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Title:

GLOBAL INFRASONIC MONITORING OF LARGE BOLIDE*S*

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GLOBAL INFRASONIC MONITORING OF LARGE BOLIDE*S*

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ABSTRACT

Using recent infrasonic data (1995-2001) and older infrasonic data recorded by AFTAC (1960-1974), we have refined our estimates of the global influx rate (cumulative influx) of large bolides with sufficient strength to deeply penetrate the atmosphere (below ~ 50 km). The number of bolides arriving as a function of their initial source energy has been estimated from a least-squares curve-fit of our database of 19 bolides (for a source energy > 0.053 kt) with the resulting values and an estimate of the associated statistical counting errors: 30.3± 6 bolides at ≥0.1 kt, 5.8± 2 at ≥1 kt and 0.84± 0.25 at ≥15 kt. In this work we also used these estimates to infer the recurrence interval for energy levels slightly outside the original source energy range, The Tunguska bolide of 1908 (~10 Mt) is a prime example of a previously observed body of great interest. Almost regardless of how we analyze the recent data, the conclusion is that bolides with Tunguska type energy levels should reoccur on the average every 120±10 years.

1. INTRODUCTION AND OVERVIEW:

Reliable influx rate estimates come from a large variety of sensors including the Lunar cratering record, Spacewatch telescope and other ground-based CCD systems, ground-based photographic meteor-fireball Networks (USA, Canada, Czech Republic, etc.), infrasonic pressure sensor arrays, US DoD Satellites (optical and infrared sensors) and other space platforms, radar systems, etc. Previous estimates have varied widely (by factors > 100 times), due largely to the uncertainties in properly calibrating various sensors.

In the last 20 years it has become possible to more reliably estimate the infrasonically measured contribution to the total NEO global influx using a better estimates of source energy as a function of readily observable parameters, estimates of percent coverage of the Earth as a function of source energy and season, a wide distribution of large arrays on global scales with the proper sensor response

2. APPROACH

Given the inputs of the bolide source energy (from the AFTAC empirical relationship, etc.), the percent coverage of the Earth as a function of source energy and season, i.e., the relative detection probability of each bolide event and the total time of operation of the infrasonic network, we can make cumulative energy influx predictions for large bolides.

Let:

$\sum N$ = Cumulative (integral) number of bolides at any source energy, E_S

A_E = Surface area of the Earth

Percent coverage = $f(E_S, \text{season})\bullet A_E$, where the function, f, is known (AFTAC network).

Δt_O = Time of operation of the infrasonic network

E_S = Bolide source energy

$$N(E_S) = \sum N\bullet\{1/[f(E_S, \text{season})\bullet A_E]\}\bullet\{1/\Delta t_O\}$$

where

$N(E_S)$ = cumulative number of bolides/(over the Earth per unit time) as a function of the deduced source energy

We have been provided with raw data that have been developed into least-squares curve-fits: (Olmstead and Leies, personal communication, 1978) of the USAF AFTAC empirical estimates for global infrasound array detection probabilities. These empirical results were obtained for a quasi-global network operation that demanded three-station detection and an additional technique for verification of the detection. The original source energy range was from $0.20 \le E_S \le 100$ kt.

i) Winter:

$$P_D(\%) = 11.74\cdot\{E_s/2.0\}^{0.375};\ r^2 = 0.9928$$

ii) Summer:

$$P_D(\%) = 12.5\cdot\{E_s/2.0\}^{0.416};\ r^2 = 0.8816$$
$$P_D(\%) = 11.35 + 15.19\cdot\ln\{E_s/2.0\};\ r^2 = 0.9870$$

The much higher correlation curve-fit for summer systematically produces negative, i.e., unphysical P_D values at small source energies (< 1 kt) that are consistently positive for the same source energies in winter. To avoid this problem, the lower correlation, curve-fit relation was used instead throughout the summer period.

2.1 Available source energy prediction methods

Among the many methods available to predict source energy, we can appeal to the following:

i) AFTAC semi-empirical, wave period at maximum amplitude approach: Olmstead and Leies (1979)-for the Stratospheric acoustic return (phase)
ii) Los Alamos wind-corrected amplitude approach: Mutschlecner and Whitaker (1988): For point source-near surface explosions
iii) Acoustic efficiency approach: Cox (1958): For point source-near surface explosions
iv) Cylindrical line source amplitude and wave period approach: ReVelle (1976); Source altitude effects included; Also, a separate wave period approach for line sources
v) Lamb wave mode approach: Pierce-Posey (1971): For point source-near surface explosions-Generally, Lamb waves are only important for very large sources. Previously, ReVelle and Delinger (1981) used this approach to analyze the Lamb waves from bolides compared to the original formulation of Pierce and Posey (1971).
vi) Combined Lamb/wind-corrected amplitude approach: ReVelle and Whitaker (1996): For point source-near surface explosions
vii) Point source, multi-modal wave synthesis: Pierce et. al. (1976)- Source altitude explicitly included
viii) Line source, acoustic-gravity wave results: Golitsyn et al. (1977)

We have decided in our analysis to use the semi-empirical yield-period relation discussed along with our reasoning directly below.

2.2 Semi-empirical yield-period relationship: Olmstead and Leies (1978)

This approach was derived from a “quasi-global” network of widely spaced arrays, with a minimum of 3 arrays being required for the detection of infrasonic waves at large ranges. These signals all had propagation in the stratospheric sound channel from large near-surface nuclear explosions (below ~15,000 feet). The nuclear explosion yield, Y was assumed to be equal to one-half of the source energy, E_S, where the factor of two accounts in an approximate way for the large amount of electromagnetic energy radiated during the detonation of a nuclear "fireball". The empirical relation developed by the US Air Force can be written as (1 kt = $4.185\cdot10^{12}$ J):

$$E_S = 2\cdot\{\tau/5.92\}^{3.34},\ E_S/2 < 100\text{ kt}$$

$$\log(E_S/2) = 3.34\cdot\log(\tau)-2.58;\ E_S/2 < 100\text{ kt}$$

where

τ = Observed infrasonic wave period at the maximum signal amplitude (only for wave frequencies >> acoustic-cut-off frequency)

Since previous influx estimates have been made using this formula or a variant of it, we decided to continue to use it for the analysis of the new data. In ReVelle and Whitaker (1999), the equations for line source blast waves were used to analyze the bolide event on 11/17/1999. Very good agreement was obtained between infrasonic source estimates and the other techniques. Since all the new events other than this one were at much greater range we decided to use an energy relation that was range independent in order to simplify the analysis.

Also, in order to process these data, we could choose to either average the wave periods from all arrays detecting a specific bolide before computing a source energy or alternatively, we could compute and evaluate all of the individual values at each array element for a specific bolide. We decided to average the wave periods and produce a single average energy for each event rather than having as many energy estimates as there were array elements detecting a specific bolide. This choice of the data analysis does have a small effect on the results quoted later below.

The source heights were assumed to be relatively low and certainly below the Stratopause (about 50 km). Thus, most of the recorded objects are likely to be deeply penetrating and of "relatively strong" composition, i.e. of bolide group I. or possibly group II.

2.3 Line source and modified line source : Observed characteristics

Previously bolide observations have been made over ranges from about 100 to ~14,000 km with the following properties:

3 Wave periods: 0.5 s to > 5 min.
4 Amplitude: 0.2 to 160 μbars: 0.02-16 Pa
5 Source energies : ~10^{-6} kt to > ~10 MT

The observed signal characteristics are similar to other explosive manmade and natural impulsive type sources: The signals generally exhibit Lamb waves (for the larger sources), multi-path (multi-phase) arrivals, with geometric and material signal dispersion effects, etc.

Similarly, most seismic signals from bolides have been observed as "forced" air-coupled Rayleigh waves or as "free" direct Earth impact waves (P and S types) and as seismo-acoustic coupled signals.

3. GLOBAL INFRASONIC INFLUX ESTIMATES

3.1 Previous infrasonic results (cumulative number of bolides per year over the earth)

These analyses were first carried out by Shoemaker and Lowery (1968). It was later discovered that the US Army Signal Corps yield-period relation was not properly calibrated (E.M. Shoemaker, personal communication, 1972). For 9 bolides, including Tunguska, they found the result:

$$\mathbf{N(E \geq E_s) = 2 \cdot 10^2 / E_s}$$

Next, Wetherill and ReVelle (1978) and later ReVelle (1980) used a proper source energy-wave period calibration provided by the USAF (AFTAC) and adjusted for the end height effects and initial kinetic energy, rather than simply the kinetic energy at the terminal release height.

For 10 bolides, not including Tunguska:

$$\mathbf{N(E \geq E_s) = 10.4 \cdot E_s^{-0.87}}$$

ReVelle (1997) additionally used 4 new bolides that were observed at Los Alamos and elsewhere since the time of the original AFTAC data. For 14 bolides, not including Tunguska, he found that:

$$\mathbf{N(E \geq E_s) = 7.17 \cdot E_s^{-0.731}}$$

3.2 Recent bolide infrasonic data: 1994-2001

We have again revised our cumulative influx rate estimates, uncertainties and implications using 9 additional bolides (5 new bolides since 1997). We have not included several bolides that were either detected by only one array or which were not enough far away to use the AFTAC energy relation in a reliable manner, etc. The bolides that were specifically omitted included the Kincardine bolide (9/16/66), the Wyoming skip-fireball (8/10/72), the Marshall Islands bolide (2/01/94), the Borneo bolide (2/18/00), the Tagish Lake meteorite fall (1/18/00) and the Moravka meteorite fall (5/06/00). Thus, the inferred influx rate is an absolute minimum.

We tried to analyze the data that are now available in several different ways, only three of which we will report on here. These included using the AFTAC empirical relation for the source energy, E_S, but only using the newest infrasound data from 1995- 2001. For an observing time of 5.41 years, we determined that:

$$\mathbf{N(E \geq E_s) = 9.53 \cdot E_s^{-0.736},\ r^2 = 0.997}$$

using the Baja, CA, 4/23/01 bolide = 0.81 k (see below).

Next we combined the AFTAC data and the new infrasound data into a single data set for a total observing time of 19.084 years and we found that:

$N(E \geq E_s) = 5.84 \cdot E_s^{-0.716}$, $r^2 = 0.9464$

using the Baja, CA, 4/23/01 bolide = 11 kt.

For this situation, the total energy flux = 219.07 kt/year on the Earth (for $0.053 \leq E_S \leq 1000$ kt), with a corresponding total mass flux = $5.66 \cdot 10^6$ kg/year on the Earth (assuming V= 18 km/s for the initial mass range from $1369 \leq m_\infty \leq 2.84 \cdot 10^7$ kg).

Finally, we repeated the above procedure for all of the available data assuming the Baja, CA bolide of 4/23/01 assuming it to be = 0.81 kt) and determined the result:

$N(E \geq E_s) = 5.66 \cdot E_s^{-0.724}$, $r^2 = 0.954$

3.3 Comparisons against previous influx estimates (ReVelle, 1997- AFTAC data):

ReVelle (1997) determined that at a source energy of 0.10 kt (1 kt), 38. 59 (7.17) bolides per year would occur (on the average over earth). Also, at a source energy of 15 kt, there were ~0.99 bolides per year over earth predicted. Events with a source energy of 10 Mt (similar to that of Tunguska) are predicted to occur once every 117.1 year, but this is clearly an extrapolated value outside the original energy range of the observations. Using the newest infrasound data (observing time = 5.41 years) and using E_S = 0.81 kt, for the 4/23/01 Baja, CA bolide, we found that at 1 kt, 9.52 bolides were predicted per year over the Earth, at 15 kt, we found 1.30 per year, while for Tunguska (~10 Mt), we found a reoccurrence every 92.6 years. Using E_S = 11 kt for the 4/23/01 Baja, CA: bolide, we found 10.98 bolides/year over the Earth and at 15 kt, we found 1.80 /year, while for Tunguska we found a rate of reoccurrence of 42.6 years. When we combined the original AFTAC data with the new data for all bolides whose source energies exceeded 0.053 kt (using E_S = 11 kt for the 4/23/01, Baja, CA bolide), we found that at a source energy of 0.10 kt and 1 kt, there were 30.34 and 5.84 bolides per year predicted over the earth. At a source energy of 15 kt, there were 0.84 bolides per year predicted over the earth and finally at a source energy of 10 Mt (Tunguska) a rate of reoccurrence of every 124.7 year was predicted.

3.4 Further comments:

As shown in Ceplecha (1997), there are probably selection effects that are affecting our results since cometary type bolides generally do not penetrate deeply enough to generate a blast wave source. Also, there is a small energy limit of ground-based detection even for chondrites. ReVelle (1976) has shown that there is a minimum blast radius (Ro > ~10 m) for bolides, below which we do not expect signals to reach ground level. This is due to very heavy wave absorption effects above 70 km for small energy sources.

In addition, extended line source effects generally produce ray paths that suffer a smaller amount of refraction and can more easily be detected at ground level. The original AFTAC source energy estimates were expected to be accurate only for the range from $0.5 \bullet E_S \leq E_S^* \leq 2.0 \cdot E_S$ which was originally derived for low altitude nuclear explosions observed at very great horizontal ranges form the explosion at altitudes below ~4.74 km or~0.70 pressure scale heights. The combination of possible source altitude effects on the wave period, combined with the fact that the kinetic energy of the bolide at the terminal point is often significantly below that at the top of the atmosphere was previously shown by ReVelle (1980) to be nearly a compensating effect.

We have also estimated statistical counting errors for our results. We have used the following definitions:

Let:
N = number of bolides/year predicted at source energy, E_S.
N' = number of bolides with source energy $\geq E_S$.

The statistical counting error is given by the standard relationship $\pm N/\{N'\}^{0.50}$. The values of these parameters for the final influx result is given in Table 2. below.

4. MINIMUM BOLIDE ENERGY FOR GROUND-BASED INFRASONIC DETECTION

There is a minimum kinetic energy, KE_{min} at which bolide infrasound can be detected at the ground, i.e., $\sim 1.55 \cdot 10^{-5}$ kt. This is the energy of the bolide that Kraemer and Bartman (1981) detected (US PN42556) at 130 km in range, which had the following entry and recorded infrasonic properties:

i) V= 16.5 km/s for ~ 320 g bolide (Maximum stellar magnitude brightness, -5.1)
ii) 0.21 seconds period at 2.3 microbars amplitude, ~ 5 s signal duration

Subsequent reverse ray tracing missed the photographed (two camera station) trajectory by < 410 m.

As noted earlier, ReVelle (1976) found the minimum ground, detectable blast radius, Ro ($\cong$ Ma·d) $\cong$ 10 m due to atmospheric absorption losses at higher frequency (for bolide sources with smaller R_o). Direct manipulation of the expression for the bolide KE can be shown to be proportional to R_o^3 and to V^{-1}. For a spherical Group IIIA. bolide with V= 30 km/s, R_o = 10 m and a bulk density = 1000 kg/m^3, a minimum detectable kinetic energy = $6.2 \cdot 10^{-5}$ kt is predicted. This value is in quite good agreement with the very small meteor that was detected by Kramer and Bartman and quoted above. Also, bolide sources < ~10^{-5} kt cannot penetrate the atmosphere deeply enough to produce a line source blast wave or even if they could the heavy absorption of the signal would not allow detection at ground level. Since typical shower meteors have kinetic energies > ~10^8 times smaller than the minimum source energies quoted above, we certainly do not expect infrasound from typical shower meteors to be detected infrasonically. This was also noted earlier in Opik (1958), i.e., sound waves at these corresponding high frequencies that are launched downward toward the ground from altitudes above ~80 km will suffer very large absorption by viscous and heat conduction effects. (For R_o $\leq$ 10 m, the initial bolide associated wave frequencies are typically $\geq$ 10 Hz at a representative sound speed for this region of the atmosphere of 270 m/s).

5. SUMMARY AND CONCLUSIONS

5.1 <u>Bolide detection using infrasonic techniques and their interpretations:</u>

We have an independently calibrated, empirical source energy relationship for line and modified line sources (including fragmentation effects), etc. The origin of the waves from such an object can be used to readily locate its position. We can readily derive both the azimuth/elevation angles of the arrival and also the three-dimensional intersecting bearings from multiple detecting arrays. There has now been detection of at least 25-30 bolides over the energy range from 0.05 kt to 10 Mt, with the minimum bolide energy detection level of ~$8.0 \cdot 10^{-6}$ kt (ReVelle, 1997). The data can be regarded historically into a period from 1960-1974 with the Tunguska detection of 1908 falling into a separate category for detection of the full range of periods in the acoustic-gravity wave realm. The second period was from about 1991 until the present with > 10 bolides detected at Los Alamos of source energy> 0.053 kt and detection's at IRF in Sweden (Greenland bolide of 12/9/1999), one in Russia detected by the Obukhov Institute of Atmospheric Physics, one at the Australian National University (August 18, 2000) and also one at NOAA in Boulder and an additional recent recording of a very large bolide at an array along the East coast (7/23/2001). In addition there have been acoustic recordings on conventional surveillance camera equipment in Spain (2 detection's) and in Colorado (2 detection's), with the best recording still that of the Boveedy-Sprucefield meteorite fall in 1969.

As a result of our work, there is a minimum expectation of ~30 bolides/year at 0.1 kt and ~1 bolides/year at 15 kt. The latter value is in very good agreement with the results of satellite systems operating in the optical and in the infrared part of the electromagnetic spectrum (Tagliaferri et. al., 1994).

Data from the future IMS infrasound system (60 arrays with uniform global coverage) will certainly improve upon our bolide influx estimates for energies < 1 kt. Also, synergy is clearly possible with other methods such as satellite systems, seismic, hydroacoustic techniques, etc. The influx we have currently estimated only represents the flux of the most deeply penetrating and "strong" objects.

Recently, we have found order of magnitude discrepancies between the two types of source energy estimates, with the satellite energy > 10X the infrasonic inferred energy (4/23/2001, Baja, CA and 7/23/2001, Lancaster, PA bolide):
The satellite data has been analyzed by assuming the bolide blast wave radiative source, black body temperature (6000 K) and a 10 % luminous efficiency factor over the wavelength interval of the sensor to derive the integrated source energy over the trail. The luminous efficiency should be highly variable, however and is now being studied intensively by our group at Los Alamos.

Recent and older volume porosity modeling efforts (ReVelle, 1983 and 2001a-this conference) have shown that significant bolide porosity produces much brighter bolides at the same mass and velocity while using the same luminous efficiency. This may be one way of trying to resolve these recent source energy discrepancies.

5.2 Acoustic(Audible) Bolide Recordings

Finally, we would like to summarize the relatively recent high frequency audible (acoustic) detections of bolides made in recent years. With the growing number of security cameras and associated microphone capabilities, the potential now exists for routine monitoring of such high frequency acoustic effect from bolides almost routinely and at very .low cost. Listed below are acoustic recordings from bolides that are presently known to the author:

i) 4/25/1969, Northern Ireland- Boveedy-Sprucefield meteorite (or the Belfast bolide). Audio recorded by Miss Eileen Brown and taken to Dr. Ernst Opik at Armagh Observatory for validation.

ii) 11/21/1995, Colorado Springs bolide: Video/audio security camera; Also, infrasonic detection at Los Alamos.

iii) 11/17/1995, 23.59.33 UTC, Spain- H. Betlem (Dutch meteor society): Recorded by video camcorders with microphones and image intensifiers at 2 temporary stations (Zafarraya and Almedinilla)-. There are also data available from 3 cameras of the European fireball network: Stellar magnitude = -15, initial speed = 32.9 km/s, end height = 29.46 km, orbital data, etc.)- Data from P. Spurny, Ondrejov Observatory, The Czech Republic.

iv) 1/11/1998, Colorado Springs: ~0709 UTC, Video/audio security camera. Also, infrasonic detection (Bedard, NOAA, Boulder, CO).

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Table 1. Recent infrasonic detections of bolides (1994-2001)

Date	Time-UTC	Lat. (deg)	Long. (deg)	Period (sec)	Energy (kt)
020194	22.38	2.6 N	164 E	--------	50-200
112195	09:18	39 N	105 W	2.0	0.053
100496	03:44	36 N	118 W	4.0-5.0	0.5-1.1
100997	18:47	32 N	106 W	3.33	0.29
120997	08:12	63 N	51 W	2.5	0.11
061398	14:06	34 N	103 W	3.0	0.21
081198	10:18	20 S	134 E	9.4	9.38
111798 (*)	10:05	36 N	106 W	1.4	0.3-1 t
081699	05:18	35 N	107 W	2.5	0.11
082500	01:12	15 N	106 W	4.6-7.2	2.5
042301	06:13	30 N	134 W	3.1-5.1	~1.0
072301	22:19	42 N	76 W	3-3.33	0.29

(*) Not used in the influx calculations- This is a large and very bright Leonid bolide detected infrasonically at Los Alamos during the night of the Leonid meteor shower and associated storm of 1998.

Table 2. Bolide Infrasound Data and the Predicted Global Influx Rate (Cumulative number of bolides per year at the Earth whose source energy exceeds E_s) as well as standard, statistical counting errors, i.e., $\pm N/\{N'\}^{1/2}$

Source Energy, E_s : kt	Number, N, per yearat the Earth	Cumulative Number, $N' \geq E_s$	Standard statistical counting errors
1100	0.05	1	± 0.05
30	0.18	2	± 0.13
26	0.30	3	± 0.17
20	0.434	4	± 0.22
14	0.63	5	± 0.28
11	1.24	6	± 0.51
10	1.55	8	± 0.55
9.86	2.21	9	± 0.74
8	1.26	10	± 0.40
6	2.51	11	± 0.76
2.5	4.58	12	± 1.32
0.84	8.04	13	± 2.23
0.29	12.8	14	± 3.43
0.21	16.2	15	± 4.18
0.20	32.3	16	± 8.06
0.112	23.6	17	± 5.74
0.11	23.7	18	± 5.58
0.053	33.1	19	± 7.59