SAND2015-1873J

Photoacoustic Sounds from Meteors

Spalding, Richard, Tencer, John, Sweatt, William, Hogan, Roy, & Boslough, Mark

Sandia National Laboratories

Spurny, Pavel

Astronomical Institute, Academy of Sciences of Czech Republic

Abstract

High-speed photometric observations of meteor fireballs have shown that they often produce high-amplitude light oscillations with frequency components in the kHz range, and in some cases exhibit strong millisecond flares. We built a light source with similar characteristics and illuminated various materials in the laboratory, generating audible sounds. Models suggest that light oscillations and pulses can radiatively heat dielectric materials, which in turn conductively heats the surrounding air on millisecond timescales. The sound waves can be heard if the illuminated material is sufficiently close to the observer's ears. The mechanism described herein may explain many reports of meteors that appear to be audible while they are concurrently visible in the sky and too far away for sound to have propagated to the observer. This photoacoustic (PA) explanation provides an alternative to electrophonic (EP) sounds hypothesized to arise from electromagnetic coupling of plasma oscillation in the meteor wake to natural antennas in the vicinity of an observer.

AUDIBLE METEORS

When a medium-to-large meteoroid enters the atmosphere, it compresses the air and forms a bow shock that can reach the ground and be heard by witnesses as a sonic boom. However, there is typically a long time delay (t>minutes) because of the long travel distance. Occasionally, there are reports of hissing or popping that are heard simultaneously with the bright light from the fireball. The sound seems to come from near the observer, not from the fireball itself. This phenomenon has been reported by many observers over the years (cf Keay1980&1993; NASA2001a, 2001b). Astapovich(1958) reported that fireballs with brightness as dim as *-9* have been heard and numerous occurrences have been recorded when the brightness (apparent magnitude) is *-11* to *-13* (Keay1980).

Many authors have hypothesized that low-frequency electromagnetic waves are generated when electric charge flows up and down the ionized trail of a meteoroid creating low-frequency electromagnetic waves that are picked up by nearby resonators, generating audible "electrophonic" (EP) sound (Keay1980; Keay1993; Spurný & Ceplecha 2008). Various materials have been suggested to act as vibrating “antennas”, including hair, dry grass, and other dielectric materials. Our photoacoustic (PA) hypothesis suggests instead that audible sounds can be generated when millisecond pulses of light from meteors heat dielectric materials near the witnesses’ ears.

The photoacoustic idea has precedence. Alexander Graham Bell and colleagues illuminated various dielectric materials with sunlight that was modulated with a chopper wheel—and they heard a tone (Bell&Tainter, 1880). In 1976 Rosencwaig & Gersho (R&G) invented Photo-Acoustic Spectroscopy (PAS) and provided the first real understanding of the physics. They related sound output to the time-varying part of the illumination and the thermal conductivity, specific heat, and density of both the solid and the air, and light penetration depth into the solid.

THE PHOTOACCOUSTIC HYPOTHESIS

We hypothesize that pulsating light from meteors can indirectly produce sound that can be heard simultaneously on the ground. Strong, millisecond-duration flares have been recorded in nearly all meteoroids observed by Spurny & Ceplecha (2008). These pulses, if converted to sound, have time characteristics consistent with the popping, swishing, or sizzling noises reported by observers. We suggest that each pulse of light heats the surface of natural dielectric transducers within the audible frequency range. The surface rapidly warms and conducts heat into the nearby air, generating acoustic waves. The succession of light-pulse-produced pressure waves then manifests itself as sound to the observer.

We describe experiments in which we illuminated dielectric materials with white light modulated at 1kHz. We chopped a LED-driven white light source, which gave an irradiance of $5w/m^2$ at the sample, producing a large signal-to-noise ratio. The microphone was 10cm from the sample. If the illumination intensity is scaled down to that of a -13 brightness bolide, then the Sound Pressure Levels (SPS) observed were as great as ~20dB, which is comparable to a very soft whisper.

Temporal fluctuations of the light from meteors was first measured by Spurný (2001). Figure 1a shows an intensity-time history for meteoroid EN160413_23_202614_8sr0 recorded by the Czech Fireball Network.

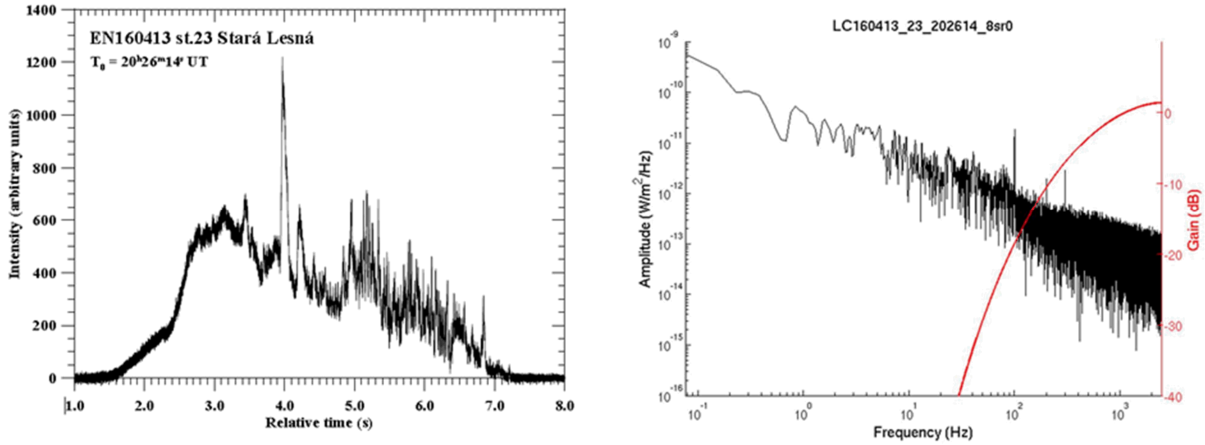

Figure 1 (a) Intensity-time history for meteoroid EN160413_23_202614_8sr0 (b) Fourier transform of intensity-time history assuming a magnitude of -3.75

Fig.1b shows the Fourier transform of the fireball light assuming an arbitrary brightness, along with the normalized sensitivity of the human ear (IEC). Unfortunately the brightness of fireball EN160413_23_202614_8sr0 was not measured so the actual spectral power is unknown. The two curves are plotted together to show that observers are most likely to hear sound with frequencies above a few hundred Hertz. The conversion ratio for changing incident irradiance into sound is not included, but we show in the next section that PA coupling is more efficient at lower frequencies, while the ear is most sensitive above ~500Hz.

PHOTOACOUSTIC EFFECT

To illustrate the application to meteors, we represent the illumination as a Fourier transform, one term of which is:

$$q''(t) = A\cos(\omega t) \tag{1}$$

Sinusoidally varying illumination, per eq.(1), would create sinusoidal surface temperature and hence a sinusoidal pressure wave or tone.

Materials that make the best light-to-sound transducers have high absorption coefficients, thus absorbing the light near the surface. They must have low conductivity to minimize heat flow, and the specific heat times the density must be low to maximize the temperature rise. This describes dark-colored dielectric materials.

It is instructive to relate light pulsations from meteoroids to sound. The oscillating component of the light is often comparable to average brightness (Fig 1a). Spurný et.al. (2001) also noted that the frequency content is often ω>40 Hz, which is audible.

As an example, the photoacoustic sound level created by -13 brightness meteoroids will have peak flux:

$$q'' \approx 1100\frac{\mathrm{W}}{m^2} \times 2.512^{(-26.74+13)} = 3.5\frac{\mathrm{mW}}{m^2} \quad (2)$$

where solar flux on earth is ~1100W/m^2 and the sun's magnitude is -26.74. Based on our experiments, typical dielectric materials change about 7E-6 percent of the light energy to sound for kilohertz frequencies. The resulting sound pressure level is thus:

$$10\log_{10}\left[7\text{E-}6\% \times 3.5\frac{\mathrm{mW}}{m^2} \div 10^{-12}\frac{\mathrm{W}}{m^2}\right] = 20\ \mathrm{dB(SPL)} \quad (3)$$

which is as loud as rustling leaves or faint whispers.

Thermal properties of selected dielectrics

Materials that seem to be likely candidates for producing photoacoustic sound are: dark paint, hair, leaves, grass, and clothing. Unfortunately published thermal properties are only available for similar materials. For example, the chemistry and microstructure of leaves, grass and cotton are roughly similar to wood. Likewise, the composition and structure of hair is similar to epidermis, and hence to leather. Finally, thermal properties of synthetic fibers in clothing should be similar to polyethylene. The density, specific heat, and thermal conductance of these materials [EngrToolbox,] can be combined to give the thermal diffusivity, which for wood, leather, polyethylene, and paint are 0.12, 0.07, 0.18, and 0.28 (μW/(Km^2)). These values are similar in magnitude so we expect that their "photoacoustic transduction" should be similar. The tests described below validate this statement.

EXPERIMENTAL INVESTIGATION

The experimental setup consisted of a 10cm square, 1.7W Commercial Electric-T41 SoftWhite LED array, the sample, and a Brüel&Kjær microphone, all inside an anechoic chamber. Outside we located an Agilent 33250A-Signal Generator plus Venable Instruments VLA1500 Linear Amplifier driving the LEDs at 1kHz and an Agilent E4446A recording the sound.

Materials that can act as sound transducers tend to fall in two categories:

- "Half-space" transducers include asphalt, tar paper, dark wood and dark paint (the substrate is unimportant).
- "Fibrous" transducers: Many catalogers of so-called "electrophonic" sound experiences (Keay1980; Keay1993; NASA2001a&2001b) note that people reporting audible meteors often have "frizzy hair". Also dark clothing, pine-needles, and grass should be good transducers.

A Plexiglas window with black Krylon paint on its front was also tested. The plate was turned around and retested resulting in a greatly reduced signal indicating that PA is a front-surface effect. Fig.2 shows the measured sound pressure levels for an incident intensity of $I = 5\,W/m^2$.

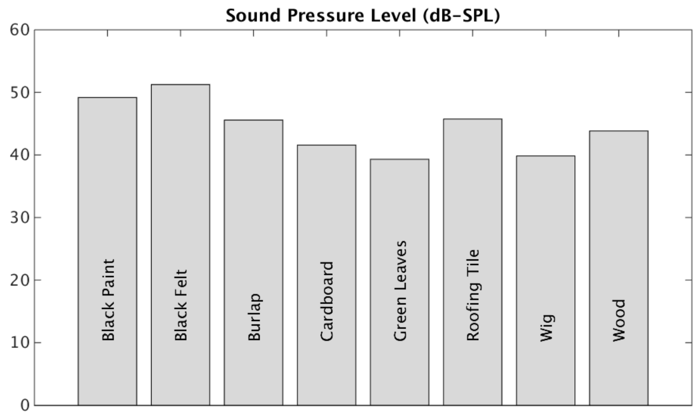

Figure 2 Measured sound pressure levels for various transducers

If the results in Fig. 2 are scaled to a -13 magnitude fireball, the loudness of black felt and dark paint would be ~20dB(SPL).

SUPPORTING CALCULATIONS FOR HALF-SPACE AND HAIR

Meteor illumination of a half space: Rosencwaig and Gersho (1976) developed an analysis for determining photoacoustic sound levels of a half space. In our analysis we used the properties of wood; specific heat=1700J/(kgK), density=700kg/m^3 , and conductivity=0.12W/(mK) (EngrToolbox 2014). A finite volume analysis was used to determine the thermal response of the half space. Using these properties, the results can be simplified to the following two equations for surface temperature and sound pressure level at the surface:

$$T(\delta,\omega) = 1.354\text{E-}7 \times q''(\delta\omega)^{-0.98} \quad (4)$$

$$\text{SPL}(\delta,\omega) = -19.6\text{dB} \times \log_{10}(\delta\omega) + 20\log_{10} q'' + 4.15\text{dB} \quad (5)$$

Where the light penetration depth δ is measured in meters, frequency ω in Hertz, and incident light flux q'' in W/m^2. The following assumptions also apply:

The surface temperature is effectively independent of the convective heat transfer coefficient and air's fluid properties. This one-way coupling allowed us to avoid modeling convection/conduction in the air adjacent to the solid surface and instead use a simple surface boundary condition.

The incident radiation is uniform, collimated, and varies sinusoidally. The light penetration depth δ is specified as an independent parameter. The peak amplitude of the intensity is arbitrarily taken to be 1W/m^2 making the temperature variations small and the problem linear.

The air pressure fluctuation at the solid's surface is calculated using the calculated surface temperature and the ideal gas assumption. The sound pressure levels are reported at or near the solid's surface so the distance to and geometry of the transducer should be considered. The SPL, is plotted in Fig.3 versus the frequency ω for several light penetration depths δ. Note the strong inverse dependence on both ω and δ.

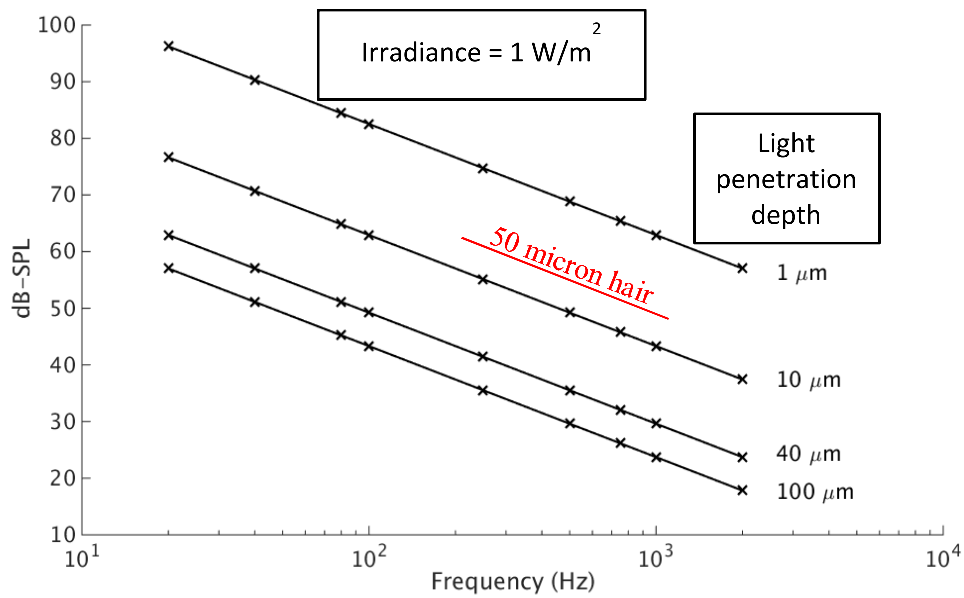

Figure 3 Simulation results for half space illuminated by uniform sinusoidally varying collimated beam
need to locate the hair line

<u>Hair as a PA transducer:</u> People with frizzy hair are said to be more likely to hear audible meteors. Why?

- Hair near the ears will create localized sound pressure, which is likely to be heard.
- Audible sound waves from closely spaced individual hairs will add coherently at the ear.
- Fine hair will have a large surface-to-volume ratio, thus maximizing sound creation.

Hair's refractive index is n=1.56 and black hair's absorption depth δ≈ cm/150 (vanKampen1997). The thermal diffusivity of leather (listed above) is similar to that of hair: 0.07 $\mu W/(Km^2)$. Fine hair diameter is d≈50μm [Franbourg2003].

A two-dimensional finite element model of a hair was developed to compute the temperature distribution due to volumetric energy absorbed from the incoming collimated, pulsing light (Gartling, 2004). Figure 4a shows the refracted ray traces within the hair and the volumetrically absorbed energy computed with an optical analysis code (Zemax 2014). The temperature profile within the hair was computed and then the surface temperature around the hair (Fig. 4b) was spatially-averaged. This was used to calculate the resulting sound pressure which is the red line in Fig. 3 with the following assumptions: Each hair should act like line sources because the wavelength of sound is much larger than the hair diameter. Therefore there will be no directionality of the sound. A thick mat should absorb all of the light and the sound waves will emanate from the mat's surfaces.

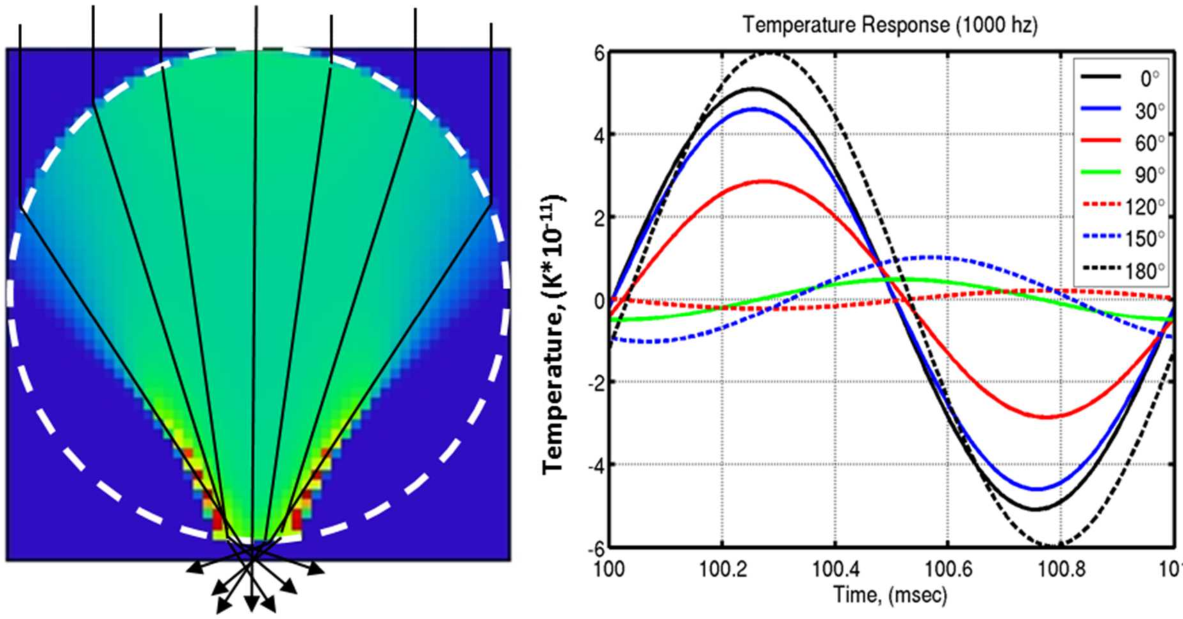

Figure 4 (a) Distribution of energy absorbed volumetrically within the hair (b) Computed surface temperatures

Comparing theory and experiment

Experimental measurements of photoacoustic sound have been made on paint, wood, a brown wig, and several types of dark cloth. These results compare well with the analytical results. The wood half-space model and experiment match if the 1/e light penetration depth is δ=20μm. The hair model differs slightly from the experiment. With a 1W/m^2 light source, the wig's measured SPL was 40dB while the calculated value was 47dB. This discrepancy could be due to the differences in diameter: 50μm for the model versus ~80μm for the wig. Also the wig was light brown while the calculations were for black hair. Given these differences, the ~7dB difference seems reasonable.

CONCLUSIONS

We have proposed an explanation for the long-standing mystery of audible meteors. Our hypothesis is based on the recently discovered pulsating quality of the radiated light. Our calculations and experiments seem to fit nicely with how observers have described the concurrent sounds associated with fireballs. They suggest that an observant young person in a quiet environment could definitely hear the photo acoustically induced sound from a -11 brightness fireball.

This explanation needs to be verified by measuring the concurrent sounds associated with real meteors. This will require the building of a set of photoacoustic sensors to be co-located with the stations in the fireball monitoring networks. Such sensors could consist of a box with a transparent cover that contains a dielectric material that is a good transducer. A microphone and recording equipment complete the unit.

Acknowledgements:

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This document has been reviewed and approved for unclassified, unlimited release under 2015-XXXX. Thanks to Mike Sinclair (SNL) who alerted us to photo acoustic spectroscopy.

References:

Astapovich, I.S. “Meteoric phenomena in the earth’s atmosphere”. *Fiznatgiz*, Moscow (in Russian and reported by Keay,1993, p.341) 1958

Bell, A.G., 1880, On the Production and Reproduction of Sound by Light: The Photophone, *American Association for the Advancement of Science*, Proceedings, Vol. 29, October 1880, pp. 115–136

Bell, A.G, & Tainter, S., 1880, Photophone patent: US patent 4028932

Engineering Toolbox, 2014….

Franbourg, Hallegot, Baltenneck, Toutain, & Leroy “Current research on ethnic hair” *J.Am.Acad.Dermatol*, June 2003, p.S115

Gartling, D.K, Hogan, R.E., & Glass, M.W., 2009, Coyote – A Finite Element Computed Program for Nonlinear Heat Conduction Problems, Part II – User’s Manual, Version 5.20, SAND2010-0714, Sandia National Laboratories, Albuquerque, NM.

International Electrotechnical Commission (IEC) 61672:2003; http://en.wikipedia.org/wiki/A-weighting

Keay, C.S.L,1993, “Progress in Explaining the Mysterious Sounds Produced by Very Large Meteor Fireballs”, *J. Sci. Exploration,* Vol.7,No.4,pp.337-354

Keay,C.S.L.,1980, “Anomalous Sounds from the Entry of Meteor Fireballs”, *Science*, 3October1980, V.210,N.4465

Leuven,K.U 1881, “Production of sound by radiant energy”, *The Manufacturer and Builder*,V.13,Issue7,pp.156-158, July 1881, https://fys.kuleuven.be/atf/Research_themes/rt_photoacoustic/rt_photo_pha

NASA,2001a, “Leonid Meteor Sounds, http://www.spaceweather.com/meteors/leonids/2001/sounds.html

NASA, 2001b,” Listening to Leonids”, *NASA Science News*, Nov 26, 2001, http://science.nasa.gov/science-news/science-at-nasa/2001/ast26nov_1/

Oberg, J.E., 2013, “The Whispering Bolide”, *Astronomy Magazine*, June 2013, http://www.astronomy.com/web%20extras/2013/04/the%20whispering%20bolide

Rosencwaig, A.& Gersho,A.,1976, “Theory of the photoacoustic effect in solids”, *J. Appl. Phys*. 47, 64

Schwarzkoph.com/sk/en/home/ Hair repair/Hair Dictionary/Hair quality, 2014

Shrbeny,L.& Spurný,P.,2009, “Precise data on Leonid fireballs from all-sky photographic records”, *Astronomy&Astrophysics*506,1445–1454

Spurný,P.& Ceplecha,Z.,2008, “Is Electric Charge Separation the Main Process for Kinetic Energy Transformation into the Meteor Phenomenon?”, *Astronomy&Astrophysics*,489,pp.449-454

Spurný,P.& Spalding,R.E.,2001, “Common Ground-based Optical and Radiometric Detections of Fireballs within the Czech Part of the European Fireball Network”, *Proc. Meteoroids 2001 Conference*, 6August,2001, Kiruna, Sweden, http://www.irf.se/Meteoroids2001/program/abstracts.html

vanKampen, Tjitske,1997, “The Optical Properties of Hair”, MS thesis, Tech.U,Eindhoven

Wikipedia ”hearing”, A-weighting, http://en.wikipedia.org/wiki/A-weighting

Wikipedia “Sound Pressure”, dB(SPL) http://en.wikipedia.org/wiki/Sound_pressure

Zemax, 2014, “ZEMAX-LLC, 22908NE Alder Crest Drive, Suite100 Redmond,WA98053

Zgrablic et.al, “Instrumental recording of photoacoustic sounds from Leonid fireballs,” *J.Geophysical Research*, Vol.107, No.A7