

Doppler VLF signals

The only results from radio observations were obtained using the VLF-ELF correlation receiver and spectrometer (*ELFO* system) connected to two loop antennas. The data, continuously recorded during 24 hours a day, consisted in sequential sampled files 2 minutes long. The analysis was carried out on snapshots of interest having a duration of 20 seconds. Some of them showed very interesting characteristics.

A lot of well known man-made and ionospheric signals were recorded and identified. Spike-like signals appeared with rigorous periodicity (of the order of a fraction of a second) as trains of impulses in the same frequency range, apparently resembling the morphology of the radio phenomena recorded by Project Hessdalen in the HF frequency range in 1984 (Strand, 1985).

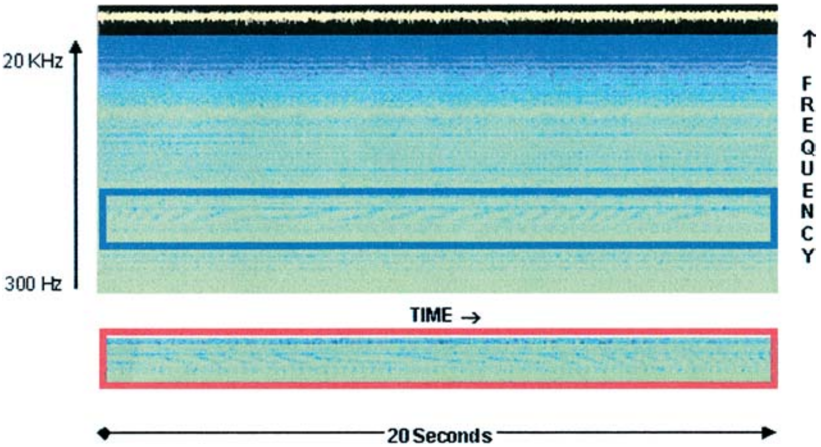

Fig. 12. Suspected Doppler signals with a gradually changing blue-shift (marked by rectangle) recorded by a VLF spectrometer. An example of gradually changing red-shift (marked by rectangle) is also shown below.

Nevertheless, in the VLF-ELF frequency range such signals were also extremely similar to those produced by the LORAN and the (Russian) ALPHA navigation transmitters,[7] and were therefore considered of likely man-made origin. Many other known signals due to man-made activity (namely: electric devices of any kind), and ionospheric signals such as sferics, "chorus sounds," and tweeks, were often recorded and promptly identified.

Peculiar signals (see Fig. 12) appeared intermittently in the 1–2 kHz range as somewhat sloping "broad lines" (Teodorani et al., 2000). The slope of these lines changed almost periodically and gradually from negative to positive, in a matter of some tens of seconds. The duration of these signals, which were reported many times, was normally of 15–30 minutes. Compared with the well known whistlers,[7] they might resemble in some aspects the variant of "diffuse whistlers," produced by charged particles traveling along a set of magnetic field lines that are not all of the same length. Nevertheless, differently from the whistlers case, in our case there was always a fast inversion of the slope (typically after 30 seconds): in subsequent snapshots, the lines were mostly rectilinear and not curved, and much more crowded together. This behavior could be explained neither by known natural signals nor by man-made signals such as electric devices or submarine communication systems. Therefore we consider these anomalous signals as a low-frequency radio phenomenon from an unidentified source. A possible way to interpret their behavior is the Doppler effect. Assuming that to be the case, using the classic relation[8] (Lang, 1998) given by $v = c\ (\Delta\nu / \nu)$, it is possible from the measured frequency to determine the velocity of the emitting source, which changes rapidly (i.e., within several seconds) by a factor of 10 from 10,000 Km/sec up to 100,000 Km/sec. The alternating positive and negative slope of the broad lines indicates that

Doppler shifts both red-wards and blue-wards are involved, and that many cycles occur for as long as half an hour, starting and finishing abruptly as if some electromagnetic phenomenon is turned on and off. The origin of an oscillating Doppler effect in these signals is presently unknown; it is reminiscent in some ways of a small-scale version of the pulsating radiation observed in such fast-spinning astronomical objects as pulsars (Lang, 1998). It must be studied further with more in-depth measurements.

In conclusion, only the Doppler-like signals were really interesting and they were considered anomalous only after we did a careful comparison with all known man-made and natural signals and internal noise such as intermodulation, which we also repeatedly recorded. Unfortunately at the precise times in which we recorded the anomalous radio signals (typical duration: 15–30 minutes), both in the day time and at night time, we did not record light phenomena (typical duration: 5 sec–3 minutes). The most probable reasons of this were that at the times of radio monitoring a constant presence of personnel in the observation points could not be guaranteed for practical reasons, and that light phenomena cannot be seen in the day time.

These anomalous signals cannot be explained by the same ball-lightning theory that seemingly is able to explain some aspects of the optical phenomenology (Turner, 2003). An alternative ball-lightning theory involving a fast spinning pulsar-like ball lightning (Endean, 2000) might account for the recorded signals if their interpretation is correct, but the standard nature of the plasma, which is predicted to be produced by nuclear fusion inside the spinning light ball, simply cannot explain the observed optical features.

Slightly radioactive powder and metallic particles

Three ground samples were collected close to a river near *Vårhus*, about 5 Km from Hessdalen, where a very close sighting of a light orb had been reported by Norwegian witnesses. A Geiger counter showed that the powder deposited on one specific rock (with an area of about 2 m^2) just on the river bank, had a level of radioactivity of 20 µrad/hour, which is higher than the average (normally: 4–9 µrad/hour). Radioactivity was used as the criterion for choosing and collecting earth and powder samples for further microscopic and spectroscopic laboratory analysis. The collected samples were:

A. <u>Target Sample</u>. Some grams of powder, radioactivity 20 µrad/h, deposited on the surface of a rock.
B. <u>Control Sample 1</u>. Some grams of powder from a rock with no radioactivity about 10 m away from the first rock.
C. <u>Control Sample 2</u>. About 1 Kg of earth extracted by coring technique at about 10 m away from the target sample and at a depth of about 10 cm.

The laboratory analysis (Teodorani & Nobili, 2002) was carried out at the *SACMI Imola* industry by Dr. Stefano Maretti.

<u>Control Sample 2</u> was subject to chemical and mineralogical analysis by

plasma spectrometry, X-ray diffraction, and microscopy. This ground sample was found to be composed of quartz (60%), albite (15%), anfibol (riebeckite and tremolite: 13%), and mica and clay minerals (12%).

Target Sample and Control Sample 1 were subdivided, and each portion subjected to morphological and chemical analysis using optical and electronic (SEM) microscopy.

Observations obtained by means of an optical microscope have confirmed the mineralogical nature of the powder and proved the presence of considerable organic material of both vegetal and animal nature. From the point-by-point micro-analysis carried out by means of the electronic microscope, three reliable results have come out:

- The diffuse presence, in all samples, of silicon "tissues" (probably micro-fossils).
- The presence only in the target sample of particles of zirconium silicate which might be the main cause of the weak radioactive emission detected in this powder.
- The presence, only in the target sample, of a perfectly spheroidal iron particle with a diameter of about 20 μm (see Fig. 13). Such a shape is unusual in nature.

It does not seem that the spherical iron particle could be explained by any after-effect of a phenomenon similar to ball lightning. Nor is it certain that the iron particle is really due to the light phenomenon and not to a micrometeoritic remnant deposited by chance in that specific location.

Observational evidence, possible interpretations, and open questions

Combining the data acquired in the first phase (Norwegian measurements) with those from the second phase (the three EMBLA investigations), we ascertain the following phenomenological features:

- The light phenomenon, mostly white and more rarely red, is reported more often in the winter season, and occurs mostly at night with a frequency peak around midnight. It shows no preferential trajectories and is distributed everywhere in the sky and on the ground. In the summers 2000, 2001 and 2002, the appearance of the phenomenon coincided with a high humidity.
- Sometimes the light phenomenon, which appears very often several tens of meters over the top of the hills, shows a jerky motion along very short distances ($d \leq 100$ m), with an almost instantaneous movement from one point to another.
- Seen from far away, in most of the instances where the luminosity is high, the light phenomenon has the appearance of a glowing light ball with no structure. In a few cases it manifests a geometric shape and blinking lights. In

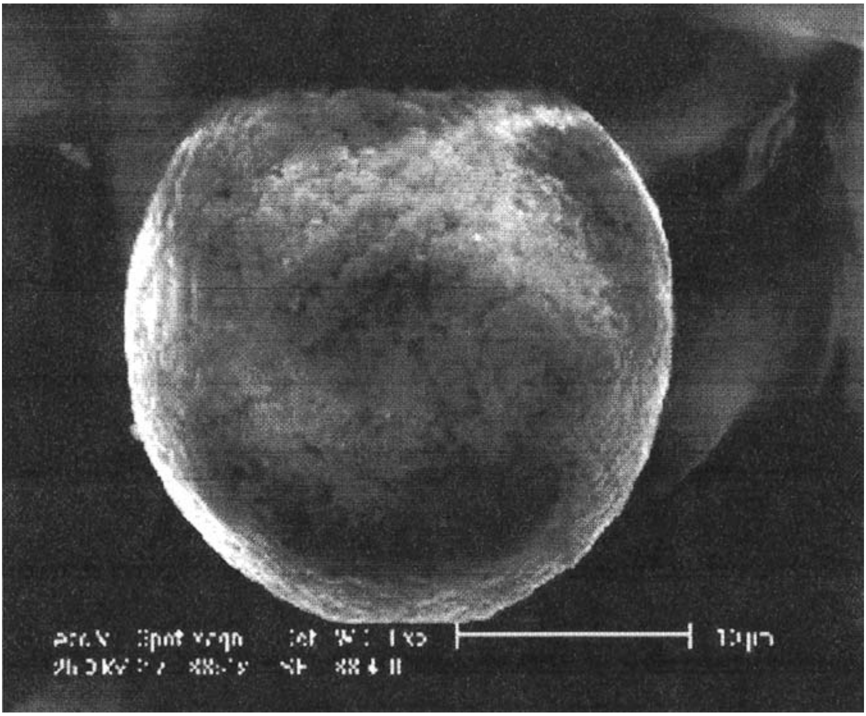

Fig. 13. Spheroidal iron particle of about 20 μm in diameter (electronic microscopy) which was found in the powder deposited on a stone approached by a light phenomenon. Analysis by SACMI Imola.

some instances with low luminosity, it manifests some kind of geometric structure.

- The light phenomenon is always preceded by very short-lasting (on the order of a fraction of second) flashes of light which appear everywhere in the valley and which emit power ranging from 10 to 300 W. Sometimes such flashes are recorded at a very short distance (up to 5 m) from the observer.
- The intensity of the light balls, which in optimal atmospheric conditions shows a steep and rectilinear 3-D distribution, is drastically different from the Gaussian-exponential shape expected from a standard plasma.
- Luminosity is time-variable with a periodicity of 1 second or less, and a maximum power of the order of about 19 kW can be produced. In most cases, irregular or semi-regular pulsations are terminated after a few cycles whose average duration is 5 seconds. In other cases, many cycles continue for as long as several minutes or more.
- Luminosity increases in a drastic way because of the sudden appearance of many small light balls around a larger luminous core. The luminosity increase is caused only by the dimensional increase of the composite light surface

formed by the cluster of light balls. Some of these secondary light balls are often ejected from the core.
- The phenomenon produces light with a constant color-temperature, behaving like a lamp with "on" and "off" phases.
- The spectrum shows three well-distinguished peaks about 500 Å wide. Each may resemble either a blend of unresolved spectral lines or a light emission very similar to that produced by LED illumination systems.
- Night vision systems revealed that the light phenomenon produces a very strong infrared signature even when it is very faint or invisible in the optical range.
- The light phenomenon is often accompanied by a pulsating magnetic perturbation with a period of few Hz and by small and very-short-duration pulsating "spikes" in the HF radio ranges (Strand, 1985).
- Sometimes long-lasting Doppler-like signals are recorded in the VLF range, mostly when the light phenomenon is not visible.
- The light phenomenon often shows strong radar tracks, including when it is optically faint or almost invisible. In some cases in which it is visible, it shows no radar track (Strand, 1985).
- The light phenomenon shows a photo-reactive capability when a laser beam is aimed at it, systematically doubling its pulsation rate (Strand, 1985, 2000).
- The light phenomenon is suspected of being able to release spherical iron particles onto the ground.

Many theories have been proposed to explain ball-lightning phenomena (Stenhoff, 1999) and a few have been proposed to explain the specific Hessdalen phenomenon and earth lights in general (Strand, 1994). The present evidence of Hessdalen phenomena makes it necessary to consider whether or not earth lights and ball lightning are two sides of the same phenomenon. This was discussed during a workshop held in Hessdalen in 1994 (Strand, 1994; Teodorani & Strand, 1998), where, in addition to the presentation of the experimental evidences and of observational techniques, three physicists in particular discussed ad-hoc theories (Fryberger, 1997; Smirnov, 1994; Zou, 1995), which were adaptations of their own theories on ball lightning to the Hessdalen phenomena. At that time, such theories could be compared mostly with simple witnesses of the phenomenon and not with real observational data. Now, with some real data in hand, it appears that two of these theories cannot explain the most important aspects of the Hessdalen light phenomenon in a satisfactory way. Fryberger's model (Fryberger, 1997), based on toroidal concentrations of electromagnetic charges similar to magnetic monopoles rotating as flywheels in a particle-antiparticle symmetry, shows many useful multi-wavelength quantities that can be observationally tested, but the standard plasma invoked to describe the light balls does not match the light distribution found. Smirnov's model (Smirnov, 1994) shows that a light ball simultaneously contains properties of a gas, a liquid, and a solid. This might be consistent with the light distribution observed. However, the model envisages light balls triggered by a single shot of energy and does not persuasively explain balls that survive for several minutes, as earth lights do. The correlation between size and life-time that Smirnov's model predicts is not convincing; there are cases that do not fit that pattern at all (Stenhoff, 1999). Zou's model (Zou, 1995) shows that in areas in which tectonic stresses are present, the ground is able to liberate simultaneously charged particles and electromagnetic radiation in the VLF (Very Low Frequency) and the UHF (Ultra High Frequency) ranges. High-frequency waves heat and ionize the surrounding air and low-frequency waves condense the plasma, while charged particles work as attracting nuclei. A plasma light ball can be formed as a final by-product of this process, which is also favored when the humidity level is high. The resulting plasma ball, according to calculations carried out using non-linear fluid dynamics, rotates as a vortex, the rotatory motion being caused by the micro-properties of molecules and atoms. This theory shows that some characteristics related to piezo-electricity can trigger the ignition of light balls, especially in the presence of tectonic stresses (Adams, 1990; Derr, 1986; Freund, 2003; Lockner et al., 1983). The abundances of quartz (the main possible source of piezo-electricity), copper, and iron favor an efficient liberation of electricity and electromagnetic fields. Even if tectonic stress producing piezo-electricity is due to other causes than seismicity (Strand, 1985), these conditions are present in the Hessdalen underground, and might be the triggering cause of the particular light phenomena which would properly be called "earth lights." The piezo-electric theory and related electromagnetic effects can furnish a satisfactory explanation concerning the way in which a light ball is initiated, but, if we consider the standard plasma signature predicted by Zou's model, it is not yet able to predict the specific light distribution of the light balls that we found. This is probably due to the fact that Zou's model does not take into account the thermochemical effects that can arise when a plasma interacts with an air medium full of aerosols. Therefore, Zou's theory is possibly correct but still incomplete.

One of the existing ball-lightning models seems to provide the most fruitful explanations of our observations of the structural behavior of the light phenomena. This model appears particularly useful as it can qualitatively explain all of the known facts about ball lightning (Stenhoff, 1999) and because the two phenomena seem so similar in many ways. Turner's electrochemical model (see previous chapter; Turner, 2003) can explain why a light ball is able to acquire structure and stability through thermochemical refrigeration that may occur as a result of evaporation of the hydrate water when a plasma event is initiated inside a humid and aerosol-rich atmosphere. The gas inflow predicted by this theory, and the resistance to the flow in the refrigerated region, provides an inward force that holds the ball together. Accordingly, the plasma ball will show a sharply defined edge at its outer surface. This is an effective mechanism for confinement and self-regulation of the ball. This seems to explain quite successfully the very sharp and steep light distribution which was found in our optical images. Thus the light phenomenon is not a standard plasma but one that triggers a thermochemical process in the surrounding medium of the atmosphere. This process is amplified when the quantity of water vapor present in the local atmosphere is high; and in Hessdalen, most light phenomena were indeed recorded when the humidity was at a high level. Other important observational evidence, such as the sudden formation of light clusters and their consequent brightness variability and the ejection processes, can likely be explained as a consequence of re-minimization of the effective surface energy, while the jerky motion can be explained by asymmetries in the layer of droplets owing to changes in either the chemical or electrical state.

Some of the available data concerning the Hessdalen phenomenon, in particular its optical behavior, seem to show that the most important aspects of the intrinsic structure of earth lights can be explained by the same physical process that characterizes ball lightning. The better established differences between ball lightning and earth lights concern the normal ranges of size and life-time. The largest sizes and lifetimes are typical of earth lights. It has been suggested (Turner, 2003) that the differences may be partly a result of differences in the air’s electrical space-charge between fine and thundery weather conditions.

As a working hypothesis, another important difference between earth lights and ball lightning, according to some of the data acquired so far, seems to consist mainly in the external cause that triggers initiation of the light phenomenon. Earth lights are more probably triggered by piezo-electric and related electromagnetic phenomena (Zou, 1995), which may account for the relatively long duration of these typically blinking light events (several minutes or more), compared to the short duration of ball-lightning phenomena (several seconds). If earth lights are phenomena that depend on the geophysical nature of the territory and on its more or less long-lasting tectonic stresses, then their precise spatial recurrence is to be expected. Variations of the phenomenon on hourly, daily, and monthly scales are likely due to (normally periodic) variations in humidity, while longer-time-scale changes are possibly due to different (possibly transient) phases of seismicity. Other time changes on various scales might be due to variation of cosmic-ray showers, and the possibility of an ‘‘Earth-sky’’ connection, due to possible interactions between geophysical and cosmic processes. These clearly need to be studied more extensively.

Ball lightning (Stenhoff, 1999) is more probably triggered by atmospheric electricity and its typically very short duration is probably (or partly) due to single shots of energy such as lightning during thunderstorms.

In general, in both cases (ball lightning and earth lights), there seems to be a satisfactory theory (Turner, 2003) as the main reason why these light phenomena are not subject to adiabatic expansion and rapid decay, and some important suggestions about the processes needed to initiate the electrochemical refrigeration. Probably one important difference between the two phenomena is a different division of electrical and chemical energy and different duration and intensity of the electric causes that trigger them. In the case of ball lightning, according to the electrochemical model, more than one means of sustaining the plasma against gravity is available. Forces will result from the total weight of the heavy aerosols surrounding the plasma and also from electrically induced changes to their distributions around it. In general, it is difficult to decide what forces must have been operational except in cases where a ball is situated too far away from the earth for currents to and from it to be significant.

Other evidence we found in Hessdalen constitutes another anomaly inside the main anomaly. We cannot yet confirm that the lights really are associated with Doppler-like signals in the VLF range or with the deposition of metallic particles. Therefore a sound comparison of these findings with Turner's model is not yet possible. On the other hand, none of the discussed theories of natural type is able to explain the geometric shapes or structures that were recorded by us in a small minority of cases. It is not yet known whether these manifestations are different and rarer aspects of the same "standard" light phenomena or whether they are distinct phenomena that overlap with the standard one for some unknown reasons. A similar strange mixture of "standard earth-light phenomena" and very exotic features are reported in other locations of the Earth too (see Appendix 2). This uncomfortable side of the anomaly constitutes valuable observational evidence and must be investigated more deeply. Also, working hypotheses different from those covering earth lights (Teodorani, 1998, 2000, 2001a, 2001b; Sturrock, 1999) should be followed up. This research must be conducted by considering how far standard physics can take us, but also with some parallel attention to those other anomalies whose possibly spurious relevance should be investigated. This means simply following one of the main prerequisites of science: methodological rigor. Methodological rigor can be applied to everything.

In general, all of the evidence we have found demands further study using more sophisticated instrumentation. For example, more precise synchronization of radio and optical detection is required if we are to understand the possible connections between them. New spectra of the light emission must be obtained at higher resolution, and recordable infra-red data are needed. Radar instruments with imaging capability are required both to determine the kinematic parameters of the tracks and to determine their cross section.

Conclusions

The observations reported here show that this light phenomenon is elusive and its behavior most often unpredictable. A significant quantity of preliminary observational data obtained by both Project Hessdalen and Project EMBLA helped us to build an empirical picture that shows some very intriguing aspects of the phenomenon's physics, but the exact origin of the phenomenon is not yet known. Even if only the general physical mechanism underlying the phenomenon can be hypothesized, some of our most important evidence suggests an interpretation that uses a physics very similar to that used in the latest models for ball lighting. It seems this physics could explain some structural aspects of Hessdalen-like earth lights too. According to one of these theories in particular, air ionized by some external cause, possibly coming from tectonic stress, could interact with water to create a hot sharp-edged ball of plasma with a cool water-and-ion coat (Turner, 2003). The sharp edge is confirmed by the light distribution we measured, and some other aspects of the phenomenon can be explained in the framework of the same ball-lightning theory. Nevertheless, even within this framework, several obscure aspects still remain and demand more in-depth investigation. Our understanding of both earth lights and ball lightning should benefit.

The instruments so far used are at least one order of magnitude less sophisticated than those needed to obtain stronger, more definitive results. Very detailed projects that utilize optoelectronic instrumentation and sophisticated measurement strategies have been prepared and updated in extensive research proposals during the last several years (Teodorani, 2001b). The field experience so far acquired shows that significant advances in this research will only be accomplished if an appropriate and complete Mobile Monitoring Station (MMS) becomes available. It is now possible to make a totally automated radar-guided and laser-telemetric sensing platform that includes all of the following sensors: a TV monitor, a very-high-resolution multifilter CCD camera, a high-resolution and wide-field fast-scanning spectrograph, a multi-filter high-speed photon-counting photometer, a multi-filter spectrophotometer, a photo-polarimeter, a FLIR (*Foreward Looking InfraRed*) detector, a microwave parabolic antenna and spectrometer, a LIDAR (*Light Detection and Ranging*) and an electrostatic detector. These sensors should be used in connection with portable VLF-ELF and ULF antennas and spectrometers, and a portable atmospheric station that registers moment by moment all the relevant parameters. Our efforts and field experience so far demonstrate that this research requires the highest level of alert-readiness. And the automation of the requested instrumentation is a prerequisite which does not remove the need for personnel in the field. A closer interaction and collaboration between physical scientists, engineers and computer scientists might be very important for several reasons.

The most important aspect of this research is probably the investigation of new sources of clean energy. This objective has provided, over many years, a justification for ball-lightning studies. However, despite all that has been learned about ball lightning, we still understand its initiation stages too poorly to permit its creation in the laboratory. A study of earth lights has the great potential advantage over ball-lightning studies that we can study the physics of very similar contained plasmas on the natural phenomenon, using a fully experimental approach. This is possible because earth lights recur at several locations on Earth (see Appendix 2); Hessdalen is only one of them. Thus we have at our disposal "natural laboratories" spread out all over the world. Using these, we can study precisely those aspects of electrochemical plasmacontainment that are most vital if we are ever to apply the technique in the laboratory or industrially.

Notes

[1] *The observed very high amplitude and morphology of the three spectral peaks cannot be compared with the well-known non-flat sensitivity curve of the used Kodak Ektachrome 100 ASA film. Known sources emitting a continuum spectrum (such as car headlights) which were used as comparison-tests with the same kind of film, show a totally different behavior.*

[2] Lamp Emission Spectra, http://cc.joensuu.fi/photobio/lamps.html

[3] *Spectra of white LED lights—several types do exist in commerce as well—are not easily found in the literature, but the spectral peak produced by some white LED lights appears to coincide with one at 5100 °K in the spectrum of the Hessdalen light.*

[4] Ansbro Wide-Field Fast Scanning High-Resolution Spectrograph, http://star.arm.ac.uk/asgi/2002_autumn_nuig_abstracts.html

[5] *Video frames in which the light phenomenon is over-exposed or saturated have been excluded from the analysis. Only correctly exposed frames have been considered. The components of a light-cluster can be resolved only when the exposure is correct. When the exposure is too high, image enlargement will merge them into a large saturated image.*

[6] Nicolosi I. & Ricchetti N., 'A simplified digital elevation model of Hessdalen valley', Sassalbo Project, http://www.sassalboproject.com/documenti/hessdalen_3dmodel.pdf

[7] Whistlers: http://image.gsfc.nasa.gov/poetry/inspire/advanced.html LORAN and ALPHA signals: http://image.gsfc.nasa.gov/poetry/inspire/advanced.html

[8] Where: v = velocity of approach (–) or recession (+), c = velocity of light, ν = rest frequency and $\Delta\nu$ = frequency shift.

* http://www.astrosurf.com/buil/us/iris/iris.htm

** http://www.kodak.com/global/plugins/acrobat/en/consumer/products/techInfo/e2328/e2328.pdf

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Appendix 1

Procedure used to determine the absolute radiant power of a light phenomenon

Several methods were used to calculate the absolute radiant power emitted by the light phenomenon of Fig. 5. The cross-check of such methods helped us to make the best choice. The following description is of the chosen method in which the absolute radiant power P was obtained by using the equation (Maccabee, 1979, 1999):

$$P = 4\pi d^2 \frac{E}{\tau \frac{\pi}{4}\left(\frac{F}{f}\right)^2 T} e^{\frac{3.9d}{V}}$$

where d is the distance (in m), $E = I \times A$ (in lm·sec) is the total energy received by the film (for a 100 ASA Kodak Ektachrome slide) integrated over the image area, I is the energy per unit area of the image (in lm·sec m^{-2}), A is the image area (in m^2), V is the optical visibility distance (in m), τ is the duration of the light phenomenon (in sec), F and f are respectively the focal length and the f-number of the camera (the ratio $D = F / f$ gives the aperture diameter of the lens, in m^2), T is the lens transmission factor.

The slide was passed to a scanner, and the image of interest was resized (image interpolation) and then transformed into a black-and-white frame (using software *Adobe Photoshop* version 5.5). Using software *Iris** the counts and the 2-D Intensity Distribution of any single component of the light cluster were measured. After determining the saturation level and ascertaining that there was no substantial over-exposure, the counts were scaled with the exposure parameter deduced from the Density–Log(Exposure) characteristic curve for the specific Kodak film.** A scanning densitometer to determine the image density directly from the photo negative was unfortunately not available to us. The average exposure value was given by $I = 8.8$ lm·sec m^{-2} (after inverting $\text{Log}(8.8) = 0.94$). The image area was obtained with good precision (error = 5%) using Adobe Photoshop 5.5 software. Any single component of the light cluster was approximated as a circle with radius 5×10^{-4} m. The area of each circle was calculated. The areas of all the light components were summed, yielding a value of $A = 3.9 \times 10^{-6}$ m^{-2}. Therefore the total energy received by the film within the boundary of the image was $E = 3.4 \times 10^{-5}$ lm·sec. The remaining parameters were fixed as follows: $d = 9 \times 10^3$ m, $\tau = 5$ sec, $F = 0.27$ m, $f = 2.8$, $T = 0.9$, $V =$ 15 Km. Knowing that 1 lm = 0.001496 W, the absolute radiant power of the light phenomenon was calculated to be $P = 18.8 \pm 5$ kW. The error associated with this figure was obtained by trying to evaluate the contributions due to the following parameters: d, τ, I, V. Their composite effect was judged to be an error range of about 30%. A cross-check of the obtained value of P was done by calculating the same value of a known streetlight that was present in the same photo. Knowing with good accuracy that this conventional light source was at a distance of 6 Km, that it was constantly turned on, and that the exposure time of the photo was $t = 60$ sec (in such a specific case $t = \tau$), we obtained the value $P = 317 \pm 50$ W, a factor 60 smaller than that of the light phenomenon.

Appendix 2

Other important locations in the world where recurrent light phenomena are reported

Light phenomena similar to the Hessdalen phenomenon (the most studied scientifically so far) are recurrently reported in several other locations of the world (Teodorani, 2001b, 2003), the most important of which are:

Min-min (Australia), Byron Bay (Australia), Northern Beaches (Australia), Lake Ontario (Canada), Lake Tagish (Canada), St. Louis (Canada), Saguenay

(Canada), Marfa (USA), The Brown Mountains (USA), The Hudson Valley (USA), Yakima (USA), Hardin-Ohio (USA), Spokane (USA), The Arizona Desert (USA), Dundee (USA), Sedona (USA), Perm (Russia), Victoria (Argentina), Cerro Uritorco (Argentina), The Wu Tai Shan Mountain (China), The Longdendale Valley (UK), The Popocatepetl Volcano (Mexico), Monterrey (Mexico), Boyle (Ireland), Monti Sibillini (Italy), Sassalbo (Italy), Valconca (Italy), Cluj Napoça (Romania), The Tatra Mountains (Poland), Arendal (Norway), Twente (Holland), Nong Khai (Thailand).

Most of these cases come from visual and photographic reports. Very detailed video, photographic, and telescopic reports (started in 1997 and ongoing) are presented at the ORBWATCH website (http://www.globalserve.net/~mallet/) by documenter Jennifer Jarvis. Valuable scientific investigations, carried out in the Yakima area (Yakama reservation) since 1972 by engineer David Akers (http://www.vogelstudy.org/), show that light phenomena are probably correlated with magnetic perturbations. Instrumented field studies are currently carried out in several areas of the world by geophysicist Marsha Adams and engineer Erling Strand in the framework of the International Earthlight Alliance (http://www.earthlights.org/).