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Optical Power Output of an Unidentified High Altitude Light Source

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Abstract — A Royal Canadian Air Force pilot while flying at an altitude of about 11 km saw and photographed a very bright, disc-like object that was remaining stationary near a thunderhead. An analysis of the photograph suggests that it would have been radiating in excess of a gigawatt of power within the spectral range of the film.

Keywords: UFOs — UFO sightings — physical evidence — photograph

Introduction

At about 7:20 p.m., MDT (about 20 min before sunset), on August 27, 1956, a Royal Canadian Air Force pilot was flying nearly due west over the Canadian Rockies near Ft. MacCleod, Alberta (49.5° latitude, 113.5° longitude). He was flying at 36,000 ft (about 11 km) in the second position (far left side) of a formation of four F-86 Sabre jet aircraft (Figure 1). While approaching a large thunderhead (cumulonimbus) at a ground speed of about 400 kts (740 km/h) he saw, at a much lower altitude, a "bright light which was sharply defined and disc-shaped" or "like a shiny silver dollar sitting horizontal." As he continued westward, the sighting line to the object rotated backward to an "eight o'clock low" position before he lost sight of it, indicating that it was stationary in the lee of the anvil of the thunderhead at an altitude considerably below the plane. It was below the upper layer of clouds but above the lower layer of clouds which, according to the pilot's weather report, were at 10,000–13,000 ft (3–4 km). The object, which was viewed against the dark purplish background of the lower cloud layer, appeared to be "considerably brighter than the sunlight." As he flew past he decided to take a photograph of the object. He had to "quarter-roll" the aircraft in the direction of the object in order to take the photograph. The exact direction to the object at the time of the photograph is not known. However, it was probably more than 30° north of the direction to the sun (276° azimuth, 8° elevation) because the sun was apparently to the left of the left edge of the film which in turn was about 28° to the left of the object. (This latter statement is based on the locations of shadows on clouds made by other clouds at the lower left side of the photograph.) The pilot estimated the sighting duration to be between 45 s [1] and 3 min [2]. After pointing out the object to the flight leader the pilot took a photograph of it

Fig. 1. Childerhose was flying west in the second position (left side) of a formation of four F-86 Sabre jets of the Royal Canadian Air Force.

Fig. 2. Photograph of an unidentified high altitude bright light source. Picture taken by Royal Canadian Air Force pilot R. J. Childerhose on August 27, 1956, from an altitude of 36,000 ft ($\approx$ 11 km). The object was higher than approximately 4 km and was observed for more than 45 s. If acting as an isotropic Lambertian radiator, the power output within the spectral range of the film would have been in excess of 10^9 W.

(Figure 2). (Appendix 1 provides further details of the sighting.) The photograph, a color slide (Kodachrome), is the subject of the analysis presented here.

The exact nature of the object has not been determined. An initial suggestion that it was merely a brightly illuminated small cloud [2] has been ruled out for two reasons. The first is that it is just as bright on the right (east) side as it is on the left side whereas clouds in the photograph are noticeably darker on their right sides, a fact that is consistent with the sunlight coming from the west. The second reason is that portions of the object were brighter than the brightest clouds. Klass [1] has suggested that the object was a plasma or something akin to ball lightning and Altschuler [3] included a discussion of the object in an article on ball lightning. Whatever the nature of the object, it would be of interest to have order of magnitude estimates of its radiance (watts/steradian/cm^2 or $W/sr/cm^2$), radiant emittance (W/cm^2) and total power output within the spectral range of the film. The radiance in the direction of the camera can be estimated from the film density of the image combined with published film characteristics and with suitable assumptions about the camera settings and the range to the object. By also assuming the object to be a Lambertian radiator with constant emittance over its surface one can estimate the total radiant emittance and the total radiated power within the spectral range of the film.

The radiance is found by solving a standard photographic equation [4],corrected for the effects of atmospheric attenuation [5] as shown in Appendix 2:

$$L = (4/\pi)E(f\#)^2\exp[(b-a)/\cos(\alpha)]/T\cos^4(\beta) \quad (1)$$

where

$$E = H/t \quad (2)$$

In these equations L is the radiance of the object in $W/sr/cm^2$, E is the irradiance on the focal plane of the camera lens in W/cm^2 and $f\#$ is the ratio of the focal length to the lens diameter (set by the operator of the camera). The factor $\exp[(b-a)/\cos(\alpha)]$ corrects for atmospheric attenuation along the slant path, at an angle α, relative to the vertical from the object to the camera. In this correction factor, b is the optical thickness of the atmosphere from the ground to the altitude of the plane and a is the optical thickness from the ground to the altitude of the object. T is the transmission of the optics (lens, aircraft window), β is the angle between the optic axis of the camera and the direction to the object, *i.e.,* the angle corresponding to the offset of the image from the center of the photograph, H is the film exposure level in J/cm^2 at any particular location within the image and t is the shutter time in seconds.

The quantities which go into Equations (1) and (2) are not definitely known. However, reasonable estimates have been made in order to carry out the calculations. Based upon the camera settings that are recommended for the film (Kodachrome ASA 10) when used under the known lighting conditions (bright daylight) it is estimated that $f\# = 8$, although it could have been one stop above or below this (*i.e.,* either 5.6 or 11). A camera is designed so that an increase in $f\#$ by one stop increases the aperture area by two and a decrease in $f\#$ by one stop divides the aperture area by two. Therefore an uncertainty of one f-stop setting corresponds to a factor of two (or half) uncertainty in the lens area and ultimately in the calculated radiance.

The values of b and a in the attenuation correction factor depend upon the particular altitudes and are weighted averages over the spectral range of the film. From attenuation data [5] for a clear atmosphere the difference $b–a$ has been determined for the airplane altitude in combination with two assumed altitudes of the object. The values of $b–a$ and angle α have been estimated in the following two ways.

The first way of determining $b–a$ and the zenith angle makes use of the statements by the pilot that (a) the object looked like a horizontal coin (*i.e.,* a thin disc with its axis vertical) seen from an angle to its axis (the zenith angle) and (b) he guessed the distance was about 3 nautical miles (5.5 km). Statement (a) implies that the image of the object would have a roughly elliptical shape. The aspect ratio of the ellipse (minor/major axis) would provide an estimate of the angle between the line of sight and the plane containing the disc (the complement of the zenith angle).

The brightest central part of the image does have a roughly elliptical shape which is moderately consistent with the shape of a thin disc viewed obliquely.[1] A good overall fit to the image is obtained with a 70° ellipse (*i.e.,* a circle viewed at an angle of 70° from the axis of the circle or 20° from the plane of the circle) with a major axis of the image being 1.28 mm long. Thus the depression angle of the line of sight from the plane to the disc would be about 20°, assuming that the disc itself was horizontal. The pilot stated that he had to roll the plane a bit in order to take the picture through the canopy indicating that the depression angle may well have been about 20° or greater. Assuming again that the disc was in a horizontal plane, then the angle from the vertical axis to the airplane, α, was about 70°. The 20° depression angle combined with the approximate 6 km range to the object yields an altitude of (11 km – 6 km $\times$ sin 20°) = 9 km. The difference $b–a$ is found for an optical path from 9 to 11 km by roughly averaging the optical thickness of the atmosphere over the sensitive spectral band of the film using tables in Ref. [5]. One finds that $(b–a)$ is approximately 0.03. Combining this with $\alpha = 70°$, $(b–a)/\cos\alpha = 0.09$ and $e^{0.09} = 1.09$.

A second estimate of the attenuation correction is obtained by using the same angle α as found above but using a lower altitude for the object. The jus-

[1] A careful study of the image reveals a brightness structure not completely consistent with the short cylinder model used here. In particular, there are two distinct bright spots, one at the left (west) end of the image and one slightly above the centerline at the right end. The structure of the image further suggests that there may have been two glowing objects very close to one another.

tification for using a lower altitude is based on two considerations: (a) the distance estimate given by the pilot was only a guess; the distance could have been greater than 6 km, and (b) the film imagery seems to show that the object illuminated the clouds just below it. (Note: the illuminated clouds are below the bright horizontal linear structure which is just below the elliptical image.) This would place the object relatively close to the lower cloud layer, which was at an altitude of about 3–4 km. Obviously the exact altitude of the object is unknown, but for the purposes of this second attenuation calculation it has been set equal to 4 km. At this altitude the range to the object is about 20 km and $(b–a)/\cos 70°$, as found from data in Ref. [5], is about 0.29. The attenuation correction factor is $e^{0.29} = 1.34$.

Each of the attenuation correction factors quoted above was calculated for clear air. Although there was water vapor in the nearby clouds, it is probable that the vapor between clouds was not sufficient to make the attenuation correction factor much larger than the largest value listed above. The optical transmission T of the camera lens and airplane window is estimated to have been about 0.7 due to glass surface reflection losses (about 4% loss at each surface), although it might have been slightly greater. The shutter time is less certain. It may have been 1/125 s, which, along with *f*/8, is the value recommended by the manufacturer (Kodak) for ASA 10 film under daylight conditions. However, it may also have been as long as 1/60 s or as short as 1/250 s. For these calculations $t = 1/125 = 0.008$ s = 8E–3 s. The angle β in Equation (1) is only about 9° so the $\cos^4(\beta)$ factor is about 0.95.

The only remaining quantity to be determined is the average exposure H over the image. H is related to the optical densities within the image of the three color forming emulsion layers which make up the film. Since the slide is a color reversal film, image density decreases as the exposure increases. The image of interest appears quite overexposed and white (*i.e.,* devoid of color). The color of the image of the object is the same as that of the images of the brightest white cloud areas which are also overexposed. Since the image of the object is white, one may assume that all three color forming layers were exposed to approximately equal amounts of energy. The minimum neutral density at several locations within the image is about 0.11, which is only slightly larger than the density of completely overexposed film. This density is also about 0.03 lower than the density of the brightest (white) cloud area. Because lower density corresponds to greater exposure, certain portions of the object were brighter than the clouds. The average density over much of the image is approximately 0.12.

An order of magnitude estimate can be made of the value of H which could create a density as low as 0.12. The estimate is made by combining the exposure curves [film density versus $\log(H)$] with the spectral sensitivity curves that are published by Kodak. The spectral sensitivity curves indicate how the monochromatic sensitivity varies with wavelength for the three emulsions, where sensitivity is the inverse of the energy density in J/cm^2.

The sensitivity values are given for a decrease in film density of 0.3 units from the maximum density which is between 3.2 and 3.5 units. Using the integral form of the van Kreveld addition law [6] one can determine the sensitivity of a film to a continuous spectrum of light.

Assuming for simplicity a flat spectrum over the spectral range of each emulsion one finds that the shorter wavelength emulsion (blue-violet to green, 350–500 nm wavelength) is roughly three times more sensitive than the mid range (green to red-orange, 500–600 nm) or long wavelength (red-orange to deep red, 600–700 nm) emulsion. Assuming that the object radiated a spectrum that would cause equal density changes in the three layers thus producing a white image, the approximate energy density needed to produce a film density decrease of 0.3 units would be 1E–7 J/cm^2. The exposure curves for the three emulsions indicate that to produce a film density decrease of about 3.2 units, *i.e.,* to cause the film density to decrease to a value comparable to that of the image of the object, the energy density would have to be about 1000 times greater. Therefore an order of magnitude estimate of H is 1E–4 J/cm^2, corresponding to the average image density of about 0.12.

Inserting the above values into Equations (1) and (2) yields a radiance of about 1.7 W/sr/cm^2 if the object were at 6 km distance and about 2.1 W/sr/cm^2 if it were at the 20 km distance. (The difference in the calculated radiances arises because of the atmospheric attenuation correction.) These values are so close to each other that the radiance will be approximated as 2 W/sr/cm^2 regardless of the assumed distance.

If the object were a Lambertian radiator then the radiant emittance, $W = \pi L$, would be about 6 W/cm^2. This value of W can be produced by a 2450 K blackbody with emissivity of 100% since it radiates about 3% of its total 200 W/cm^2 emittance within the bandwidth of the film [7]. However, the color balance of the film suggests that at that temperature the image would have a distinctly reddish hue. On the other hand, a 3200 K greybody with an emissivity of about 10% would provide approximately the same radiant emittance in the bandwidth of the film, but the color temperature would be high enough to produce a white image. A 10% emissivity is typical of some polished metals [7] which, even though hot enough to radiate, might give the visual appearance of a "shiny silver dollar sitting horizontal."

It is possible to estimate the total power output of the object within the spectral range of the film by assuming a specific shape for the object and also that it was a Lambertian emitter with constant emittance over its surface. For simplicity the following calculations have been done assuming that the object was a cylinder with length 1/10 of its diameter. Assumptions of other shapes will yield comparable or higher power outputs.

The diameter of the cylinder is estimated from the major axis of the ellipse fitted to the image length (0.00128 m) combined with the focal length of the camera (50 mm = 0.05 m) and an assumed distance to the object. Using the simple imaging relation established by the camera lens, if the object had been

6 km distant then its diameter would have been (6000 m/0.05 m)$\times$ 0.00128 m or about 150 m. The total radiating surface area (top, bottom and the cylindrical surface) would have been about 42,000 m^2 = 4.2E+8 cm^2. Multiplying this by the emittance, 6 W/cm^2, yields about 2.5E+9 W within the spectral band of the film. If the object had been at 20 km distance the diameter would have been about 500 m, the surface area about 4.7E+9 cm^2 and the power output would have been about 3E+10 W within the spectral band of the film. Of course, the total power emitted over all frequencies might be much greater.

A second method of estimating the total power, a method which treats the object as a "point" source emitter and which requires an estimate of the total energy deposited on the image, is presented in Appendix 2. This second method yields powers of 1.8E+9 W (instead of 2.5E+9) and 2.4E+10 W (instead of 3E+10). Since both methods require assumptions about the data, it is difficult to decide which is more likely to be correct. However, the rather close agreement suggests that, at the very least, the numerical results to be calculated by either method for any chosen set of values for the *f*#, the shutter speed and the distance to the object would be acceptably accurate.

The radiation power levels calculated here make it difficult to sustain the argument that the object was a plasma as ordinarily understood. Neither the origin of such a plasma, its size, its duration nor its total power output seem consistent with known plasma phenomenology. Its location near a huge thunderhead suggests that some transient electrical effect of the storm (*e.g.,* lightning bolt) might have created it, but this would not explain its duration of many tens of seconds. Assuming a minimum estimated sighting duration of 45 s and a minimum estimated distance of 6 km the energy radiated would have been of the order of 1E+11 J (about two orders of magnitude greater than the energy in a typical lightning stroke [3]) and the volume energy density of the assumed (cylindrical) plasma would have been about 4E+5 J/m^3. An energy density this great could be attained with single ionization of a portion of the air at 9 km altitude [3]. However, the recombination time for a plasma is very short, typically 100 ms or less. Therefore energy storage (ionization) during a transient event (*e.g.,* a lightning bolt) followed by relatively slow energy release during recombination could not account for the sighting duration. This implies that there must have been a continuous power source either within or outside the plasma. To determine whether or not such a power source exists would require theoretical and speculative analyses which go beyond the scope of this paper.

An alternative phenomenon which may be considered is ball lightning or "kugelblitz." Ball lightning has some characteristics of an ordinary plasma but it exists for much longer periods of time and therefore must have some (unknown) energy storage mechanism "built in" or else it is continually powered in some (unknown) way by an external power source. According to independent surveys by McNally and Rayle totaling 627 sightings (see Ref. [1], pp. 32 and 35–38 for details) observers of ball lightning usually report sighting durations on the order of seconds. Although about 8% have reported durations exceeding 1/2 min and about 2% have reported durations greater than 2 min. Therefore, because of the duration of this sighting one might consider the possibility that the photographed object was a ball lightning. However, typical ball lightnings are roughly spherical blobs with diameters of the order of tens of centimeters, although about 4% of the observers have reported sizes greater than 1.5 m and at least one observer (a pilot, see Ref. [3]) has reported diameters up to 30 m. Since the photographed object was well over 100 m in diameter (depending upon the assumed distance), at the very least this object was a highly unusual example of ball lightning. Unfortunately, there is no good theory that explains how even a typical ball lightning could exist. Therefore there is no way to scale predictions for ball lightning from the typical size under 1.5 m up to the size of the photographed object and to thereby determine whether or not it was ball lightning.

By way of comparison with the radiation of this object (1E+9 to 1E+13 W for 45 s or more), lightning radiates 1E+13 W for 1E–4 s, 1 kiloton of TNT "radiates" 1E+13 W for 1E–3 s, the Grand Coulee Dam power station generates 1E+10 W, a nuclear rocket can generate exhaust power at a rate of about 1E+10 W and the Saturn space rocket generates 1E+11 W at maximum thrust.

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Note Added in Proof

The original version of this paper was submitted to *Applied Optics* magazine in 1984. It was rejected because of my claim that the object was unidentified. The editor believed that it could be identified as some natural phenomenon. The editor first rejected the paper because, in his opinion, the photograph showed a sun dog. I then pointed out that there was a large angle difference between the direction to the object and the direction to the sun and also that the object appeared below the aircraft and "hidden" from the sun behind a large thunderhead. The editor then passed the paper to a referee who suggested a solar reflection in a lake. I responded that such a reflection, should it occur, would appear directly below the sun and not way off to the right, and that it would appear reddish because of passage of the light through a long atmospheric path at sunset. The referee responded that a rough lake surface could scatter light at considerable angles from the sun. He also pointed out that the film was saturated and therefore did not register the correct color of the image. At this point the editor ended the debate with a final rejection.

Had I been able to respond I would have pointed out that colored light sources leave their color "fingerprint" even if the image is saturated. This is because sideways scattering of light within the image causes film exposure outside the geometric boundary of the image (the boundary given by the equation, image size = object size times focal length divided by distance). This has been proved numerous times in experiments and is especially evident with red light. The image of a red light that is so bright as to achieve complete over-exposure (white) at the center of the image will have a rather wide red-colored annular region around the central overexposed region. Hence, if the pilot had photographed the reflection from a lake just before sunset, the atmospherically reddened reflection would have caused reddening of the image around the central overexposed region. However, there is no such reddening, nor is there evidence of any other coloration. Instead, the image is totally consistent with a white light source. Hence, it was not a reflection in a lake.

Had I been able to respond further, I would have pointed out that the pilot flew past this object as you would drive past a telephone pole or any other object fixed to the earth. This object seemed to remain stationary relative to the thunderhead. He last saw it dropping behind him as he flew on westward, *i.e.,* at a very large angle relative to the direction to the sun.

References

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Appendix 1

Pilot Testimony

The following statement by pilot Robert J. Childerhose was published by *Flying Saucer Review* in October 1958. It was written in the late spring of 1958, roughly 1 3/4 years after the event. Note that the date given here was not recalled correctly. During the 1968 investigation of this sighting by James McDonald, Childerhose referred to his log book and found the correct date, August 27, which was two days before he and another Sabre jet pilot set a speed record flying east over Canada. The time, 1820 h, is also incorrect. In another correspondence Childerhose stated that he landed in Vancouver at about 7:20 PDT which corresponds to 8:20 MDT. He estimated that the sighting took place about an hour before the landing, which would be at 7:20 MDT. The one hour estimate is based on the calculated flight time from a location near Ft. MacCleod to Vancouver (445 miles, 450 miles per hour estimated ground speed).

On the afternoon of 23 August 1956 the writer was flying #2 position in a four plane formation of Sabre 6 (F-86) aircraft from Gimli, Manitoba, to Vancouver, B.C. Our flight altitude was 37,000 feet, weather was good with cumulus and cumulonimbus cloud formations forming an intermittently broken undercast beneath us. Visibility was unlimited.

At about 1820 hours (local time) and at a point roughly over the foothills of the Rocky Mountains along a direct path between Gimli and Vancouver, we encountered a larger-than-usual thunderstorm. The leader of the formation elected to climb over the storm and called for climb power. The writer, who was shooting 35 mm color pics, decided to get a shot of the dark purple areas beneath the CB (cumulonimbus).

On looking down, he saw a bright light which was sharply defined and disc-shaped. (Like a silver dollar lying on its side.) The light being emitted from this source was considerably brighter than the sunlight which was beginning to set (sic). The sunlight was reflecting on the tops of cumulus formations, and was coming from our 10 o'clock position. (This is relative to the aircraft's heading.) The white disc was at 1 o'clock.

The writer called the attention of the formation to the light, asking for an opinion. The leader, F/L Ralph Annis, commented at that time: "Maybe it's a shaft of reflected sunlight."

(Note: Speaking to F/L Annis in May 1958, writer asked if he recalled the incident. F/L Annis said that he didn't.)

The writer took a photo of the disc, thinking only that it was a peculiar phenomena (sic). The idea of it being "reflected sunlight" did not sound plausible then, or since.

The disc of light appeared to be at a distance 3 miles from our position and at an altitude of about 20,000 feet. However, since the size of the object is unknown, the range quoted above is strictly a fighter pilot's guess.

On landing at Vancouver a short while later, the members of the section discussed the light briefly. Everyone agreed that it was an unusual sight. Nobody had ever encountered a similar orb of light; nobody had any reasonable explanation to offer; nobody suggested that it might have been a "Flying Saucer."

In correspondence dated ten or more years after the above written testimony (and 12 or more years after the event) Childerhose stated that he had made an error in the above testimony: the object was at 10 o'clock and the sun was at 1 o'clock. Moreover, he claimed he rolled his aircraft to the left in order to take the picture. He said that he doubted that he rolled his aircraft to the right since that would have taken him toward the other planes, an action which "frightened him." In other correspondence (see below) he indicated considerable confusion over his recollection of the direction to object from the aircraft. On the other hand, he also recalled (see below) that the flight leader wanted the jets to turn to the right while climbing to avoid the anvil of the thunderhead, so perhaps he took the picture as he began his right turn at a time when the other aircraft were also turning to the right. He may have confused the avoidance maneuvers with his maneuver to photograph the object. Whatever may be the explanation for his confusion, the fact is that the original slide photograph shows light coming from the left (west) which means the sighting line to the object was toward the northwest. The photo format (50 mm focal length, 35 mm film) and the image location in the picture can be used to determine the angle between the image and the left edge of the film. That angle is about 28°. Therefore the sighting line to the object must have been greater than about 28° to the right (north) of the sun, or greater than 304° azimuth. The lighting on the clouds, as shown in the original slide photograph, is consistent with this.

In his later correspondence he was more specific with details about the object and the sighting. From a letter to Philip Klass, September 1966:

I had the object in good view for upwards of 45 seconds. It was stationary, with sharply defined edges. Looked like a shiny silver dollar sitting horizontal. The light emitted was much brighter than the existing sunlight and overexposed the film causing blurred edges in the picture... It neither moved nor changed shape while I had it in sight... I remember looking down at the object from 38,000 feet and thinking that it was close to about 12,000 feet since it appeared to be close to the scattered layer of fluffy cumulus which I recollected was forecast to be between 10 and 12,000. (Pretty standard.)

From a letter to Dr. James McDonald, June 12, 1968:

I don't know whether I mentioned this to you but the photo of the bright object doesn't represent quite what appeared to the naked eye. When I first saw the object it appeared as a very bright, clearly defined discoid, like a silver dollar lying on its side. The photo makes it look like a blob of light, the result of light intensity. It appeared much brighter than that (sic) of the sun which, of course, was setting behind the clouds up ahead. What appears in the Kodachrome slide is a disappointment, really.

From a letter to Jim McDonald, March 22, 1969:

It was in good view for some minutes because I looked at it trying to figure out what I was seeing and I called the attention of the formation to it before remembering that I had a camera in my leg pocket.

From a letter to this author, September 19, 1984:

The object remained perfectly stationary throughout the period that I witnessed it. I recall the formation turned starboard and began climbing. The UFO, now at 8 o'clock low position relative to me was lost to view behind a cloud. This could have been the low cumulus near the UFO or in the mists of the scud roll of cloud which we climbed through to reach our (final altitude).

Appendix 2

Derivation of the Photometric Equation

Equation (1) is based on the standard "camera equation" for film exposure as modified for off-axis light sources [7] and for atmospheric transmission, written in the units of power rather than the usual (for photography) lumens:

$$E = \pi LT\, e^{-k} \cos^4(\beta) \,/(4f\#^2) \qquad (3)$$

where E is the irradiance in W/cm^2 within the image on the focal plane, L is the radiance in W/cm^2/sr of the source (sr = steradians), T is the transmission of the lens, k is the optical thickness of the atmosphere between the light and the camera, $f\#$ = "f-number" = f/D, where f is the focal length and D is the diameter and β is the angle between the lens axis and the direction to the source (and image).

The irradiance reaches the focal plane for a time t determined by the shutter setting. Thus a total energy per unit area or "exposure" of the film, H, is the product Et (pun intended). Inverting the equation for E to get L, with $E = H/t$, yields

$$L = (4/\pi)\, H(f\#^2)\, e^k/tT\cos^4\beta \qquad (4)$$

which, except for the form of the atmospheric correction, is the result of combining Equations (1) and (2).

The atmospheric attenuation over a slant path distance from one altitude to another is most easily found from tables of calculated attenuation from the ground up to a particular altitude. (Direct calculation is not easy since the absorption and scattering of light by the atmosphere are functions of altitude and light wavelength.) Suppose a light beam travels vertically upward from the ground to altitude h_1. The exponent k is replaced by the tabulated optical thickness value a. The beam power reaching h_1 is therefore e^{-a} times the initial power. Similarly, when the light beam travels vertically upward to h_2, k is replaced by the tabulated value b so the beam power at h_2 is e^{-b} times the initial power. When the power at h_1 is known, the power at h_2 can be calculated by multiplying the power at h_1 by the ratio of these two attenuation factors, $e^{-b}/e^{-a} = e^{-(b-a)}$. This is the ratio for a vertical path. For a slant path the distance traveled is greater than the vertical distance by a factor $1/\cos(\alpha)$, where α is the angle measured from vertical. The optical thickness is therefore greater by the same factor so e^{-k} in Equation (3) is replaced by $e^{-(b-a)/\cos(\alpha)}$. The inverse of this quantity replaces e^k in Equation 4 and yields the form shown in the combination of Equations (1) and (2).

An alternative estimate of the total radiated power can be derived under the assumption that the light source was effectively a "point" source unresolved by the camera. Under this assumption the intensity of the source, I , in W/sr, is calculated from the camera optics, the range to the light source, the shutter time and the energy density on the focal plane integrated over the image area. The integrated energy is approximated here by the product HA_i, where A_i is the image area over which H is approximately constant. In this case the power J which passes through the lens to the focal plane is given by

$$J = I\,(A_L/R^2)\,T\,e^{-(b-a)/\cos\alpha}\cos\beta \tag{5}$$

where A_L is the area of the lens aperture and R is the range. Note that this expression contains the inverse square law explicitly whereas the previous expression does not. Also, in this expression the cos β enters only to the first power to account for the oblique incidence of the light on the lens area. This power reaches the film plane for a time t and deposits a total energy over the image area which is approximated as

$$HA_i = Jt \tag{6}$$

Solving Equations (5) and (6) for intensity yields

$$I = (HA_i/t)R^2\,e^{(b-a)/\cos\alpha}/(A_L T\cos\beta) \tag{7}$$

The image area over which the exposure seems to be nearly constant is approximated as an ellipse with dimensions 1.28 mm by 0.6 mm for which A_i = 6E–3 cm^2. Therefore, with H = 1E–4 J/cm^2, A_L = 3E–5 m^2 (based on $f\#$ = 8 and a 50 mm focal length lens), T = 0.7, t = 8E–3 s, cos 9° = 0.987 and using the closer distance, R = 6000 m and $e^{(b-a)/\cos\alpha}$ = 1.09, Equation (7) yields I = 1.4E+8 W/sr. Assuming uniform radiation in all directions (a "4π" radiator) we find the total power emitted within the bandwidth of the film to be $P = 4\pi I$ = 1.8E+9 W. Similarly, for the 20 km assumed distance and the associated atmospheric attenuation factor 1.34, I = 1.9E+9 W/sr and P = 2.4 E+10 W. These values of total power are within a factor of two of the values calculated from Equation (1).