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Fluorescence caused by ionizing radiation from ball lightning: Observation and quantitative analysis

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ABSTRACT

Ball lightning is a rare phenomenon, typically appearing as a glowing sphere associated with thunderstorms. In 2008 one of the authors witnessed a blue ball-lightning object hover in front of a glass window that appeared to glow yellow. Calibrated quantitative fluorometry measurements of the window show that the glow was probably due to fluorescence caused by ionizing radiation (UV or possibly X rays). Based on the measurements performed, estimates of the total ionizing-radiation power emitted by the object range upward from about 10 W. These are among the most reliable semi-quantitative measurements so far of ionizing-radiation output from a ball-lightning object.

1. Introduction

Ball lightning is a phenomenon whose existence has been known since the pre-scientific era (Stenhoff, 1999), but which has so far eluded both a widely accepted scientific explanation and reproduction in the laboratory, although many theories have been proposed to account for it. Its rarity compared to conventional lightning makes instrumented scientific observation difficult, with the result that most of what we know about it is based on the testimony of eyewitnesses who happen to be present when a ball-lightning event occurs. Rakov and Uman list four features of ball lightning that are common enough in eyewitness reports to be regarded as characteristic (Rakov and Uman, 2003, p. 662): (1) its association with thunderstorms, (2) its light emission, spheroidal shape, typical size range of 10–50 cm, and relatively constant appearance during its lifetime, (3), its occurrence both in open air and enclosed spaces, and (4) the fact that it moves in a way that is inconsistent with a hot gas. Horizontal motions are more common than vertical ones (Rayle, 1966). One of the few cases in which the optical spectrum of a probable ball-lightning object has been reported (Cen et al., 2014) covered only the range 400–1000 nm, so the object's emission at wavelengths below 400 nm, if any, was not determined in that event.

The scarcity of observational data makes it hard to select among the myriad of theories that have been proposed to explain ball lightning. Some of the theories (e g. Shmatov, 2003) imply that ball lightning should emit ionizing radiation (UV and X-rays, in particular), while others (e. g. Abrahamson and Dinniss, 2000) do not. One of the theories that has received much attention in the last two decades is the chemical-combustion theory (Abrahamson and Dinniss, 2000). Abrahamson and Dinniss propose that a lightning strike to soil reduces silica by means of carbon-bearing compounds, leading to the production of elemental silicon which then slowly oxidizes in air. Burning silicon has a black-body-like spectrum with an equivalent radiation temperature in the range of 3000 K (Stephan and Massey, 2008). The emission in the short-wave UV region from such an object would be roughly seven orders of magnitude less than its peak emission in the visible range —in other words, negligible. Spectral lines from silicon and other common soil elements in the Cen observation lend some credence to the Abrahamson-Dinniss theory, although the Cen data are also consistent with other theories of a primarily electrical or plasma nature.

Two leading electrical-plasma theories are a totally-ionized-plasma model (Shmatov, 2003) in which electron-ion recombination is delayed by the high energy of the electrons, and a microwave-soliton model (Wu, 2016), in which a coherent relativistic electron bunch produced by a lightning leader collides with matter to produce an intense electromagnetic pulse, giving rise in turn to a high-intensity standing electromagnetic wave inside a spherical plasma cavity.

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Both of these theories entail that at a minimum, the object is surrounded by a halo of highly ionized air, whose nitrogen molecules can produce lines and bands in the UV range, as well as visible-light emission primarily in the blue region (similar to emissions of high-voltage corona discharges). Also, the Shmatov model predicts substantial amounts of X-ray production due to brehmsstrahlung radiation. At present, the field is perhaps better served by observation of ball lightning and quantitative measurements rather than by development of additional theories, and this paper is a contribution to observations of ball lightning which involve quantitative measurements.

We describe an eyewitness report of a ball-lightning object observed by one of the authors (Krajcik). This report has a feature that, to the best of our knowledge, is unique: the ball-lightning object caused the glass in a window to fluoresce brightly with a color that was different than the color of light emitted by the object. We have subjected the window glass involved in this incident to a calibrated fluorometric study, and show that the glass fluorescence observed during the event implies that significant amounts of ionizing radiation (short-wave UV or possibly X-rays) must have been emitted by the object in order to cause the observed fluorescence. The combination of eyewitness observation and fluorometric analysis makes this the among the most well-documented semi-quantitative measurements of ionizing radiation from a ball-lightning object, although earlier studies (Dmitriev, 1969; Fleming and Aitkin, 1974) provided somewhat ambiguous evidence for such radiation.

2. Material and methods

2.1. Eyewitness report of the incident

The following report contains material transcribed from a recorded interview that one of the authors (Stephan) conducted with the eyewitness (co-author Krajcik) on July 3, 2008. The incident itself took place on June 23, 2008, so the interview was performed only ten days after the incident itself. The eyewitness has a scientific education at the doctoral level and has been professionally employed in research. Following the incident, co-author Martin learned from the eyewitness about the incident. Realizing its significance, he put the eyewitness in contact with Stephan, and conducted preliminary investigations to ascertain if the window fluoresced when exposed to UV light. This preliminary study was followed up with a quantitative calibrated fluorometry measurement when such facilities eventually became available.

On the evening of June 23, 2008, at approximately 8:45 PM (00:45 June 24 GMT), the eyewitness arrived by car in the driveway of her home in southern New York State. An intense thunderstorm was in progress, and this fact is confirmed by data obtained from the National Lightning Detection Network. From 00:41 to 1:13 GMT, the NLDN recorded 24 cloud-to-ground flashes within a radius of 5 km of the eyewitness's home (NLDN, 2008). She stayed inside her vehicle in the driveway to wait for the rain and lightning to decrease. From her vehicle she could see her front porch approximately 6 m away. Her front entry to the house consisted of a transparent and colorless glass outer door (storm door) behind which stood a solid door painted off-white. Here are her words from the transcript of the interview made ten days after the incident: “I just happened to glance over at my porch and I was stunned. I mean, I saw that fiery ball, yellow-flame appearance in my front door… . It was the center of the door, at least twice, two and a half times more area than you'd expect from that small canteloupe-size blue object that I saw.”

An artist's conception of this moment is shown in Fig. 1. What the eyewitness described during the interview, and has consistently described since, was the sight of a glowing blue sphere approximately 14 cm in diameter, suspended a few cm in front of her door. The glass of the door was glowing over a diameter 2–2.5 times that of the blue sphere. The color of the glow from the glass appeared yellow, in contrast to that of the blue sphere.

Fig. 1. Artist's conception of eyewitness's initial sighting of ball-lightning object in front of glass window in front door (artwork by P. Stephan).

After this sighting, the eyewitness saw the blue object move rapidly to the right, between her house and her car. The object passed behind a tree at the corner of her house (not shown in Fig. 1) while brightening somewhat, passed to an open space between her house and the next residence, and she eventually lost sight of it.[1] The eyewitness also reported that the electric-utility power had failed before she arrived at home, and was not restored until well after the incident was over.

Summarizing the relevant data from the eyewitness's report, we have the following: (1) during a thunderstorm, a sphere about 14 cm in diameter emitting blue light appeared in front of the glass window of the front door, and subsequently moved in a mostly horizontal direction until the eyewitness lost sight of it; (2) with the sphere a few cm distant from the window, the glass emitted light of a contrasting color over an area larger than that of the sphere's diameter. Although it is possible that the paint on the solid door could have contributed to the observed effect, we have assumed in this paper that all fluorescence was due to the glass and not the solid door.

In what follows, we will combine these data with subsequent measurements and estimates to draw conclusions concerning ionizing radiation emitted from the object.

2.2. Fluorescence of window glass

The same clear window glass was present in the eyewitness's front door from the time of the incident reported above in 2008 until the glass was measured fluorometrically on June 4, 2016. A brief discussion of glass fluorescence and the results of these measurements will now be presented.

Certain types of glass are known to fluoresce in the visible range when subjected to ultraviolet light (Lloyd, 1981) or X-rays (Clark, 1955, p. 78). The fluorescence is generally due to the presence of trace amounts of heavy metals in the glass. For example, a type of glass containing uranium is known as “vaseline glass” because of its yellow-green color, and fluoresces bright green when

[1] The entire transcript of about 6300 words contains more details, omitted here for clarity and space reasons, but the details most relevant to this paper have been included here.

exposed to ultraviolet light.

In the 1960s, manufacturing architectural glass by the float-glass process became widespread, replacing older methods that required polishing operations. In the float-glass process, molten glass is floated on the surface of a pool of molten tin, which gives an optically flat surface to the glass as it cools without the need for costly polishing. During the float process, a small amount of tin diffuses a few microns into the surface of the glass. This trace amount of tin is probably responsible for fluorescence in architectural glasses manufactured since the 1960s (Lloyd, 1981). It also explains why some glass samples we have tested exhibit greater fluorescence on one side (presumably the side exposed to tin) than the other.

We have performed calibrated fluorometric measurements on the actual glass that was observed to fluoresce during the 2008 ball-lightning incident. A description of these measurements follows.

2.3. Fluorometer measurements of window glass

A fluorometer is a device which measures the fluorescence emitted by a given surface when exposed to a known amount of fluorescence-inducing radiation. A fluorometer measures a special case of a dimensionless ratio called the *spectral reflectance factor* β.

The general definition of β for a non-fluorescent surface involves the exposure of the surface to a source of illumination with a spectral radiant power denoted by $P_{0\lambda}\Delta\lambda$, where $P_{0\lambda}$ is in W nm^{-1} and $\Delta\lambda$ is in nm (Wyszecki and Stiles, 1982, pp. 234–237). The typical case is that of an approximately monochromatic source, in which the product $P_{0\lambda}\Delta\lambda$ expresses the total radiant power emitted by the source within a narrow range $\Delta\lambda$ of the source's peak emission wavelength λ. The source first illuminates the surface to be tested for reflectance, and the spectral radiant power in a solid angle ω reflected into a suitable detector is denoted as $P_{\lambda}^{(\omega)}\Delta\lambda$. Next, a perfectly diffuse 100% reflecting surface is substituted for the test surface, but the incident power $P_{0\lambda}\Delta\lambda$ and all other physical parameters and relationships remain the same. The spectral radiant power at the wavelength λ received from the diffuser is denoted as $P_{D\lambda}^{(\omega)}\Delta\lambda$. The spectral reflectance factor for this (non-fluorescent) surface is defined as

$$\beta(\lambda) = \frac{\boldsymbol{P}_{\lambda}^{(\omega)}\Delta\lambda}{\boldsymbol{P}_{\boldsymbol{D}\lambda}^{(\omega)}\Delta\lambda}. \qquad (1)$$

In other words, β is simply the ratio of power received from the surface under test to that received from an ideal diffusing surface, under the same conditions of illumination.

In the case of a fluorescent surface, the wavelengths of the light used for illumination and the light resulting from fluorescence are in general different. Denoting the received (fluorescence) wavelength by σ and the illumination wavelength in a narrow band $\Delta\lambda$ as λ, the total spectral reflectance factor $\beta_T(\lambda, \sigma)$ depends on both the fluorescence wavelength σ and the illumination wavelength λ. It is the sum of a non-fluorescent reflectance term $\beta_S(\lambda)$ at the incident illumination wavelength λ, plus a fluorescence term $\beta_L(\lambda, \sigma)$ at a different wavelength σ:

$$\beta_T(\lambda, \sigma) = \beta_S(\lambda) + \beta_L(\lambda, \sigma). \qquad (2)$$

If the detector is wavelength-selective (e. g. a spectrometer) and the fluorescence of interest is sufficiently far removed from the illumination stimulus wavelength, the non-fluorescent term can be rejected from the total spectral reflectance factor, resulting in the measurement of the fluorescence radiance factor $\beta_L(\lambda, \sigma)$ only. However, the mechanics of measurement are identical to the measurement of a non-fluorescent surface. This measurement is what the fluorometer we now describe is designed to do.

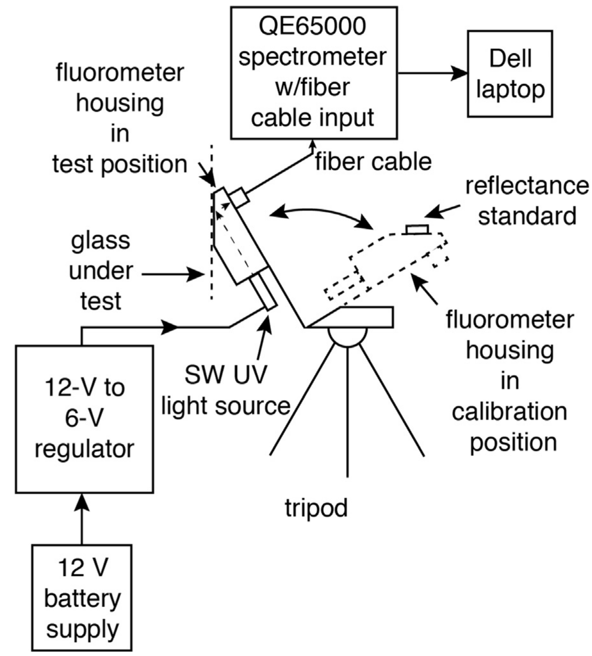

Fig. 2. Fluorometer setup used to measure fluorescence of glass window.

The fluorometer setup is shown in Fig. 2. The fluorometer enclosure itself situates a shortwave UV source (Home Science Tools UV-Tool) at a distance of 11.4 cm from the center of a circular viewport 2.7 cm in diameter cut in the black-painted aluminum fluorometer housing. The UV radiation is incident at that point at an angle of 26.5 degrees from the horizontal (horizontal = parallel to the surface). The end of a 1-mm fiber cable (part of a calibrated absolute radiometric measurement system using a QE65000 Ocean Optics spectrometer) is supported at a distance of 3.9 cm from the center of the viewport, and its line of sight is at right angles to the line from the UV source to the viewport. This angular relationship ensures that any specular reflections (for which the angle of incidence equals the angle of reflection) will not enter the detector cable. The shortwave UV source is a quartz-tube mercury-vapor lamp behind a UV filter that eliminates most, but not all, visible Hg lines, while passing the 253-nm shortwave UV line. It was operated from a battery-powered regulated 6-V supply and was allowed to warm up for at least 15 min before any data were taken, to allow its output to stabilize.

The reflectance standard used is a LabSphere AS-01158-060 USRS-99-010 specified to have 95% reflectance at 250 nm, in the shortwave UV region. The fluorometer mounts on a tripod and is hinged so that the reflectance standard can be placed on top of the viewport for the reference measurement. Then the test measurement is performed by removing the standard and rotating the fluorometer 90 degrees so that the viewport is covered by the glass surface to be measured. To reduce stray light leakage into the setup, the measurement was performed at night and a piece of black paper was affixed to the opposite side of the glass to reduce the ingress of stray light. A test spectrum with the UV source turned off showed that virtually no stray light entered the fluorometer during the test.

The spectrometer system was calibrated by the manufacturer (Ocean Optics) with the specific 1-mm-dia. fused-quartz fiber cable used in these tests, to produce absolute radiometric measurements over the range 250 nm to 700 nm, and was within the 1-year calibration period at the time the measurement was made. Therefore, not only could we perform the relative measurement of $\beta_L(\lambda, \sigma)$ (the fluorescence spectral reflectance factor), but we also knew what absolute intensity of UV radiation at 253 nm was required to produce a resulting absolute intensity of visible fluorescence. This absolute radiometric data is vital in deriving an estimate for the ionizing-radiation power produced by the original ball-lightning object, as we will now describe.

3. Calculation of ionizing-radiation intensity from estimated glass fluorescence brightness

The human eye is very sensitive to low light levels when dark-adapted, but is relatively poor at estimating absolute brightness levels. Only by comparison with sources of known brightness can the eye be used in absolute measurements of brightness, or its technical equivalent, luminance. However, the absolute fluorometric measurements presented below establish a precisely known quantitative relationship between the (estimated) fluorescent luminance of the glass during the ball-lightning incident, and the emission of ionizing radiation power from the object, expressed in terms of an equivalent amount of 253-nm UV radiation.

The fundamental photometric unit is the lumen (lm), which plays a role analogous to the watt in radiometry. The definition of the lumen is in terms of light's effect on the human eye, as defined by the CIE luminosity functions for either normal-illumination (photopic) or low-light illumination (scotopic) conditions (Wyszecki and Stiles, 1982). The luminance of an extended source such as the fluorescent glass in this study is expressed in terms of lumens per steradian per square meter (lm sr^{-1} m^{-2}), equivalent to candelas per square meter (cd m^{-2}).

The brief time during which the eyewitness saw the effect did not allow for a good estimate of absolute brightness. However, the object was bright enough to attract the eyewitness's attention. In the absence of other data, the most conservative approach is to choose the lowest estimate of luminance that is consistent with the sequence of events. The brightness of an average electroluminescent panel such as those formerly used for nightlights is about 30 cd m^{-2}, and this level can serve as a working lower bound for the actual glass fluorescence luminance that was seen. Deriving an estimated ball-lightning equivalent ionizing radiation power from this lower-bound luminance will therefore produce a lower-bound estimate of ionizing-radiation power emitted by the object.

When the QE65000 spectrometer is calibrated to measure absolute irradiance, its output is a set of ordered pairs of wavelengths (in nm) and irradiance (in units of μW cm^{-2} nm^{-1}), as measured at the end of the fiber-optic cable that is exposed to radiation. These irradiance values can be numerically integrated over any desired wavelength range to produce total irradiance over that range (in μW cm^{-2}) or further processed to derive values such as photopic or scotopic illuminance in lux (lx), equivalent to lumens per square meter (lm m^{-2}).

The illuminance or irradiance measured at the fiber-cable entrance can be used to calculate either the luminance of the fluorescent glass, or the UV irradiance arriving at the glass location, using the calibration data obtained when the glass is replaced with the 95%-reflectance diffuse reflectance standard. Referring to Fig. 3, the 24.5° field of view of the fiber cable, as it is actually mounted (a) in the fluorometer at an angle, projects a cone whose base lies wholly within the viewport. As the brightness of a Lambertian surface does not change with viewing angle (Smith, 2008, p. 256), we can imagine the cable mounted normal to the viewport plane as shown at (b) without encountering significant errors. While a polished glass surface is far from Lambertian in ordinary reflectance, the fluorescence from the surface layer a few microns thick is probably distributed in a roughly Lambertian

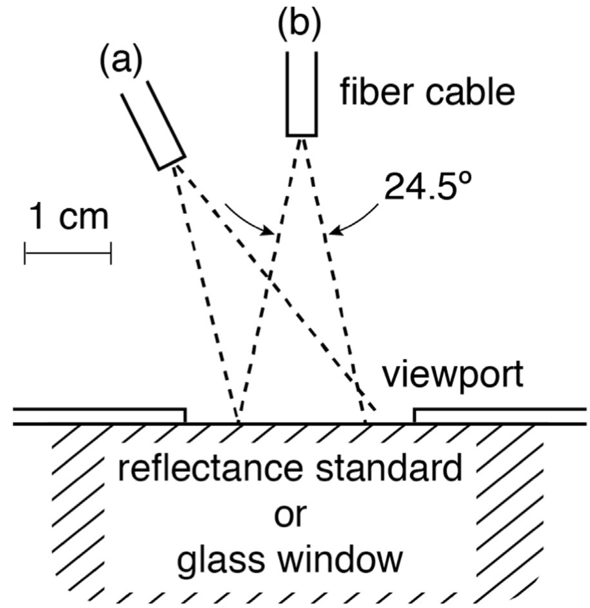

Fig. 3. Detail drawn to scale, showing viewport and 24.5° field of view of fiber cable in fluorometer. (a) actual position of fiber cable (b) equivalent position normal to viewport plane.

fashion, and the reflectance of the calibration target is closely approximated by a Lambertian dependence on angle.

The relationship between irradiance H in W m^{-2} (or illuminance in lm m^{-2}) at a receiver, and radiance N in W sr^{-1} m^{-2} (or luminance in lm sr^{-1} m^{-2}) emitted by a circular extended source is given by

$$H = \pi N \sin^2\theta_m, \quad (3)$$

where θ_m is one-half of the angle subtended by the source (Smith, 2008, p. 258). In the case of the fiber cable used, the total subtended angle over which light can enter the cable and be transmitted is 24.5°, and therefore $\theta_m = 12.25°$. Eq. (3) allows us to derive a value for incident radiance N in the 253-nm mercury band from the measured absolute irradiance H when the reflectance standard is in place. A Lambertian surface that reflects an incident UV irradiance of U (W m^{-2}) with an efficiency E into a hemispherical volume has a radiance (W sr^{-1} m^{-2}) of (Smith, 2008, p. 257)

$$N = \frac{UE}{\pi}. \quad (4)$$

Combining Eqs. (3) and (4), we can solve for the incident irradiance on the reflectance standard in terms of E, θ_m, and the measured value of irradiance H reflected from the standard and arriving at the fiber:

$$U = \frac{H}{E \sin^2\theta_m}. \quad (5)$$

These expressions allow us to calculate (a) the absolute value U of 253-nm UV irradiance reaching the glass sample during the fluorometry measurement, and (b) the luminance N of the fluorescing glass when it is exposed to that level of UV irradiance. Assuming the fluorescence is linear with respect to the UV irradiation level, we can then calculate the UV irradiation required to produce fluorescence having any desired luminance value.

One step remains to enable us to estimate the total flux of ionizing radiation from the ball-lightning object. While the above calculations will provide an estimated UV flux at the location of the glass during the ball-lightning incident, we must make assumptions about the distance between the glass and the object and about any directional characteristics of the object's radiation in order to estimate a total ionizing-radiation power output, which will be in terms of equivalent 253-nm radiation. The following analysis also neglects any absorption or scattering by air, which can be significant for shortwave UV radiation over long paths, but the distance involved here is short enough for these effects to be neglected. Radiative transfer theory (Howell, 2008) relates the irradiance U at a differential area normal to a line connecting the area to a radiating sphere whose center is at a distance h from the area. The radius of the sphere itself is $r < h$. We make the following assumptions: (1) radiation from the ball-lightning object is basically isotropic (but see remarks about this below), (2) the ionizing radiation from the object, whatever its spectrum, is as effective at causing glass fluorescence as the 253-nm line used in the fluorometry test, and (3) the distance between the glass surface and the center of the radiating object is $h = 30$ cm. Although the actual value of h is not known accurately, an upper bound is set by the fact that the object appeared to pass behind the porch post shown in Fig. 1, and 30 cm appears to be a best estimate for this distance. If the radiant exitance on the ball-lightning object's surface is U_{BL} (W m^{-2}), the irradiance U_S at a distance h from the object on a normally-oriented differential plane surface is

$$U_S = U_{BL}\left(\frac{r}{h}\right)^2. \tag{6}$$

Assuming the total ionizing-radiation power emitted by the object is P_{BL} (W) and is emitted isotropically, the radiant exitance U_{BL} (W m^{-2}) is given by

$$U_{BL} = \frac{P_{BL}}{4\pi r^2}. \tag{7}$$

Substituting Eq. (7) into Eq. (6) gives the estimated power P_{BL} in terms of the distance h and the irradiance U_S at a point on the glass closest to the object:

$$P_{BL} = 4\pi h^2 U_S. \tag{8}$$

(Note that the radius r of the object cancels.) If the fluorescent luminance is proportional to the effective UV irradiance that causes the fluorescence, we can set up the following proportion:

$$U_S = U_T\frac{N_S}{N_T}, \tag{9}$$

in which U_S is the ionizing-radiation irradiance on the glass during the ball-lightning incident, N_S is the resulting fluorescent luminance during the incident, U_T is the 253-nm irradiance on the glass during the fluorometry measurement, and N_T is the resulting fluorescent glass luminance during the measurement. Substituting Eq. (9) into Eq. (8) yields the following equation for P_{BL}:

$$P_{BL} = 4\pi h^2\frac{U_T}{N_T}N_S. \tag{10}$$

In Eq. (10), the variable with the largest uncertainty is N_S, the estimated luminance of the glass fluorescence during the incident. However, the lower bound of 30 cd m^{-2} is a conservative minimum, and the uncertainty in h is so small compared to the uncertainty in N_S that it can be neglected. In the following section, we will present the results of the fluorometry investigation and draw conclusions about the estimated ionizing-radiation power emitted by the ball-lightning object.

4. Results

As described above, the fluorometer was used on June 4, 2016 to measure the fluorescence of the outside surface of the window

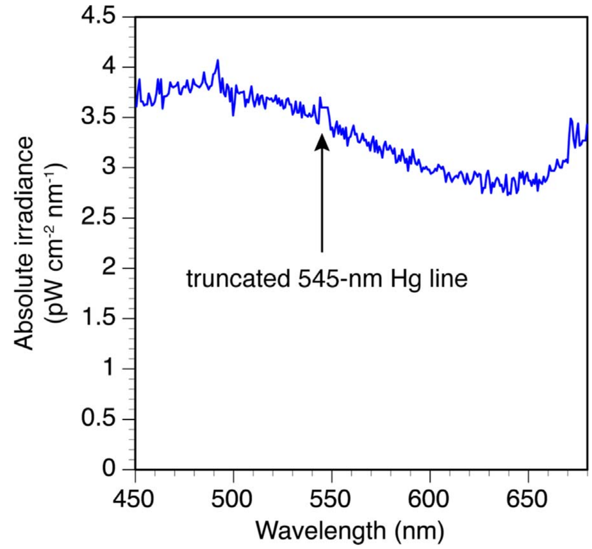

Fig. 4. Measured absolute spectral irradiance at fiber cable end from glass fluorescence (average of two trials). Incident 253-nm UV radiation was 5.35 μW cm^{-2}.

glass that was observed to glow during the ball-lightning incident of June 23, 2008. To minimize CCD noise during the measurements of the low light intensities involved, the spectrometer's internal thermoelectric cooler maintained the sensor temperature at -10 C throughout the series of measurements. A 1-s exposure time was used for the calibrated absolute irradiance measurement of the UV irradiance reflected from the reflectance standard target, while a 15-s exposure was used for measurement of the much dimmer glass fluorescence. Because the visible-light filter on the shortwave UV source allows some of the 545-nm green Hg line to pass, this line was manually truncated from the data over the range 541.7–548.6 nm, and the missing data was replaced with a constant value that was the average of the two data points closest to the truncated data (540.9 and 549.4 nm). This truncation is indicated in Fig. 4, which shows the average of two fluorescence data runs taken about 5 min apart during the experiment. Although the truncation is noticeable in Fig. 4, any error it introduces is less than the substantial error that would result from leaving the strong 545-nm line in.

As explained in standard texts on photometry (Wyszecki and Stiles, 1982), the scotopic illuminance H corresponding to the absolute irradiance data of Fig. 4 is calculated by integrating the product of the raw irradiance data with the CIE standard scotopic spectral luminous efficiency function derived from the eye's sensitivity to dim light, which peaks at unity for blue-green light (approximately 507 nm). Eq. (3) can then be solved for the fluorescent surface's luminance N, given the known value of illuminance H and fiber acceptance half-angle θ_m. In addition, the CIE chromaticity coordinates x_{10}, y_{10}, and z_{10} can also be calculated from this data, using a MATLAB program based on tables in the public domain (Walker, 2003). From measurement of the

Table 1
Glass Fluorescence Photometric and Colorimetric Values (average of two trials). UV irradiance on glass surface at 253 nm: 5.35 μW cm^{-2}.

Quantity	Result
Scotopic luminance	2.2×10^{-3} cd m^{-2}
CIE x_{10} coordinate	0.32305
CIE y_{10} coordinate	0.36195
CIE z_{10} coordinate	0.3150

irradiance in the 253-nm region when the 95% reflecting diffuse reflectance standard was substituted for the glass sample, we found that the UV flux incident on the glass during these measurements was 5.35 μW cm^{-2}. The results of these calculations are shown in Table 1.

The CIE chromaticity coordinates of significance are x_{10} and y_{10} (the z_{10} coordinate is a linear combination of the other two and carries no independent information). The x_{10}–y_{10} location of a spectrum on the CIE chromaticity diagram is an objective measure of the color of the spectrum as it will be perceived by a standard observer. We note that while the chromaticity coordinates in Table 1 do not lie in the "yellow" region of the chromaticity diagram (the center of which is about $x_{10}=0.4$, $y_{10}=0.5$), the coordinates of Table 1 lie in a region of the diagram that, according to Kelly (Kelly, 1963), is closely approximated by blackbody radiation of a temperature of about 5880 K. While this color temperature is white rather than yellow, one possible explanation for why the eyewitness perceived the glass fluorescence as yellow is that yellow is a contrasting color to blue or violet, and the presence of the blue-colored sphere adjacent to the glass may have biased perception of the glass fluorescence toward yellow instead of white.

Because of the great uncertainty regarding the absolute luminance of the glass when it was fluorescing, we can calculate only a rough lower-bound estimate for the amount of ionizing radiation required to produce a minimal level of luminance from the glass. Using Eq. (10) and an estimated distance between the center of the ball-lightning object and the glass of $h=30$ cm, the constant relating the fluorescent luminance N_S during the incident and the estimated ionizing-radiation power output P_{BL} is found to be

$$4\pi h^2 \frac{U_T}{N_T} = 3.89 \text{ W m}^2 \text{ cd}^{-1}. \tag{11}$$

Multiplying this constant by an estimated fluorescent luminance N_S during the ball-lightning incident yields an estimate for the equivalent isotropic ionizing radiation power P_{BL} from the object. Table 2 shows the estimated total ionizing-radiation emitted power, in terms of equivalent 253-nm radiation, that would be required to produce a fluorescent luminance of the values shown. The luminance values typical of various illumination conditions are shown by the selected values (Wikipedia, 2016).

As Table 2 shows, if the glass fluorescence was at least as bright as a typical surface illuminated by an outdoor floodlight, the total equivalent ionizing-radiation output of the object was 7.8 W. And if the fluorescence was as bright as an electroluminescent panel, the equivalent power was on the order of 100 W. In any case, the total amount of ionizing radiation emitted from the object was substantial, in all likelihood several watts, in order to produce the fluorescent effect seen by the eyewitness.

The fluorescence as seen by the eyewitness was not uniform, and appeared to have some motion and irregularities that led the eyewitness to use the words "fiery" and "yellow-flame" in the transcript excerpts reported above. These irregularities would be due to nonuniformity in the radiation pattern from the object, and if recoverable could provide information about the object's internal structure. Unfortunately, the eyewitness can recall no more details than have already been stated, so the only conclusion we can draw is that there was some angular dependence of the ionizing radiation from the object.

Some remarks can be made about the possible spectrum of ionizing radiation emitted from the object. The glass window was checked visually for fluorescence under long-wave UV radiation (375 nm), and did not fluoresce. Therefore, the ball-lightning object must have been radiating some energy at a wavelength considerably below 375 nm, and probably in the range of 250 nm or below.

Table 2
Ionizing-radiation power output for various fluorescent luminance levels.

Typical illumination condition	Assumed luminance level (cd m^{-2})	Equivalent 253-nm power from object (W)
Phosphorescent watch dial after 1 h. in dark	40×10^{-3}	0.2
Outdoor floodlight illumination	2	7.8
Electroluminescent panel luminance	30	116
Standard SMPTE cinema screen luminance	55	214

5. Discussion

We have shown that in order to produce glass fluorescence of a different color than that of the ball-lightning object witnessed on June 23, 2008, the object must have been radiating ionizing radiation (<375 nm). The exact intensity and spectrum of this radiation is unknown, but fluorometry measurements show that if the visible fluorescence during the incident was at least 2 cd m^{-2} (the typical illumination level of a building exterior lit by floodlights), the equivalent isotropic ionizing-radiation output of the object was on the order of 10 W. If the fluorescence was as bright as a typical electroluminescent panel, the power required to produce it was on the order of 100 W.

Nothing is known about the ionizing radiation's spectrum other than its upper wavelength bound of about 375 nm. Fluorescence can also be caused by X-ray emission as well as, or in addition to, UV radiation. We have no quantitative data on the X-ray intensity required to produce glass fluorescence of a given luminance. X rays of 20 keV and higher energy are not absorbed well by glass, and so it is likely the conversion efficiency from X rays to visible fluorescence would be even lower than that which we measured with 253-nm UV radiation, which is absorbed completely within a few microns of the glass surface. So if X rays played a role in the effect observed, the X-ray power density would probably need to be at least as great as the estimated UV power density, if not greater.

This observation tends to support theories of ball lightning which propose that the energy source of the object is plasma- or electromagnetic-field related, rather than combustion-related. This includes the Shmatov totally-ionized-plasma theory (Shmatov, 2003) and the Wu electromagnetic-soliton theory (Wu, 2016), as well as many others. If a basically electromagnetic-plasma object encounters soil containing silicon and calcium, it is likely that those elements will be drawn into the object's plasma to be ionized and to radiate characteristic emission lines, as Cen et al. observed (Cen, 2014). On the other hand, it is difficult to see how combustion alone could account for both the blue color of the object seen in the event recounted herein, and for the relatively intense ionizing radiation that must have been present in order to cause the observed fluorescence.

Any theory of ball lightning must account for energy transfer that occurs during the object's lifetime. If the object emitted on the order of 100 W during an estimated lifetime of a few seconds, we must account for the storage of a kJ or so of energy in a volume of 1.44×10^{-3} m^3 (assuming a diameter of 14 cm), which is an energy density of about 0.7 MJ m^{-3}. Fortunately, this energy-density estimate is at the lower range of a set of energy densities calculated by Bychkov et al. (Bychkov et al., 2002) for 17 ball-lightning cases in which various circumstances made it possible to estimate the object's energy density. The lowest estimate in the Bychkov study was 0.96 MJ m^{-3}, so in the matter of energy storage at least, the object described in this paper was at the low end of the distribution described by Bychkov et al.

6. Conclusions

We have shown that the description of the object seen on June 23, 2008 by one of us (Krajcik) fits the typical characteristics of ball lightning very well: its occurrence during thunderstorms, its size, shape, and relatively constant appearance, and its motion. In addition, we have shown that the glow in a nearby window, of a contrasting color to the object, is most readily explained by fluorescence. Quantitative measurements of the actual glass observed during the incident correlate the fluorescent luminance of the glass to a known excitation irradiance at a UV wavelength of 253 nm. In terms of irradiation at that wavelength, the object's ionizing-radiation output during the incident was probably at least on the order of 10 W and perhaps much more, especially if the radiation was at shorter wavelengths (e. g. X rays). This conclusion has important implications for the development and refinement of theories intended to account for ball lightning observations, and may also guide efforts directed toward its replication in the laboratory.

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