Earth Moon Planets (2014) 113:33–41
DOI 10.1007/s11038-014-9443-9

Electrophonic Sound Generation by the Chelyabinsk Fireball

Martin Beech

Received: 20 January 2014 / Accepted: 1 August 2014 / Published online: 8 August 2014

Abstract Simultaneous, also called electrophonic sounds were widely reported by eye-witnesses to the Chelyabinsk fireball. The available data indicate that such sounds were heard at ranges to at least ~ 100 km from the fireball's atmospheric path. We estimate that the fireball may have generated of order 625 W of energy in the form of very low frequency radiation, and we find some tentative evidence to indicate that the acoustic conversion efficiency at a 100 km range was of order 0.1 %. Numerical simulations of the atmospheric flight path indicate that electrophonic sounds should have commenced some 5 s after the fireball first became luminous and would have lasted for some 7.5 s prior to the moment of catastrophic break-up.

Keywords Meteorites · Chelyabinsk · Electrophonic sounds · Ablation

1 Introduction

Much has already been published with respect to the 15 February 2013 Chelyabinsk fireball and meteorite fall (Parigini et al. 2013; Popova et al. 2013; Borovicka et al. 2013b; Brown et al. 2013; Tauzin et al. 2013). The parent object was likely derived from the Flora asteroid family, but has a relatively young cosmic ray exposure age of some 1.2 million years (Popova et al. 2013). Within the first month of the fall date, several kilograms of LL5 ordinary chondrite meteorites were collected, with the largest fragment so far being recovered weighing-in at 654 kg. Infrasound detectors situated around the world recorded the end-phase air-burst detonation and the data indicates an energy of 500 $\pm$ 100 kiloton's of TNT equivalent for the Chelyabinsk event (Brown et al. 2013). In addition to the infrasound data, the luminous phase of the fireball's atmospheric flight was recorded by numerous video camera systems and this has resulted in the detailed annotation of the time

M. Beech (✉)
Campion College, The University of Regina, Regina, SK S4S 0A2, Canada
e-mail: beechm@uregina.ca

sequence relating to the fireball's height and velocity. In this analysis we use the atmospheric flight data to investigate the conditions under which electrophonic (also called simultaneous) sounds might have been generated prior to the fireball approaching its catastrophic break-up point. Our aim here is to characterize the size and extent of the zone, relative to the fireball's ground track, over which electrophonic sounds might potentially have been heard.

The observation that bright fireballs can generate electrophonic sounds has been discussed for many years now, but the essential physics behind the phenomenon were first elucidated by Colin Keay (1980a, 1992). Keay outlined the 'magnetic spaghetti' mechanism in which ELF/VLF radiation is produced through the entrapment of the geomagnetic field in the turbulent wake behind an ablating meteoroid. While the ELF/VLF radiation cannot be directly heard by a human observer, Keay's model invokes the presence of local transducers (e.g., dry leaf matter, lose hair, even spectacles) which upon interacting with the radiation field produce audible sounds—typically described as buzzing, clicking and/or sizzling. Importantly, in terms of characteristic phenomenology, electrophonic sounds are heard at the same time as the fireball is seen in flight. This behavior is in contrast to the explosive blast wave generated through the catastrophic disintegration of the incoming meteoroid which propagates at the appropriate altitude and temperature dependent speed of sound. In the case of the Chelyabinsk event the blast wave required some 2.5 min after the passage of the fireball to reach the ground at the City of Chelyabinsk itself.

The two essential conditions for the onset of the Keay mechanism are that the Reynolds number $Re > 10^6$, this is the turbulent flow condition, and that the magnetic Reynolds number $R_{em} = V\ \tau_m/D > D/10$, where D is the diameter of the ablating meteoroid in centimeters, V is the flow velocity in cm/s, and τ_m is the decay time for the diffusion of the magnetic field in seconds (Keay 1993). It is the latter of these two conditions which ensures that the geomagnetic field is entrapped within the turbulent flow directly behind the ablating meteoroid. ReVelle (1979) provides a convenient expression for the transition height at which a certain Reynolds number will be realized, namely, $h_{tran} = -H \ln(Re\ \mu_0/V\ \rho_0\ D)$, where H is the atmospheric scale height, μ_0 is the dynamic viscosity and ρ_0 is the atmospheric density at sea-level. For a given velocity the turbulent transition height is inversely dependent upon the size of the meteoroid and typically a threshold size of several meters in diameter is required before electrophonic sound generation is likely to proceed (Molina and Moreno 2013). Indeed, the onset condition is satisfied under the Keay model once $h < h_{tran}$, where h is the actual atmospheric height of the meteoroid.

In addition to the tangling of the geomagnetic field model, Beech and Foschini (1999, 2001) have outlined a secondary process by which short-duration or burster electrophonic sounds might be generated. This second mechanism relies upon the abrupt variation in the electron and ion densities across a shock boundary formed within the fireball wake. This mechanism, it is argued, generates very low frequency (VLF) radiation through charge separation rather than via magnetic field entanglement. The burster mechanism is thought to most likely operate at those times of short-duration fragmentation events—rather than during the times of steady ablative mass loss when the Keay mechanism is expected to run more efficiently. Both burster and long-duration electrophonic sounds appear to have accompanied the Chelyabinsk fireball and it is the details of this event that we discuss next.

2 Atmospheric Path Reconstruction

Borovicka et al. (2013a) and Popova et al. (2013) have published the most detailed and accurate accounts of the atmospheric flight path as well as data concerning the orbital characteristics for the parent asteroid. For this analysis, however, we only require the initial mass and atmospheric velocity estimates for the incoming object, along with an estimate of the angle of the flight path with respect to the horizon. Infrasound data gathered from numerous stations indicate an initial mass M_∞ in the range $12.5 \pm 0.5 \times 10^6$ kg, and detailed reconstructions of the atmospheric flight path further indicate an initial atmospheric velocity V_∞ in the range 19.16 ± 0.15 km/s. Reconstruction analysis of the video observations by Popova et al. (2013) further reveal a shallow angle of entry with the horizon angle θ being $18.3 \pm 0.2°$. The point of peak brightness (estimated to be of order magnitude −28: Brown et al. 2013) occurred at an altitude of about 30 km.

Within days of the fireball event meteorite fragments were found in the region of Lake Chebarkul, some 70 km west–south–west of Chelyabinsk. Later searches further revealed that many small meteorites had fallen to the south and southwest of Chelyabinsk, in the region between and close to Pervomayskiy and Timiryazevskiy (a detailed map of the strewn field has been compiled by Buhl and Wimmer 2013). The meteorite material is that of an LL5 ordinary chondrite with a moderate shock rating of S4—indicative of having suffered at some earlier (pre-Earth encounter) stage shock metamorphism at a pressure in the range 30–35 GPa. The meteorite composition data indicate that the initial diameter of the Chelyabinsk meteoroid would have been about 19 m (taking the material density to be 3,300 kg/m^3 as found by Popova et al. 2013). The yield strength of stony meteorite material is expected to be of order 10 MPa (Beech and Brown 2000; Petrovic 2001; Parigini et al. 2013), and the analysis of video data by Borovicka et al. (2013a) and Popova et al. (2013) indicates a range of fragmentation heights equivalent to yield strength values in the range 5–15 MPa. The analysis presented by Borovicka et al. (2013a, b) and Popova et al. (2013) indicate that the luminous path of the fireball began at an altitude of about 97 km, with a number of flares and fragmentation events occurring at altitudes between 40 and 30 km, with a final, catastrophic break-up taking place at an altitude of about 25 km.

3 Numerical Scheme and Results

In this analysis the equations of meteoroid ablation have been solved for numerically allowing for a spherical Earth and surrounding atmosphere (Beech 2013). We constrain the input data with respect to initial mass, velocity and horizon angle according to the data given by Popova et al. (2013), and we adopt an assumed constant value for the ablation coefficient of 0.06 (s^2/km^2), which is consistent with the value range suggested by Ceplecha and ReVelle (2005), and very similar to those values derived from the video data analysis conducted by Borovicka et al. (2013b—their extended data figure 6d). The initial mass of the Chelyabinsk body is still somewhat uncertain but Popova et al. (2013) give a value of 1.3×10^7 kg, but note that the uncertainty is of order a factor of two; accordingly we adopt a range of values in our simulations. In each simulation the motion of the meteoroid through the atmosphere is determined and a test is made to see if the actual body height is below that of the turbulent flow transition height. If this latter condition is satisfied then electrophonic sounds may accordingly follow. The model keeps track of the time, altitude and path length over which the turbulent flow condition holds and follows the on-coming ram pressure to determine the end point for catastrophic break-up which we

Table 1 Initial parameter range and resultant atmospheric flight characteristics

M_∞ ($\times$ 10^6 kg)	h_{ES} (km)	ΔT (s)	ΔR (km)	R (km)	H_{end} (km)
8	65.85	7.54	136.1	242.38	24.71
12	66.30	7.62	137.6	242.40	24.71
16	66.64	7.68	138.7	242.41	24.70
20	66.86	7.72	139.4	242.42	24.70

Column 1 indicates the initial mass. Column 2 indicates the height of turbulent flow onset. Columns 3 and 4 indicate the time and ground track range between the onset of turbulent flow and catastrophic break-up location. Column 5 is the total ground track range from the starting altitude of 100 km to the end height at ~25 km (as shown in Column 6). For each calculation the initial velocity and inclination were taken as 19 km/s and 18° respectively

take to be the height at which a ram pressure of 10 MPa is attainted. The results from the numerical calculations are summarized in Table 1.

Our numerical model indicates that the height at which turbulent flow begins is about 66.5 km in altitude and this condition holds for some 7–8 s prior to the assumed final break-up phase, at about 25 km, once the atmospheric ram pressure exceeds 10 MPa. These results are not highly sensitive to the initial mass adopted, and additional simulations indicate that they are they are not particularly sensitive to the adopted value of the ablation coefficient—these latter quantities tend to have a much more pronounced affect on determining the final mass rather than the velocity, and it is the velocity that determines the onset of turbulence condition and which dictates the magnitude of the ram pressure. Accordingly, we conclude that electrophonic sound generation should have begun about 5 s after the onset of luminous flight (achieved at h $\approx$ 97 km) and would have continued to the moment of catastrophic fragmentation (when h $\approx$ 25 km).

While Keay's turbulence onset condition provides a guide to when electrophonic sound production might begin, it does not provide any direct information over what kind of distances observers might expect to hear such sounds. An estimate of the detection range, however, can be derived from past electrophonic producing fireball events. In the case of the 9 October 1992 Peekskill fireball and meteorite dropping event, the range over which electrophonic sounds were reported varied from of order 75 km to a maximum of 300 km (Beech et al. 1995a). Likewise, the range over which electrophonic sounds were reported in the case of the 21 November 2008 Buzzard Coulee fireball and meteorite producing event corresponded to distances of order 50 to a maximum 400 km (Beech 2009). A study of bright fireball events by Romig and Lamar (1963) further indicates that anomalous sounds have been reported up to a maximum range of order 500 km, but that the typical observer distance was of order 100–150 km. These data suggest that a range of order 100 km from the fireball path is our characteristic distance of interest.

In order to estimate the radiative power P_m associated with the displacement of the geomagnetic field we treat the system as a magnetic dipole with a characteristic size L comparable to that of the fireball's wake. In the far-field approximation the total radiated power by a magnetic dipole is

$$P_m = \frac{\mu_0}{12\,\pi\,c^3} m_0^2 \omega^4 \tag{1}$$

where μ_0 is the permeability of free space, c is the speed of light, m_0 is the magnetic dipole moment and ω is the characteristic angular frequency of oscillation (see, e.g., Griffiths 1981). We approximate the dipole moment as being that of a superconducting sphere of radius L in an otherwise uniform magnetic field B_0—the analogy being invoked here is that the energy which ultimately drives the production of electrophonic sounds is produced through the relaxation of geomagnetic field lines to their non-perturbed configuration. This process is, to a first approximation, similar to that of placing, and then quickly removing, a superconducting sphere within a uniform magnetic field. Indeed, when such a sphere is placed within a uniform magnetic field, a spherical exclusion region or cavity is produced according to the Meissner effect. Once the superconducting sphere is removed the magnetic field will then relax to its uniform state, filling-in the previously excluded cavity. According to this analogy, we express the magnetic moment as $m_0 = -2\pi L^3 B_0/\mu_0$(Poole et al. 2010; Mohamed et al. 2013). The characteristic angular frequency is approximated according to the fact that the wavelength of the geomagnetic field vibrations will be of order 100 km—the height h_{ic} of Earth's ionospheric cavity, and therefore, we take $\omega = 2\pi f = 2\pi\ c/h_{ic} \approx 2 \times 10^4\ (s^{-1})$. The radiative power, Eq. (1), now reduces to

$$P_m = \frac{\mu_0}{12\,\pi\, c^3} m_0^2 \omega^4 \approx \frac{1}{6}\left(\frac{c}{\mu_0}\right)\frac{(2\pi)^5}{h_{ic}^4} L^6 B_0^2 \approx 625\ (\text{Watts}) \quad (2)$$

where we have used the additional characteristic approximation (Bronshten 1983) that $L \approx 10\,D$, with $D \sim 20$ m being the diameter of the Chelyabinsk meteoroid and were $B_0 = 5 \times 10^{-5}$ T. At a range of 100 km from the fireball the energy flux will be of order 6×10^{-8} W/m^2. If the transduction process can successfully generate local pressure waves with a similar intensity then acoustic levels of some 50 db(SIL) might result. Such sound levels are generally described as being equivalent to that of ordinary speech at a few meters away from the listener's ears. Even if the transduction process results in pressure waves with an intensity of just 10 db(SIL)—equivalent to an intensity of 10^{-11} W/m^2, or for this model calculation a conversion efficiency of 0.01 %—then sounds at a level equivalent to that of 'distant rustling leaves' could, in principle, result.

The radiative power of the magnetic dipole, as shown in Eq. (2), is strongly dependent upon the adopted characteristic size L (the expression varying as the sixth-power) and the characteristic angular frequency ω (the expression varying as the fourth-power). Of these two terms it is the characteristic size L that is most poorly constrained. If L is smaller by a factor of ½ then the power is reduced by a factor of 64. Accordingly, for our calculation, *ceteris paribus*, the intensity at 100 km range is reduced to $10^{-}9$ W/m^2. To produce an acoustic signal with an intensity of 10 db(SIL) now requires a conversion efficiency of about 0.1 %. For the angular frequency term, the characteristic wavelength of the magnetic field vibrations might reasonably be taken as being of order 50 km, rather than the 100 km adopted in our provisional calculation. By reducing the wavelength term by a factor of one-half the radiative power derived from Eq. (2) increases by a factor of 16. With this increase, *ceteris paribus*, the conversion efficiency to produce a 10 db(SIL) acoustic signal at 100 km requires a conversion efficiency of 0.001 %.

While some experimental work has been conducted with respect to the transduction mechanism (Keay 1980b; Keay and Ostwald 1991; Zgrablic et al. 2002) it is not presently clear how efficient the whole process might be and neither is it clear upon what physical characteristics (e.g., surface area and make-up of the transduction medium) it might dependent upon. In addition, some research indicates that the auditory response may be entirely physiological and that no medium external to the body is required for electrophonic sounds to be heard (e.g., Elder and Chou 2003). Indeed, observers of bright fireballs, including that of Chelyabinsk as well as the recent 2008 Buzzard Coulee fireball, have additionally reported the sensation of feeling heat upon their skin. At present it is not at all clear if this phenomenon has anything to do with the mechanisms being invoked to explain electrophonic sounds. Popova et al. (2013) note, for example, that the estimated UV dose resulting from the passage of the Chelyabinsk fireball would not have exceeded 200 W at a range of 30 km, and yet reports of suffering sunburn and skin peeling, the latter requiring a minimum dosage of at least 1,000 W, were reported—indeed, the sensation of feeling heat was reported at ranges in excess of 100 km from the Chelyabinsk fireball path (Popova et al. supplementary data tables S7A and S7B). Clearly, this is an area requiring continued investigation.

4 Observations

The Chelyabinsk fireball must have been witnessed by many thousands of people, and indeed, many hundreds of eyewitness reports were submitted within hours of the event having taken place. An on-line article published in a Chelyabinsk newspaper (chelyabinsk.ru/text/newsline/625214.html) for 17 February 2013, indicates, for example, that over 700 reports were submitted to an internet-based survey site (www.chel-meteorit.youini.ru) within just a few days of the fireball's passage, and that of these, Stanislav Korotkiy (Ka-Dar Scientific Center and Public Observatory, Moscow) explains, 27 eyewitnesses reported hearing "hissing" sounds while the fireball was in flight and prior to the arrival of the sonic boom associated with its catastrophic break-up. Submitting to no statistical finesse, these numbers suggest that of order 4 % of observers reported hearing an anomalous sound—this, in fact, is a fairly typical reporting percentage. In a survey of Canadian fireballs observed between 1962 and 1989, for example, it was found that if electrophonic sounds were associated with a specific fireball event then of order 6 % of the eyewitness reported actually hearing them (Beech 2003).

The extended results from the internet survey are given in the supplementary data of Popova et al. (2013), where in their table S9 it is indicated that of the 1,674 submissions a total of 198 observers reported hearing typical electrophonic sounds—hissing, crackling, rustling, humming, and whistling. This indicates a rather high, but not totally unprecedented, 12 % of observers hearing what can be reasonably interpreted as electrophonic sounds. This seemingly enhanced percentage of electrophonic sound reports is most likely reflective of the large physical size and energetic interaction of the Chelyabinsk fireball with Earth's atmosphere—it also relates, no doubt, to the fact that an intensive effort was made to record eye-witness accounts almost immediately after the event occurred. The survey data presented by Popova et al. (2013) indicates that electrophonic sounds were heard in the same general locations as those from which heat sensations, sunburn effects and sonic booms were reported, and that the observers were typically located in urban environments. The greater than usual number of electrophonic sound reports is consistent with that fact that many outdoor observers (of order 50 %, in fact) reported feeling a 'warming heat' during the passage of the fireball, as well as other observers (about 2 %) reporting the experiencing of mild sunburn effects (indicative of a relatively high UV flux). These latter effects are typically only rarely mentioned in fireball reports (Romig and Lamar 1963) and, for example, only one observer (constituting 0.2 % of reports) described the experience of a heating sensation during the passage of the magnitude −20 Buzzard Coulee fireball while 14 % of observers reported hearing sonic booms and/or electrophonic sounds (Beech 2009). In general it would appear that the many reports of electrophonic sounds, heat sensation and sunburn effects associated with the passage of the Chelyabinsk

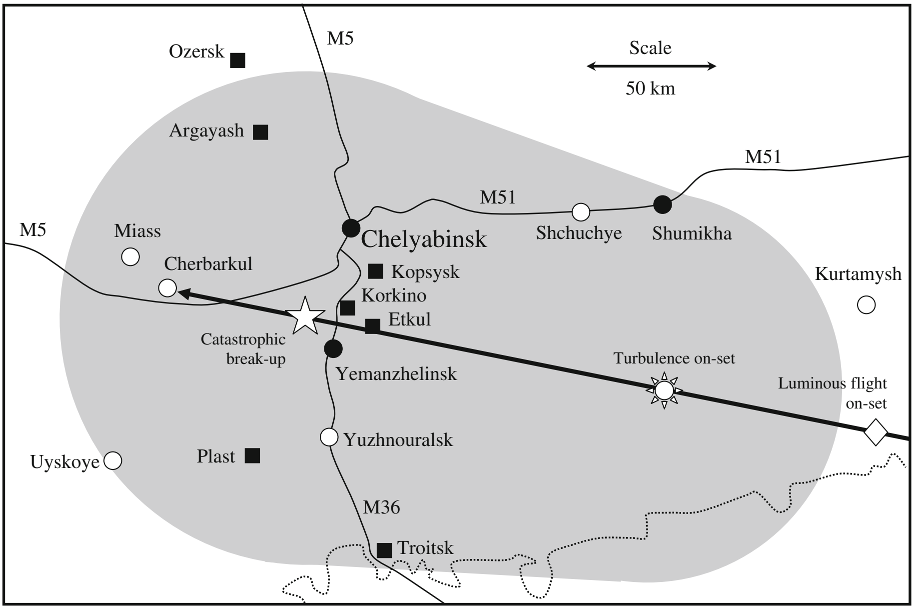

Fig. 1 Schematic map of the Chelyabinsk fireball ground path (*solid straight line*) and the ground intercept region for ranges of 100-km and less from the fireball path (*shaded gray*). The onset location of luminous flight is indicated by the *open diamond*, while the location of catastrophic break-up point is indicated by the *five-pointed star*. The on-set of turbulent motion position is indicated by the *multiple-pointed star* symbol. Meteorite fragments were recovered in the region of Lake Chebarkul and in regions slightly to the south of the ground path line and to the west of the M5 auto route (see, Buhl and Wimmer, 2013). The *filled circles* correspond to those locations at which electrophonic sounds were definitively reported. The *filled square* symbols indicate a selection of the locations at which observers reported the feeling of a 'warming heat' during the passage of the fireball. Image based upon Google Maps

fireball are not inconsistent with what might be expected given the extreme characteristics of the atmospheric interaction that took place.

Popova et al. (2013) report that no power surges were recorded as a result of the passage of the fireball nor were there any reports of interference effects relating to the function of electronic equipment in general. As with most reports relating to electrophonic sounds, the observers reporting such sounds were variously located inside of buildings, within cars, open spaces or just on City streets. Figure 1 shows a schematic map of the regions surrounding Chelyabinsk along with the fireball ground track and the ground zone corresponding to an electrophonic sound perception distance of 100 km. The reports from Yemanzhelinsk and Chelyabinsk are consistent with minimum fireball path ranges varying from of order 30–50 km, while that at Shumikha (Spaceflight 2013), described as being like a, "low level hum, very similar to what you hear near high voltage power lines", is consistent with a minimum range of 100 km. The observer at Shumikha would appear to have perceived electrophonic sounds almost as soon as the turbulent flight onset condition was satisfied, while those observers in Yemanzhelinsk and Chelyabinsk appear to have heard electrophonic sounds generated at a location closer to the fireballs catastrophic break-up point.

5 Discussion

According to the numerical simulations described in Sect. 3 and summarized in Table 1, it would appear that the Chelyabinsk fireball satisfied the conditions for the possible generation of electrophonic sounds for about 7.5 s. The turbulent wake onset condition began at an altitude of about 66 km and continued until the moment of catastrophic break-up at an altitude of ~ 25 km when the atmospheric ram pressure exceeded 10 MPa. During this time interval we estimate (via Eq. 2) that the radiative power, in the form of very long wavelength electromagnetic radiation, was of order 625 W. At a range of order 100 km it is conceivable, given a conversion efficiency of 0.1 % that sounds with an acoustic intensity of some 5×10^{-11} W/m^2 might be produced. Such an acoustic intensity corresponds to about a 10 db(SIL) level background noise—the observational report from Shumikha (Spaceflight 2013) is consistent with such a sound level. Given the same conversion efficiency, the acoustic intensity at ranges of 30–50 km would be of order 20–25 db(SIL). The eye-witness reports which indicated that the fireball sounded "like a plane passing" are much less easily explained although the description itself is rather vague and not easily interpreted—indeed, even if one allows for a 100 % conversion efficiency, the maximum acoustic intensity at a range of 50 km would be no more than 10^{-7} W/m^2, or some 50 db(SIL), which is orders of magnitude smaller than the implied ~ 100 db(SIL) sounds, requiring an intensity of some 0.01 W/m^2, being reported.

While the Chelyabinsk fireball undoubtedly produced electrophonic sounds we remain in the unfortunate position that no clear conclusions concerning the local sound generating mechanisms can be made—the required data simply does not exist. Likewise, it is not entirely clear what the acoustic conversion efficiency is and how it might vary with location and observer—our analysis above, however, suggests that the conversion efficiency might be of order 0.1 %, but we additionally note that some reports appear to indicate a much high conversion efficiency. Indeed, one of the long-running problem issues with respect to electrophonic sounds has been that of explaining exactly how the sounds might be generated and with what acoustic conversion efficiency (Keay 1980b; Keay and Ostwald 1991); and at no less a level is the problem of trying to evaluate exactly what it is that the observer actually means by their description. Clearly, these questions will not be fully answered until more unambiguous instrumental data becomes available along the lines of that gathered by Beech et al. (1995b), who monitored VLF emissions, and Zgrablic et al. (2002), who also monitored VLF emissions and additionally recorded the very first associated electrophonic sounds from meteors. Ironically, for all of the multitudes of visual, video, infrared, seismic and infrasound data that have been collected with respect to Chelyabinsk fireball none provide definitive information with respect to electrophonic sounds. This latter comment is in no way intended to lessen the importance of the eye-witness data and the Herculean efforts that were made to collect it, but it underscores the fact, that progress in understanding electrophonic sounds will only move forward once good instrumental data becomes available. On this front, however, we note that there are now many automated fireball detection systems located around the world, and we would accordingly encourage the operators of these stations to look into the possibility of installing sound-level monitoring devices, such as those described by Zgrablic et al. (2002), along with VLF radio receiver systems, to compliment the acquisition of the optical video data.

References

M. Beech, J. R. Astron. Soc. Can. **97**, 71 (2003)
M. Beech, Meteor. Q. **15**(2), 5 (2009)
M. Beech, Earth Moon Planets **111**, 15 (2013)
M. Beech, P. Brown, R.L. Hawkes, Z. Ceplecha, K. Mossman, G. Wetherill, Earth Moon Planets **68**, 189 (1995a)
M. Beech, P. Brown, J. Jones, Earth Moon Planets **68**, 181 (1995b)
M. Beech, P. Brown, Planet Space Sci. **48**, 925 (2000)
M. Beech, L. Foschini, Astron. Astrophys. **345**, L27 (1999)
M. Beech, L. Foschini, Astron. Astrophys. **367**, 1056 (2001)
J. Borovicka, P. Spurny, L. Shirbeny, IAU Telegram No. 3423 (2013a)
J. Borovicka et al., Nature **503**, 235 (2013b)
V.A. Bronshten, *Physics of Meteoric Phenomena* (D. Reidel, Dordrecht, 1983)
P. Brown et al., Nature **503**, 238 (2013)
S. Buhl, K. Wimmer, (2013), http://www-niger-meteorite-recon.de/img_inventar/Chelyabinsk_strewfiled_map_7500.jpg
Z. Ceplecha, D.O. ReVelle, Meteor. Planet Sci. **40**, 35 (2005)
J.A. Elder, C.K. Chou, Bioelectromagn. Suppl. **6**, S162 (2003)
D.J. Griffiths, *Introduction to Electrodynamics*, 3rd edn. (Prentice-Hall, New Jersey, 1981), p. 454
C.S.L. Keay, Science **210**, 11 (1980a)
C.S.L. Keay, J. Roy. Astron. Soc. Canada. **74**, 253 (1980b)
C.S.L. Keay, Meteoritics **27**, 144 (1992)
C.S.L. Keay, J. Sci. Exploration **7**, 337 (1993)
C.S.L. Keay, P.M. Ostwald, J. Acoust. Soc. Am. **89**, 1823 (1991)
M.A. Mohamed, E.D. Kuester, M.C.E. Yagoub, Electromagnetic Res. B. **46**, 101 (2013)
A. Molina, F. Moreno, Astron. J. **145**, 89 (2013)
C. Parigini, J.L. Cano, R. Haya-Ramos, arXiv:1304.2410v1 (posted 8 April 2013)
J.J. Petrovic, J. Material Sci. **36**, 1579 (2001)
C.P. Poole, H.A. Rarach, R.J. Creswick, R. Prozorov, *Superconductivity* (Academic Press, New York, 2010), p. 128
O. Popova et al., Science **342**, 1069 (2013)
D.O. Revelle, J. Atmos. Terr. Phys. **41**, 453 (1979)
M.F. Romig, D.L. Lamar, *Memorandum RM-3724-ARPA* (The Rand Corporation, Santa Monica, 1963)
Spaceflight (2013), http://forum.nasaspaceflight.com/index.php?topic=31118.465. See reply #475 posted on 26 Feb 2013
B. Tauzin, E. Debayle, C. Quantin, N. Coltice, Geophys. Res. Lett. **40**, 3522 (2013)
G. Zgrablić et al., J. Geophys. Res. **107**, 1124 (2002)