ARTICLE IN PRESS

Journal of Atmospheric and Solar-Terrestrial Physics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Quantitative intensity and location measurements of an intense long-duration luminous object near Marfa, Texas

Karl D. Stephan [a,*], James Bunnell [b], John Klier [c], Laurence Komala-Noor [a]

[a] School of Engineering, Texas State University, San Marcos, TX 78666, USA
[b] Director of Mission Planning Systems, BAE Systems (retired), Benbrook, TX 76132, USA
[c] Department of Geography, Texas State University, San Marcos, TX 78666, USA

ARTICLE INFO

Article history:
Received 25 August 2010
Received in revised form
13 May 2011
Accepted 1 June 2011

Keywords:
Ball lightning
Lightning
Marfa lights
Photometry
Rydberg matter
Vortex

ABSTRACT

On June 3, 2005, in western Texas, luminous phenomena, including an extremely bright luminous object (EBLO), which emitted light for over 3 h, were photographed by two automated monitoring stations during a series of intense thunderstorms. Certain lightning strokes recorded by the National Lightning Detection Network (NLDN) correlate well with the origin of the brightest object in time and space. Optical triangulation located it on the ground at a distance of about 28 km from the farthest station, and absolute radiometric measurements indicate the object's peak emitted visible-wavelength power was of the order of 10 kW. Possible explanations for these objects are discussed.

1. Introduction

We report in this paper quantitative photographic and photometric observations of intense, long-lasting light sources, which occurred during a series of thunderstorms on the night of June 2–3, 2005 (CDT), at Mitchell Flat between Marfa and Alpine, Texas. The objects photographed included one extremely bright luminous object (EBLO) that persisted for more than 3 h. The light emission and duration of the brightest object photographed was greater than what would be expected from an artificial light source or ball lightning. A good time and space correlation was found between a set of simultaneous lightning discharges recorded by the National Lightning Detection Network (NLDN) and a lightning flash photographed less than 1 min before the EBLO appeared. The presence of contemporaneous star images and the accessibility of the original camera equipment for laboratory evaluation have allowed us to produce estimates of the object's absolute visible-light-flux output as a function of time. At its peak output, the EBLO was found to be producing about 10 kW of visible-wavelength optical power, given certain reasonable assumptions about the emitted spectrum.

2. Observational equipment

Since 2003, one of us (Bunnell) has operated a system of unmanned video surveillance cameras on Mitchell Flat, with the primary purpose of observing rare atmospheric phenomena that are reported to occur in this region. The observation system consisted of two unmanned monitoring stations (station 1, nicknamed "Roofus" and station 2, nicknamed "Snoopy") equipped with low-light surveillance cameras (Watec model 120 N), which use monochrome 1/2-in CCDs to provide analog NTSC video signals. These signals were fed to multichannel digital video recorders (CBC Corp. model ZR-DH111NP GANZ) recording to hard drives. The system produces images with 8-bit (256-level) pixel-value resolution consisting of 720×480 pixels covering a field of view of about 28° (H) by 21° (V) using lenses with 12-mm focal lengths. Data is recovered every 1–2 month and observed manually for unusual events. Because of the volume of data, the images must undergo a lossy M-JPEG compression process, but this does not significantly affect the usefulness of the data for obtaining intensity or location information. For the observations in question, the cameras were operated in a "128-stack" mode, which sums the images from 128 frame scans at 30 frames per second, effectively producing a series of 4.26-s time exposures. A brief description of this system is given in van der Velde et al. (2007).

The extreme sensitivity and low noise level of the cameras makes images of stars with brightness down to about the 6th

* Corresponding author. Tel.: +1 512 2453060; fax: +1 512 2453052.
E-mail address: kdstephan@txstate.edu (K.D. Stephan).

1364-6826/$ - see front matter
doi:10.1016/j.jastp.2011.06.002

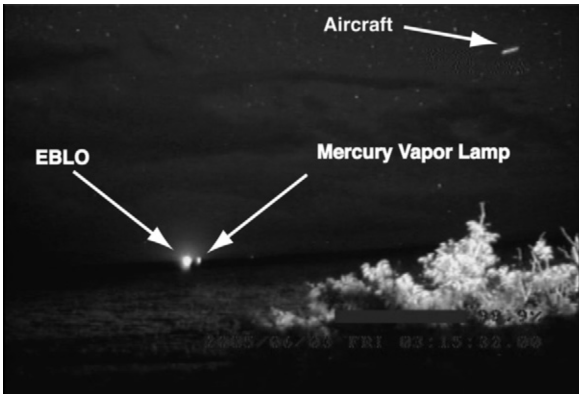

Fig. 1. Frame from DVR recording of monitoring station 1 showing trees illuminated by security lamp in right foreground, DVR timecodes (uncorrected CDT) in lower right corner, track of aircraft during 4.2-s time exposure, a mercury vapor lamp (distance 16 km), stars in the cloudless portions of the sky, and the EBLO (distance ~28 km).

Fig. 2. View from station 1 showing EBLO at its brightest point, as it illuminated low-lying clouds. Most of the lightning activity had moved out of the area by this time (0720 UTC ± 2 m). Mercury-vapor light is to right of EBLO.

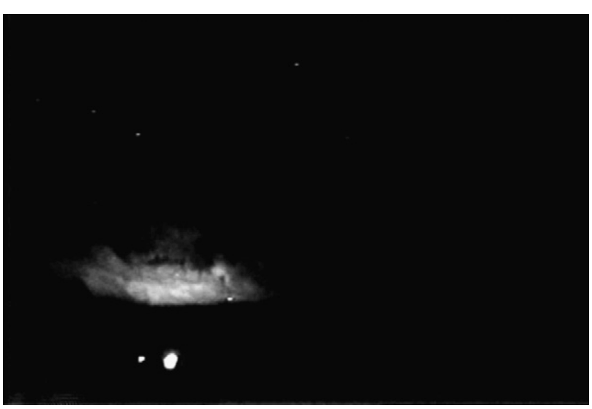

Fig. 3. View from station 2 of EBLO at about 0720 UTC (same time as Fig. 2). Mercury-vapor light is to the left of the EBLO, due to parallax caused by distance between stations 1 and 2 (contrast enhanced to show clouds more clearly).

magnitude easily visible on clear nights. An image produced by a camera at Station 1 during the last few minutes of the EBLO's existence is shown in Fig. 1. It is obvious that the EBLO is brighter than a streetlamp-type mercury vapor lamp that is only about half the distance away (~16 versus 28 km). At its brightest, the EBLO was bright enough to illuminate low-lying clouds, as Fig. 2 illustrates. This shows that the EBLO was radiating approximately isotropically into the upper hemisphere. Fig. 3 shows the object at about the same time as Fig. 2, but as viewed from station 2.

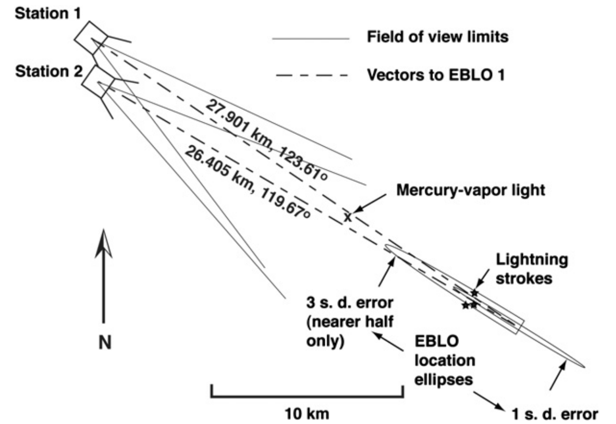

Fig. 4. Map of the Mitchell Flat area showing relative orientation of monitoring stations, mercury-vapor light (*x*), 1- and 3-standard-deviation location error ellipses for location of long-lasting EBLO, and three NLDN locations of lightning strokes (star symbols) occurring at 0530, 3 June 2005 UTC in or near error ellipses.

3. Observations

On the night of 2–3 June 2005 CDT (3 June 2005 UTC), a series of intense thunderstorms moved northward across northern Mexico and western Texas. An NLDN database extract provided by the Vaisala firm indicates that over 8000 cloud-to-ground (CG) lightning strokes occurred in the area bounded by latitudes N 28° 30′ and N 30° 20′, and longitudes W 104° 10′ and W 101° 30′ over a time span from 0200 UTC to 1100 UTC Friday 3 June 2005 (from 9 PM CDT Thursday 2 June to 6 AM CDT Friday 3 June). The NLDN data has a median location accuracy of about 300–500 m, depending on region, and a detection efficiency (percentage of actual strokes recorded by the network) of around 90% (Cummins and Murphy, 2009). Many of these strokes were visible in the time exposures obtained from the two monitoring stations, whose relevant cameras were positioned northwest of Mitchell Flat and aimed southeast so as to view the Flat and the mountains beyond, as Fig. 4 shows.[1] Although the bulk of the lightning activity occurred in the region covered by our cameras between about 0400 UTC and 0600 UTC, some lightning was visible in the distance for several hours after that.

During the course of the storm, at least five persistent luminous objects were photographed by the two automated monitoring stations. Display timelines for all five objects are shown in Fig. 5. The fifth and last object (the EBLO) was the longest lasting and most intense one. This report is focused on analysis of this EBLO.

We developed an image analysis process to transform pixel locations on a given image to a direction vector from the camera location, expressed in terms of altitude in degrees above the true horizon and azimuth with respect to true north. This process was based on the analysis of star images and yields an accuracy of about ±0.5° (±1 standard deviation) in both azimuth and elevation. The triangle formed by the two observation stations and the bright EBLO is "weak" in the sense that it is very sensitive to small errors in azimuth. This means that when we form error

[1] *Note*: Since most of Mitchell Flat is private property, including the locations of the EBLO and monitoring stations, the property owners have requested that absolute locations not be disclosed publicly. The map of Fig. 4 is exact with regard to relative locations.

Please cite this article as: Stephan, K.D., et al., Quantitative intensity and location measurements of an intense long-duration luminous object near Marfa, Texas. Journal of Atmospheric and Solar-Terrestrial Physics (2011), doi:10.1016/j.jastp.2011.06.002

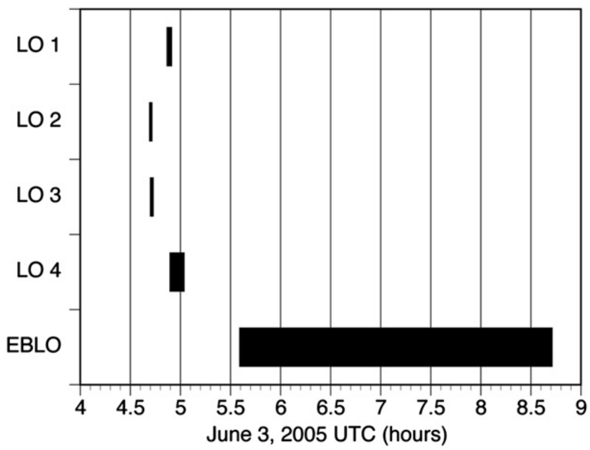

Fig. 5. Graph showing durations of luminous objects (LO) nos. 1–4 and extremely bright luminous object (EBLO).

regions by varying the direction vectors over the range of their error limits, the resulting ellipses are narrow in the direction perpendicular to observation, but very long (several km) in the directions toward and away from the stations, as Fig. 4 shows. The entire 1-standard-deviation error ellipse is shown, but only the nearer half of the 3-standard-deviation ellipse is shown because high cliffs behind the nominal intersection point made it impossible for the object to be much farther away from that point than a few km.

Despite this relatively large uncertainty in the object's location, a set of essentially simultaneous lightning strokes occurred at 0530:00 UTC (as recorded by NLDN), including three strokes that fell in or near the 3-standard-deviation error ellipse of the EBLO location. These were all negative-cloud strokes with indicated peak currents ranging from 8.8 to 27.1 kA. These strokes are shown as star symbols in Fig. 4. Observation of the time sequence of photographs shows a bright flash at a time consistent with these strokes (within the ± 2 min error with respect to UTC of our corrected video timebase). The EBLO originates within about 15 s of this flash by gradually increasing from invisibility to its initial steady brightness over a period of about 20 s. These observations are consistent with the object originating at or near the location of one of the three 0530 UTC CG strokes identified from the NLDN database. They are also consistent with one of the very few eyewitness accounts of the formation of ball lightning (Tar, 2006), which reported the gradual formation of a glowing ball of increasing intensity a few seconds after a CG lightning stroke in the immediate vicinity.

We calibrated the photographs in terms of absolute radiance using images of known-brightness stars (both contemporaneous to the June 2–3, 2005, observations and also observed with a laboratory camera of the same type) and a laboratory system capable of reproducing a simulated star image with known absolute magnitudes ranging from +7 (too dim to be seen by the naked eye) to –7 (brighter than Jupiter). Star magnitudes can be converted to visible-wavelength flux intensity (W m^{-2}) if the object's spectrum is known in the visible-wavelength region, which for the astronomical V-magnitude system lies between about 450 and 700 nm (Bessell, 1990; Tüg et al., 1977). The wavelength response of the Watec CCDs used in these observations closely approximates the astrophotometric V response, but is not identical to it. More significantly, the spectra of the observed light sources are unknown, and could conceivably be "pathological" (e.g. completely in the IR wavelengths, where the CCDs have some response). However, for the purposes of this paper, we will assume a spectrum for the EBLO identical to that of the reference-magnitude star Vega, which is roughly that of a blackbody at about 8900 K and has an astronomical magnitude of 0.03 by convention. Vega was used as our primary absolute reference for camera calibration; so this is a convenient assumption to make. Reducing the exoatmospheric Vega flux by 0.35 magnitude to allow for estimated typical atmospheric extinction at the altitude of Mitchell Flat, we arrived at the following relation between visible-wavelength flux intensity F arriving at the camera lens, and the observed magnitude of the object m:

$$m = -2.5\log_{10}\left(\frac{F}{10.63\ \text{nW m}^{-2}}\right) \tag{1}$$

This relation allows us to evaluate photographs in terms of magnitudes and find the equivalent flux values of the observed (equivalent point-source) objects or vice-versa.

A separate calibration issue concerns the fact that while most astrophotometric observations are made with CCDs and amplifiers that produce a linear output in "counts" (proportional to electron charge per pixel) with respect to optical flux, the Watec cameras were not operating this way. Instead, the luminous-object images (as well as some star images) were bright enough to saturate the camera amplifier output (though not the CCD itself), which in addition was adjusted to produce a nonlinear input-to-output relation ("gamma") of either 0.35 or 0.45. In this mode, the camera output is proportional to I^{γ}, where I is the optical intensity.

However, once the image saturated, its size continued to increase as pixels on the periphery of the image became saturated as well. Using astrophotometric plugins provided with ImageJ, a public-domain image-analysis software package maintained by the U.S. National Institutes of Health (http://rsbweb.nih.gov/ij/), we obtained laboratory curves for the nonlinear relation between pixel counts and image magnitude over the range of absolute magnitudes from –7 to +7. Depending on the camera settings at the time of observation (which were not known precisely), these functions varied in shape. By comparing intensity data from monitoring station nos. 1 and 2 and assuming that the EBLO radiation was isotropic to the extent that both stations received approximately the same flux from it, we arrived at a relation between photometrically measured image counts and magnitude, which allowed the measurement of the EBLO's equivalent magnitude during most of the 3-h period of its existence.

A graph showing this magnitude as a function of time is given in Fig. 6. The left-hand scale of Fig. 6 shows astronomical magnitude, and the right-hand scale is calibrated in terms of the equivalent isotropic radiated power that an object 27.9 km away would have to radiate in the visible-wavelength range in order to produce that magnitude. Many images during the first hour or so were contaminated by almost continuous lightning flashes, which is why the first few data points in Fig. 6 are widely spaced. Because of the uncertainty in the original camera settings and other factors, the probable error of this data is ± 0.5 magnitude, which in terms of estimated power flux is a fractional error range of +60%, –37%. However, even if the lower limit of this error (−37%) is assumed, the power emitted by the EBLO, in the visible-wavelength region only, at its peak output was 9.5 kW. Assuming the object has no greater than ~20% conversion efficiency from its initial energy form to optical energy, this means the total expended power at its peak brightness was of the order of 50 kW. A check on our calculations was conveniently provided by the presence of a mercury vapor lamp at a known location 16 km away from observation station 1. Direct inspection of the light showed that it is a type that typically uses a 175-W (electrical input power) lamp inside a housing, which concentrates the emitted light in a horizontal direction. When the same

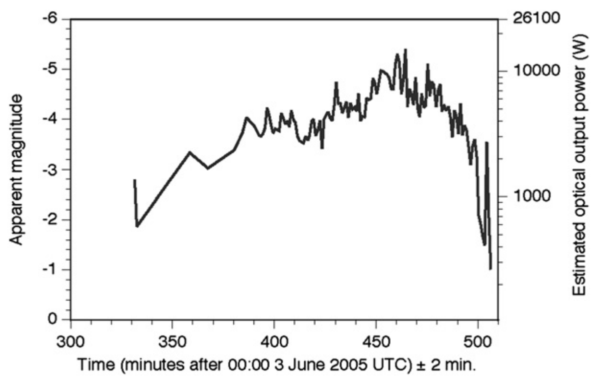

Fig. 6. Graph showing magnitude and estimated total optical power flux from EBLO of Figs. 1–3 versus UTC time. Probable error of measurement is ± 0.5 magnitude ($+60\%$, -37% in terms of power).

magnitude-to-power conversion used for the EBLO is applied to this object, we obtain an equivalent isotropic emitted optical power of only 235 W. Considering that the lamp's housing may concentrate the emitted power in a way that more than compensates for its ~20% electrical-to-optical conversion efficiency, this is a reasonable result and serves as an indication that our estimates are correct to within at least a factor of 2 or so.

With regard to location, the good time and space correlation between the NLDN 0530:00 UTC lightning strokes and the initiation of the EBLO leads us to believe that one of these strokes was the chief causative factor in the EBLO's genesis. While it is true that most Marfa lights are not associated with lightning, and the correlation between lightning and the EBLO may be a coincidence, it is possible that in this case lightning triggered the same basic type of mechanism that is responsible for other Marfa lights, which in turn are triggered by other means. During the sequence of photographs from both station nos. 1 and 2, the object's position is seen to move slightly to the south a distance of approximately 150 m during the last hour of its existence. This movement indicates that the object was not confined to a fixed location. After about 3 h, the object's brightness gradually decreased, went off and on a few times, and then permanently ceased.

4. Discussion

This data is one of the most interesting of a large number of photographs taken as part of a multi-year investigation of the phenomenon known as "Marfa lights." For over a century, there have been numerous reports of lights of uncertain origin occurring east of Marfa, Texas, USA, in a region known as Mitchell Flat. This includes the area where the EBLO was photographed on June 3, 2005. One of the authors (Bunnell) has been engaged in research regarding these lights since 2001. He has observed (both in person and with manned and unmanned photographic equipment) infrequent occurrences of unexplained lights between sunset and sunrise. These lights vary in color and intensity (Bunnell, 2009). They sometimes hold their position in the air above the ground even in windy conditions. At other times, they move cross-country, usually at relatively low altitudes and in directions independent from prevailing air currents. These events have been observed to last from less than a second up to 7 h (Bunnell, 2009). The most common colors range from orange to red. The lights frequently turn completely off and on again throughout their lifetimes, whether they are stationary or moving.

The Marfa region is not the only location where such lights have been observed. Similar phenomena have been witnessed elsewhere in the United States and in other countries worldwide including Hessdalen, Norway (Teodorani, 2004), Min-Min, Australia (Kozicka, 1994) and Taro Valley, Italy (Straser, 2007). The widespread nature (in both time and space) of luminous near-ground phenomena resembling Marfa lights is cited here to show that such objects are not unprecedented either at Mitchell Flat or other locations. A comprehensive discussion of theoretical explanations for these types of lights is beyond the scope of this paper. For an extended discussion of several of the leading theories about such lights in general, see Bunnell (2009).

The events reported in this article were unusual in several respects, even considered within the category of unexplained light sightings. In particular, the duration and the intensity of the EBLO are remarkable. Also, its correlation with a severe thunderstorm is atypical, although other unusual persisting lights have been documented by the automated camera system during thunderstorms. This EBLO was easily the most intense such object recorded by the camera system during nine years of investigations. As mentioned earlier, a major concern in any investigation of this kind is that the object in question may be either an artificial light source, or a naturally occurring one, which can be explained by conventional means. We will address each of these possibilities briefly.

An artificial light source capable of producing several kW of optical output flux when radiating isotropically is a major technical undertaking. A state-of-the-art high-pressure xenon arc lamp capable of this output level would require about 50–100 kW of primary input power and auxiliary equipment that would be difficult to transport or operate even in the daytime, let alone at midnight during a dangerous thunderstorm on a remote ranch location accessible only by traversing several kilometers of dirt roads. While such a prank is logically possible, it is not one of the most reasonable conclusions to draw from these observations.

It has been suggested (Uman, 2010) that some or all of the objects photographed on the night of June 3, 2005, and described herein could be explained as power-line arcs. These are common occurrences during windstorms and tornadoes, which physically disrupt power lines, producing momentary flashes powered by fault currents of hundreds of amperes from distribution lines at voltages in the range of 12–50 kV. For the duration of the fault, the power into the arc can reach MW levels and could account for the intensity of the objects we photographed. Our onsite inspection showed that at least one above-ground distribution line crosses the 3-sigma error ellipse in the vicinity of the nominal location of the EBLO, about 500 m from a ranch house.

To assist in the evaluation of this possibility, the photos of Figs. 1 and 2 and the intensity graph of Fig. 6 were sent to D. Lassanske, area operations manager for the Rio Grande Electric Co-op Alpine regional office. This firm and another called American Electric Power share the responsibility for the distribution lines in the area of West Texas in question. According to him, the possibility of these images being produced by power-line arcs is "not out of the question" (Lassanske, 2011). The distribution lines in the area in question carry 14.4-kV energy and are protected by 15-A fuses and 30-A circuit breakers. It is not an unusual occurrence for a downed line to produce a fault of insufficient current to activate protection equipment, yet enough to make a very bright display until utility workers arrive to manually interrupt the circuit.

Three factors can be cited as arguments making the power-line-arc explanation less likely in the case of the EBLO described in this paper. One concerns the instability of airborne AC arcs. For an arc to exist for many power-line cycles, there must be enough resistance in the circuit to counteract the negative-resistance characteristic of the arc plasma (i.e. to serve as a ballast, much as an inductive fluorescent-light ballast stabilizes the current in a fluorescent lamp tube). This negative-resistance characteristic is why arcs to good grounds increase in intensity over a small fraction of a second and terminate only when protective equipment goes into action. For a resistive object (bush, tree, high-resistance patch of ground, etc.) to absorb, say, 10 A at 14 kV (140 kW) for over 3 h without allowing the current to exceed 15 A and blow a fuse, and without itself being burned into nonexistence, is a feat comparable to the Biblical story of the bush witnessed by Moses, "which burned, but was not consumed." Second, power-line arcs usually initiate in a fraction of a second, but the EBLO initially increased in intensity gradually over a series of three or four 4.2-s frames, and also faded away in a gradual and intermittent manner. Third, as noted above the EBLO appeared to move about 150 m south during the last hour of its existence. It is difficult to imagine a scenario in which a localized arc at a downed power line or faulty insulator maintains enough current to be as bright as the EBLO, but not enough current to blow a fuse, and also moves at least 150 m in the course of an hour (and possibly farther if foreshortening is taken into account). While a power-line arc is probably the best artificial-source explanation of the EBLO, the behavior of the object in question makes such an explanation unlikely in this case.

The leading candidates for conventional natural causes of a bright glow commencing immediately after a lightning stroke lie in the area of chemical combustion, such as burning trees or combustion of natural gas. By a conservative estimate, the amount of wood needed to provide the peak visible-light output of the bright EBLO over the 3-h period it was observed, could be provided by a tree 30 cm in diameter and 100 m high. Even a burning power-distribution pole could not account for this volume of fuel. Direct visual on-site inspection of the most likely location of the bright EBLO on June 30, 2010, showed that the largest vegetation in the area for many km in every direction were cacti and mesquite brush no larger than about 3 m high. A conversation with the ranch manager in charge of the region confirmed that no grass or other fires had been seen in the area of the 3-sigma error ellipse in the last five to seven years. Although some natural gas exploration has taken place about 15 km to the south in recent years, a continuous flow rate of $\sim$600 l/s of methane at atmospheric pressure would be required to sustain a flare whose brightness would be comparable to the EBLO we observed. During a 2008 investigation (Stephan et al., 2009) we telescopically observed actual natural-gas flares at distances comparable to that of the EBLO from the monitoring stations. An unrestrained gas flare has unmistakable flickering and quasi-oscillatory movement, which was not observed in the data presented herein. These facts cast serious doubts on the possibility that the EBLO was a conventional combustion process such as burning grass, trees, utility poles, or natural gas flares.

If the EBLO was not artificially produced (e.g. a power-line arc) or attributable to conventional combustion, what was it?

One possibility is the liberation of pyrophoric chemicals, that is, substances that spontaneously ignite in air. The long history of Marfa lights in the region indicates that there is possibly something about the geology of the region, which can produce luminous chemical reactions under the right conditions. Photographs of other luminous objects in this region at other times identified as Marfa lights (see e.g. Bunnell, 2009) show processes that appear to be similar to combustion. Although natural gas has been discovered in the region and flared from time to time as mentioned earlier, it is not pyrophoric and would require an ignition agent or catalyst to burn. It is possible that an unknown mineral in Mitchell Flat becomes pyrophoric under the right conditions. Merzbacher (2002) describes several naturally occurring minerals such as iron pyrite, which are pyrophoric if finely divided or subjected to humidity. The theory of pyrophoricity is also compatible with the fluid-dynamic effect known as vortex breakdown, which we will discuss next.

Coleman describes a theory involving vortex breakdown and the formation of a fireball within the breakdown region. Vortex breakdown (Hall, 1972) is a phenomenon that occurs in "swirling" vortices (ones with a substantial movement of fluid in the axial as well as the rotatory direction). It is a region of divergent flow where the fluid behaves as though it encounters a barrier, and can produce a roughly spherical region of diminished velocity. Coleman's theory involves combustion inside a vortex, which he claims may be able to account for both ball lightning and other types of atmospheric lights such as Marfa lights and the EBLO we observed (Coleman, 2006). Coleman's theory is compatible both with the possibility of pyrophoric materials being involved, and with many aspects of the observed behavior of both the EBLO described in this paper and the general structure and behavior of Marfa lights as observed at other times. Attempts to obtain spectra of Marfa lights with enough detail to ascertain information about the chemistry of the light emitted have so far been unsuccessful, although we believe this could be a fruitful line of future research.

A related but more remote possibility is that the chemicals liberated (possibly by the heat and electrical excitation due to a lightning strike) are chemiluminescent rather than pyrophoric. Chemiluminescence is associated with the slow oxidation of many compounds, and does not necessarily produce as much heat as conventional combustion does. For example, a chemical called "Wöhler siloxene" ($Si_6H_3(OH)_3$) emits chemiluminescence in the green region, although at very low intensities (Molassioti-Dohms et al., 1996). While the precursor elements for this chemical were undoubtedly present in the soil during the time of observation, it is not clear how Wöhler siloxene or any of a number of other inorganic chemiluminescent substances would be produced in nature in sufficient quantities to emit visible light.

A reaction that is lower in probability but has been cited in the ball-lightning literature (e.g. Manykin et al., 1998) is the production of Rydberg matter (RM). RM has been produced in the laboratory (Holmlid, 2002) by the slow heating of potassium-bearing compounds in a vacuum. The resulting RM consists of small clusters of Rydberg atoms of potassium with their outer electrons in a highly energetic state (at least $\sim$4 eV). Although RM's energy content could account for the EBLO activity we photographed, no one has yet demonstrated that RM can be produced at atmospheric pressure in air.

As we showed during a previous investigation (Stephan et al., 2009), light from objects in this region farther than a few km away typically undergoes a type of scintillation, which preserves total light flux, but prevents the resolution of features smaller than about 0.035° in angular extent unless the atmospheric "seeing" is unusually good. At a distance of 28 km, this means no feature smaller than about 16 m could be resolved, even if a telescope instead of the relatively low-resolution cameras had been used. Conversely, this also means that an object up to about 16 m in diameter would appear the same to the cameras as a much smaller object, as long as the total light flux output was the same. If we assume an energy conversion efficiency as high as 25% and integrate the visible-wavelength output power in Fig. 4 from t=386–506 min, where the recoverable intensity data samples are spaced no farther apart than 3 min, the total energy (not just optical output) expended by the EBLO can be estimated to be on the order of 140 MJ. The required energy density for a spherical object 1 m in diameter would thus be 267 MJ m^{-3}, which falls for a 2-m-diameter object to only 33.4 MJ m^{-3}. As was mentioned, the same images would have resulted from an object with any diameter up to about 16 m, which would require even lower energy densities.

Please cite this article as: Stephan, K.D., et al., Quantitative intensity and location measurements of an intense long-duration luminous object near Marfa, Texas. Journal of Atmospheric and Solar-Terrestrial Physics (2011), doi:10.1016/j.jastp.2011.06.002

A study of 17 reported incidents in which ball lightning objects apparently contained an unusually large amount of energy (Bychkov et al., 2002) gives estimates for energy density ranging from 0.96 to 2.4×10^6 MJ m^{-3}, so our estimates of ~30–300 MJ m^{-3} for an EBLO 1–2 m in diameter fall into the low end of this range. Most of the objects in the incidents reported by Bychkov et al. lasted only a few seconds, which is typical of most ball-lightning observations. Even if the EBLO described herein was only a few cm in diameter, its energy density would still fall in the range documented by Bychkov et al.

Nevertheless, any stored-energy theory that can claim to account for the phenomena described in these observations must explain (a) the stable storage of at least ~100 MJ of energy in electrical or chemical form, and (b) the relatively constant-rate conversion of this energy into light over a period of more than 3 h, during which time the radiant output did not appear to vary by more than a factor of 4 or so until just before extinction. Most ball-lightning theories are not developed in enough detail to predict how light output should vary with time, although those that rely basically on radiant cooling cannot show such constancy of output. It seems that only a theory, which posits a light-emitting surface reaction of some kind, while allowing most of the energy to remain stored in the volume of the object, will account for such relative constancy of light emission, a feature that is evident in the vast majority of eyewitness accounts (Rakov and Uman, 2003).

5. Conclusion

To summarize, we have presented quantitative evidence that an extremely bright luminous object came into being near a lightning strike on June 3, 2005, and emitted at least 10 kW of optical-wavelength energy at its peak, persisting for over 3 h. This object appeared in the same general region that is known for the production of other luminous objects termed Marfa lights, which can appear in the absence of lightning or thunderstorms. From this data it is not yet clear what mechanism, if any, is in common between the EBLO described in this paper and other Marfa lights observed at other times. A variety of artificial and natural explanations have been considered for this event, including the possibility of a power-line arc.

Observers of statistically uncommon naturally occurring phenomena whose mechanism is not yet understood do not have the luxury of testing hypotheses in the laboratory. The long observation times required often limit the types of observation possible to simple photography, as in this case. When an unusual event is recorded, whatever objective data can be extracted from the observations are primarily useful to eliminate the hypotheses that are inconsistent with the observed data. Eliminating hypotheses is not as dramatic as confirming them. But in the early stages of some fields of research, clearing the field of inadequate hypotheses allows limited resources to be concentrated on those hypotheses that are consistent with the observations. As we have stated, none of the hypotheses we have considered is so well developed that it could have been used to predict quantitative features of the event we observed in detail. But several of them are consistent with the observations, and so merit further scrutiny. In particular, the vortex-fireball theory of Coleman allows for the introduction of external energy in the form of pyrophoric or flammable material, and also allows for the movement of the object in a manner consistent with both the results of this study and the observations of other Marfa lights (Bunnell, 2009). Further research in this area using more sophisticated instrumentation (including spectroscopy) may produce data that will allow us to select the leading hypotheses for more detailed examination through both observations in the field and laboratory experiments.

Acknowledgments

We express our thanks to Vaisala Inc. for providing the extract from their NLDN database. We also thank the property owners on whose land this research took place for their permission to establish monitoring stations and investigate sites of interest. This research was partially supported by a Texas State University Research Enhancement Grant for calendar year 2010.

References

Bessell, M.S., 1990. UBVRI Passbands, vol. 102. Publications of the Astronomical Society of the Pacific, pp. 1181–1199.
Bunnell, James, 2009. Hunting Marfa Lights. Lacey Publishing Co. (320 pp.).
Bychkov, A.V., Bychkov, V.L., Abrahamson, J., 2002. On the energy characteristics of ball lightning. Philosophical Transactions: Mathematics, Physics, and Engineering Science 360, 97–106.
Coleman, P., 2006. A unified theory of ball lightning and unexplained atmospheric lights. Journal of Scientific Exploration 20, 215–238.
Cummins, K.L., Murphy, M.J., 2009. An overview of lightning locating systems: history, techniques, and data uses, with an in-depth look at the U.S. NLDN. IEEE Transactions on Electromagnetic Compatibility 51, 499–518.
Hall, M.G., 1972. Vortex breakdown. Annual Reviews of Fluid Mechanics 4, 195–218.
Holmlid, L., 2002. Conditions for forming Rydberg matter: condensation of Rydberg states in the gas phase versus at surfaces. Journal of Physics: Condensed Matter 14, 13469–13479.
Kozicka, M.G., 1994. The Mystery of the Min Min Light. Queensland, Australia.
Lassanske, D., 2011. Private Communication with K.D. Stephan .
Manykin, E.A., Ozhovan, M.I., Poluetkov, P.P., 1998. Decay of long-lived excited states of condensed matter and the problem of ball lightning stability. Journal of the Moscow Physical Society 8, 19–22.
Merzbacher, C.I., 2002. Materials that emit light by chemical reaction. Proceedings of the Royal Society of America 360, 89–96.
Molassioti-Dohms, A., Dettlaff-Weglikowska, U., Finkbeiner, S., Hönle, W., Weber, J., 1996. Photo- and chemiluminescence from Wöhler siloxenes. Journal of the Electrochemical Society 143, 2674–2677.
Rakov, V.A., Uman, M.A., 2003. Lightning: Physics and Effects. Cambridge University Press, Cambridge, UK (687 pp.).
Stephan, K.D., Ghimire, S., Stapleton, W.A., Bunnell, J., 2009. Spectroscopy applied to observations of terrestrial light sources of uncertain origin. American Journal of Physics 77, 697–703.
Straser, V., 2007. Precursory Luminous Phenomena Used for Earthquake Prediction—The Taro Valley, Northwestern Apennines, Italy. New Concepts in Global Tectonics Newsletter, No. 44.
Tar, D., 2006. Observation of lightning ball. In: Proceedings of the International Symposium on Ball Lightning, 16–19 August 2006. Eindhoven, The Netherlands, pp. 223–226.
Teodorani, Massimo, 2004. A long-term scientific survey of the Hessdalen phenomena. Journal of Scientific Exploration 18, 217–251.
Tüg, H., White, N.M., Lockwood, G.W., 1977. Absolute energy distributions of α Lyrae and 109 Virginis from 3295 Å to 9040 Å. Astronomy and Astrophysics 61, 679–684.
Uman, M., 2010. Private Communication.
Van der Velde, O.A., Lyons, W.A., Nelson, T.E., Cummer, S.A., Li, J., Bunnell, J., 2007. Analysis of the first gigantic jet recorded over continental North America. Journal of Geophysical Research D 112, D20104. doi:10.1029/2007JD008575.