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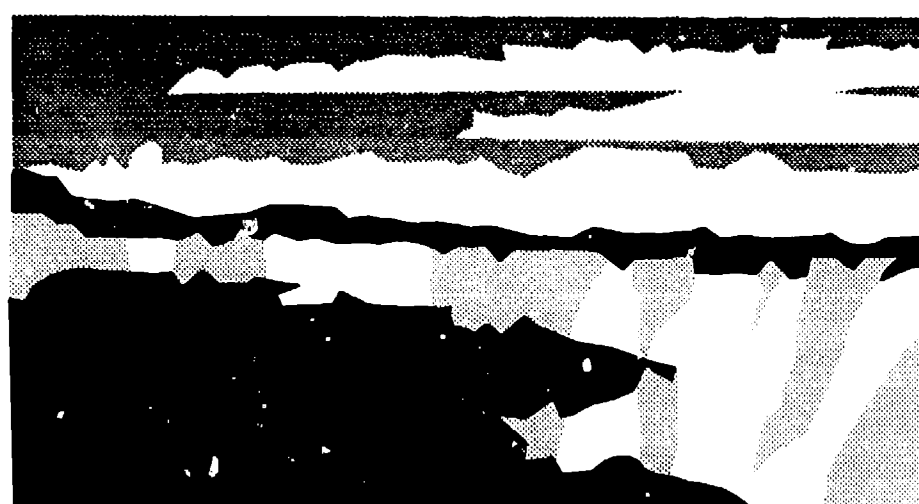

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Historical Detection of Atmospheric Impacts by Large Bolides Using Acoustic-Gravity Waves

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Abstract:

During the period from about 1960 to the early 1980's a number of large bolides (meteor-fireballs) entered the atmosphere which were sufficiently large to generate blast waves during their drag interaction with the air. For example, the remnant of the blast wave from a single kiloton class event was subsequently detected by up to six ground arrays of microbarographs which were operated by the U.S. Air Force during this pre-satellite period. Data have also been obtained from other sources during this period as well and are also discussed in this summary of the historical data. The Air Force data have been analyzed in terms of their observable properties in order to infer the influx rate of NEO's (near-Earth objects) in the energy range from 0.2 to 1100 kt. The determined influx is in reasonable agreement with that determined by other methods currently available such as Rabinowitz (1992), Ceplecha, (1992; 1994b) and by Chapman and Morrison (1994) despite the fact that due to sampling deficiencies only a portion of the "true" flux of large bodies has been obtained by this method, i.e., only sources at relatively low elevations have been detected. Thus the weak, fragile cometary bodies which do not penetrate the atmosphere as deeply are less likely to have been sampled by this type of detection system. Future work using the proposed C.T.B.T. (Comprehensive Test Ban Treaty) global scale infrasonic network will be likely to improve upon this early estimate of the global influx of NEO's considerably.

I. Introduction

A. The Bolide-Atmosphere Interaction Spectrum

We now know that in the size range of interest of the NEO (near-Earth object) population, i.e., from about 1 m to several km across, the bolide population is comprised of at least ordinary Chondritic materials, Carbonaceous Chondrites, regular Cometary materials, "Soft" Cometary materials and finally Nickel-Iron materials (Ceplecha, 1992; ReVelle and Ceplecha, 1994). ReVelle (1993) has recently analyzed the entire spectrum from small to large bodies using a unified energetics approach that can be used to infer the observed behavior of entering bodies in a self consistent way. The observed bolide phenomena fit within this framework in such a way that if only four independent parameters are specified the consequences of the drag interaction with the atmosphere can be immediately anticipated. From this energetics viewpoint only six discrete interaction regimes are predicted to occur. This unified pattern of the meteoroid-atmosphere interaction spectrum, along with its predictors are given in Table I..

Only regimes iv). through vi). are of direct interest to the NEO population under consideration with regard to blast wave generation and its subsequent decay to acoustic-gravity waves that can be detected by ground based sensors. The specific body size that corresponds with regimes iv). through vi. depends on the meteoroid group properties themselves (bulk density, ablation coefficient, material strength, etc.) as well as on entry parameters directly, i.e., initial velocity, entry angle, atmospheric scale height, surface pressure, etc..

B. The Blast Wave Interaction Remnants at Great Ranges

During the continuum flow interaction and the impact and explosion cratering regimes of bolides with the atmosphere, i.e., iv). to vi). above, a line source explosion is generated which subsequently decays first from a strong to a weak shock front and eventually to a nearly linear acoustic-gravity wave. In addition, for some bodies a strong, point source terminal explosive fragmentation event can occur near the end of the visible trajectory as well. Multiple explosions are also possible (for example, Spalding et. al., 1994). The recent impact of Shoemaker-Levy 9 with Jupiter make the need for realistic solutions of the large body impact regime with a planetary atmosphere far more urgent than previously considered (Crawford et. al., 1994).

It has long been known that the fundamental period of observed explosive waveforms (independent of nonlinear propagation effects or of geometric or material dispersion phenomena) is inversely related to the energy deposited into the fluid, i.e., higher fundamental frequencies correspond to smaller energy releases in the atmosphere. Using this consideration and the predictions of spherical and cylindrical blast wave theory, we can anticipate that the signals of interest should range from frequencies of a few Hz down to periods approaching 1 minute or more depending on the magnitude and altitude of the energy release by the entering bolide.

II. Detection of Airwaves from Large Bolides

A. Measurement Systems

Conventional arrays of microbarographs with Daniels-type pipe type noise filters, were operated at numerous stations globally by NOAA, the U.S. Air Force (previously operated by the U.S. Army) with the prescribed system bandpass generally in one of two separate frequency intervals depending on the expected signal amplitudes (or ranges) and associated frequencies of interest.

The basic sensor for all these measurements is a relatively high frequency acoustic capacitance microphone whose low frequency response is adjusted using a large backing volume which is connected through a leak valve to the background air pressure. Operating below the normal auditory hearing limits of humans, these microbarographs responded to the so-called atmospheric wave "zoo", i.e., a very large number of natural and man-made events such as aurora (including auroral electrojet surges), volcanic eruptions, meteor-fireballs (bolides), earthquakes, mountain associated waves, severe weather (tornadoes, hurricanes, thunderstorm convective processes, etc.), atmospheric boundary layer processes such as nocturnal low-level jets and wind shear events like gust fronts, etc., Microbaroms (with the same source as Microseisms in the Earth) the Polar Troposheric jet stream, sub- and supersonic aircraft, commercial mining and other man-made chemical and nuclear explosions, etc. (Georges and Young, 1972).

The M4 Signal Monitor operated by the U.S. Air Force had the following frequency bandpass characteristics (Personal Communication with MSgt Harold M. Baker Jr., 1979):

i) High Frequency Filter N10: 3 db down at 8.2 Hz and 25 seconds, respectively.

ii) Low Frequency Filter N9: 3 db down at 44 and 440 seconds, respectively, but a significant frequency response extended as low as 15 minutes in period.

In addition, there was also a separate very high frequency and close range sensor incorporated into the overall M4 system as well, the Millibarograph N2 system which operated within nearly a constant gain (+\- 1 db) over the range from 0.0001 to 0.1 Hz and could detect pressures as great as 10 mb (M4 Signal Monitor Technical Manual, March

7, 1972: TI 141-1MA-1). The CORAL N4 system (Correlator-Analyzer) provided continuous cross-correlation of all the relevant signals of interest. The entire system was routinely calibrated in both frequency and amplitude to ensure reliable operation in both detection and location capability in as near to continuous operation as possible.

Such infrasound stations are still in operation today at only a few stations such as Los Alamos National Laboratory (Mutschlecner and Whitaker, 1988; Whitaker et. al., 1990; Whitaker et. al., 1994), at Uppsala, Sweden, (Liska, 1980), in Japan, in the Netherlands, etc., but the probability is quite good that within 5 year's time from 60 to 75 stations will be operating worldwide as one integral part of the four proposed technologies of the C.T.B.T. (Comprehensive Test Ban Treaty) monitoring program. These four element arrays are currently proposed to have wide passband operation with a nominal response from 50 seconds period to about 10 Hz.

Using beamforming and cross-correlation techniques, the following parameters are continuously available for signals with sufficiently large signal to noise ratios at each element of the microbarograph array (usually conditions of low wind noise):

a) Amplitude: Signal to noise ratio
b) Period: For Lamb, compressional and gravity waves
c) Signal Duration
d) Elevation Arrival Angle: Through the characteristic velocity (horizontal trace velocity)
e) Azimuth Arrival Angle: At maximum cross-correlation
f) Power Spectral Density

Signals consist of generally lower frequency Lamb waves traveling at signal velocities (travel distance/travel time) that average about 0.34 km/sec (Posey and Pierce, 1971; Pierce and Kinney, 1976) followed by acoustic arrivals at average signal speeds from 0.29 km/sec for refractive returns from the ozonosphere (about 50 km aloft) to about 0.24 km/sec for refractive returns from the lower ionosphere (about 100 km aloft). These waves are indicative of a very large part of the acoustic-gravity wave spectrum, which can also be subdivided at angular frequencies much larger than the Brunt-Vaisala (buoyancy frequency) as a class of waves known as infrasound (Georges and Young, 1972). For such waves the restoring force to the wave motion is not buoyancy as it is at low frequencies large compared to the inertial frequency, but instead is dominated by the elasticity of the medium and modified by stratification effects as compared to simple, high frequency, longitudinal and irrotational, linear acoustic waves.

These signal velocity values are indicative of data taken at Los Alamos, but are generally confirmed by the U.S. Air Force results provided in Table II..

Specific techniques have been developed to facilitate analysis of both the Lamb wave and of the separate acoustic arrivals as will be discussed below.

B. Historical Database

In Table III. to VII., the historic database of signals detected by such global scale microbarographs has been summarized. In Table III., some of the event energies have also been confirmed by other techniques as well (for example by seismic detection by Earth impact and for air-coupled Rayleigh waves, etc.). Unfortunately only the U.S. Air Force data have a truly global sampling efficiency as will be seen in Table VIII. below, so that the other detections can not readily be used in estimating the global influx of NEO's. Previously these events were tabulated and interpreted in ReVelle and Wetherill (1978a, 1978b).

The classic event that basically started researchers working on this class of problems was the unique event of June 1908 in the Tunguska region of Siberia in the former U.S.S.R. and reported by F.J.W. Whipple and by numerous other later authors.

Other groups have also detected meteor-fireballs on occasion by either the recognition of its large amplitude, low frequency signature or by noting an exceptionally large characteristic velocity (horizontal trace velocity across the array) or by aircraft reports or other visual confirmation of exceptionally bright, fast objects in the night sky. On occasion an exceptionally bright bolide also occurs during daytime, such as the famous August 10, 1972 skip fireball that was witnessed by Jacchia and whose orbital change was calculated initially by Ceplecha and later refined based on refined mass estimates (Ceplecha, 1994a). This event was also recorded on two U.S. infrared satellite systems (Rawcliffe et. al., 1974). Infrasonic signals were also recorded from this object which was estimated to be about 5 meters across, but to date no infrasonic data have been available from the U.S. Air Force on this unique event, even though the author was informed that acoustic signals from this event were detected (Personal communication with F. L. Whipple, 1975). A similar, but much larger bolide and higher velocity was also observed by both visible and infrared military satellite sensors on February 1, 1994 (Spalding et. al., 1994), but only a marginal detection directly confirming its associated infrasonic signals have been reported (personal communication with R. Whitaker, 1994), probably due to a lack of such sensors operating currently and to the relatively high frequency passband of most currently operational systems (> about 0.1 Hz). A very definite detection of either the impact of part of the original body or of the blast wave itself was made by hydroacoustic sensors in the Pacific however (R. Spalding, Personal Communication, 1995).

Other data recorded by N.O.A.A. (National Oceanographic and Atmospheric Administration) at the Wave Propagation Laboratory by A. Bedard, V. Goerke, G. Greene, J. Young and others as well as signals detected by U.S.G.S. (U.S. Geologic Survey) by Shoemaker and by researchers at the University of Alaska (C. Wilson) are given in Table V..

Analyses of these events as summarized by ReVelle (1975; 1976) and interpreted for line source explosion geometry are given in Table VIA..

We can also compare these estimates by ReVelle (1976) with those deduced using the semi-empirical period at maximum amplitude relations given below in III. C. (equation (3). From this relation which has been extensively tested and confirmed by alternative detection methods, the doubled source energy for each of these events is given in Table VIB..

It would be very beneficial to further evaluate and refine these data by using both realistic multi-modal analyses (Pierce and Kinney, 1976), i.e including zonal and meridional steady state winds and by using the pressure amplitude wind normalization factor developed by Mutschlecner and Whitaker (1988). This refinement of the above source energy estimates could impact upon the NEO flux estimate and associated error limits discussed in III.E..

Still other data have been recorded using relatively high frequency sensors similar to those in use today at Los Alamos (Globe Universal Sciences Model 100 C.). For these sensors the -3 db bandpass is from about 10 Hz to 0.1. These data were recorded again at Boulder by N.O.A.A. researchers, by the University of Michigan in Sioux Falls, S. Dakota and at the National Research Council Canada at the now defunct Springhill Meteor Observatory. The first event was confirmed by visual and by aircraft reports on the night in question, the second was confirmed by association with the photographed event, PN42556 of the Smithsonian's U.S. Prairie Network and the latter event was detected in association with a meteor patrol radar during the Geminid meteor shower in 1975. These events and their analyzed properties are detailed in Table VII.

III. Analysis of Airwave Data from Large Bolides

A. Ray Theory Approaches

This approach allows the altitude of the source and the azimuth arrival angle to deduced. As noted earlier depending on the altitude of the ducted refractive return, differing signal velocities are expected on the basis of previous U.S. Air Force and Los Alamos experiences, etc.. Also in the case of PN42556 (U.S. Prairie Network Fireball Number), Kraemer and Bartman (1981) were able to ray trace form the ground array back to the source with very great precision. After a travel of some 250 km, the back ray tracing missed the known three-dimensional trajectory by only 10 meters.

For truly line source signatures the entry angle of the entry is very critical, since the steep angled entries which are typical of smaller bodies produce corresponding ray paths which are less likely to reach ground level (ReVelle, 1976). For corresponding shallower entries ray paths are more nearly vertical and consequently are less likely to suffer from significant refraction effects. Such arguments are more useful at close range to the entry which seems most applicable to only one of the ten U.S. Air Force events (0.1 kt event).

Numerous acoustical data were reported from the first meteorite which was photographed and subsequently recovered on the ground, the Pribram meteorite in the Czech Republic (formerly Czechoslovakia) in 1958. These data were catalogued by Ceplecha and illustrated the well known anomalous propagation of sound effects first noted dramatically at Queen Victoria's funeral in Great Britain. In such cases semi-spherical zones of audibility and of silence are found surrounding the acoustical source region. These zones are readily predictable on the basis of ray acoustics if the corresponding atmospheric properties, primarily the temperature and wind structure, are sufficiently well known.

B. Lamb Wave Approach

Pierce and Kinney (1976) and co-workers have developed a prediction of source yield, Y, as a function of the arriving Lamb wave period, T, at corresponding amplitude, Δp, which can be written for distances, r, small compared to the earth's radius in the limiting form:

$$\log(Y) = 1.5*\log(T) - 3.37 + \log(\Delta p) + 0.5*\log(r) \quad (1)$$

with Δp in μbars, T in seconds, r in km and Y in kt TNT.

Lamb (or edge) waves , which are guided acoustic waves at high frequencies and guided gravity waves at low frequencies, take time to develop in association with a given source. These waves are evanescent and are only of significant amplitude near the earth's surface. Thus, for close ranger and progressive higher frequency these waves are less likely to be observable (ReVelle and Delinger, 1981). From the analysis of the meteor data ReVelle and Delinger (1981) were able to deduce an empirical fit to the arriving Lamb waves in the form:

$$\mathrm{Log}(Y) = 2.0*\log(T) - 3.18 \log(\Delta p) + 0.5*\log(r); \; r^2 = 0.58 \quad (2)$$

C. Period at Maximum Amplitude Approach

This approach is semi-empirical and relates the period at maximum amplitude to the source energy at sufficiently large range from the source. In a private communication between the author and Dr. G. Leies (1978) the following relations were disclosed (deduced from the data from low altitude nuclear explosions listed in S. Glasstone, Effects of Nuclear Weapons, 1968), connecting the yield, Y, in kt for each explosion and the observed period, P, at the observed maximum amplitude of the arriving acoustic signal:

$$\log(Y) = 3.34*\log(P) - 2.58 \quad : Y <= 100 \text{ kt} \quad (3)$$

$$\log(Y) = 4.14*\log(P) - 3.61 \quad : Y > 40 \text{ kt} \quad (4)$$

In the Air Force analysis of the meteor-fireball data, an equation similar to (3). was used for the analysis for events < 40 kt and (4) was used for events exceeding 40 kt. The yield is these equations is the source energy release, E_s, divided by 2, corresponding to the large fraction of radiation emitted during a low altitude nuclear explosion event. This is justified since the original microbarograph data recordings used in the empirical least squares curve fit all originated from low altitude nuclear explosion events.

Motivated by the Air Force meteoroid airwave data, ReVelle and Delinger (1981) have also interconnected the Lamb wave approach and the period at maximum amplitude approach and derived an expression for the Lamb wave period as a function of the period at maximum amplitude of the arriving explosive source waveform.

D. Waveguide Normal Mode Analysis

Again, Posey and Pierce (1971) and Pierce and Kinney and (1976) and other earlier co-workers have developed waveguide modal analyses that allow an estimation of the normal modes that are excited by a point source explosion in the atmosphere. Such a scheme was used by Shoemaker (personal communication with the author, 1971) to estimate the energy release of the Revelstoke meteorite (Bayer and Jordan, 1967). Such analyses are typically of greatest utility far from the source region in contrast to the ray approaches which are more applicable at relatively close range. As discussed in ReVelle (1980), Golitsyn and Korobeinikov, Chuskin and Shurshalov have considered the theoretical modeling of bolides from the line source viewpoint and in the latter case with the addition of a terminal point source like explosion at the end of the visible trajectory. In the latter case the emphasis was on the modeling of the Tunguska fireball of 1908.

For completeness sake, we should also note that numerous recordings have also been made of air-coupled Rayleigh waves from large bolides at sufficiently low altitudes (ReVelle, 1980b). Such waves are traveling in the Earth at the speed of sound in air and are readily detected by conventional seismic sensors.

E. NEO Influx Rate Estimation

Using the percentage area coverage of the earth information in Table VIII. and the 10 events listed in Tables III., all provided by the U.S. Air Force, ReVelle (1980) was able to predict the influx rate of NEO's as a function of source energy and the cumulative mass influx per year over the earth, assuming that these signals emanated from low altitude near-point source type explosions

We have recently refined two of the E_s values in Tables III. and IV. and have again determined the influx rate of NEO's in the form (cumulative number of bodies with source energy ≥ E_s per year over the entire earth, with E_s in kt):

$$N(E_s) = 12.3 * E_s^{-1.06} \quad ; \quad r^2 = 0.965 \qquad (5a)$$

or in the cumulative flux form, with E_s in kt:

$$N(E_s) = 7.61 * 10^{-26} * E_s^{-1.06} \ ; \quad \text{Number}/(\text{cm}^2\ \text{sec}) \qquad (5b)$$

This result was obtained by computing the highest correlation, least squares curve-fit of the E_s versus the cumulative number of events per year on earth whose source energies equalled or exceeded each of the individual event source energies. We have excluded the 1100 kt event during the curve fitting process since we found that it allowed a maximized cross-correlation coefficient to be determined for the data being analyzed. The resulting equation was not greatly different from the result determined using all of the 10 events, but the correlation was somewhat higher without including the largest event detected. Clearly a more refined analysis should now be determined using all the possible techniques discussed in this article along with a more refined discussion of possible errors.

Thus, by multiplying the cumulative number of events for each bolide by the inverse probability of detection of each event in the appropriate season from Table VIII. (the corresponding percentage coverage of the earth's surface at the deduced yield or $E_s/2$) and by dividing by the total time that the Air Force global network was in operation, i.e., 13.67 years, we were able to obtain the number of events expected at a specified E_s in kt per year of observing over the entire earth. Also by multiplying each individual yield by these same factors, we were able to determine the total amount of bolide energy released per year over the entire earth to be about 102.9 kt. This can be reduced to a cumulative mass value by assuming a mean entry velocity of about 17 km/sec (for the deeply penetrating part of the NEO's, i.e. the non-cometary part of the flux) to a value of about 3*10(6) kg/year over the mass range from about 10(3) to 10(8) kg. Wetherill and ReVelle (1978a; 1978b) had earlier determined a preliminary value with this same data to be about 10(6) kg/year at V= 20 km/sec. The analysis of these data reveal that we should expect at least one 10 kt, deeply penetrating event to occur every year, on the average, over the entire earth. In addition, using 10 MT as the equivalent energy release of the Tunguska event (1908), we can estimate using (5a) that events of this energy can reoccur once on a timescale of about every 1464 years over the earth.

ReVelle (1980) has studied the possible error limits of the above result using differing source altitudes above the ground and of the yield-source energy relationship and has concluded that equation (5a) is as reliable as can be deduced given the observable data and its associated error bar uncertainties. Allowing for these various uncertainties in analyzing the data we can conclude that the corresponding uncertainty in the mass influx is about a factor of 2 larger or smaller than the value given above over the stated mass range. Another factor not considered previously is that if we include the other infrasonic detections during the period from 1960 to the middle of the 1970's besides just the Air Force data, the influx rate will become even higher (for example, the Kincardine event in 1966 which most likely dropped meteorites into Lake Huron was clearly a very large and significant event during the above time period which wasn't detected by the Air Force by was by NOAA in Boulder).

The associated yield was determined using the semi-empirical method connecting the period at maximum amplitude of the arriving signals given above for each of the ten U.S. Air Force events (a self-consistent global scale data set) and using other independently derived yields. For example, in the case of the Revelstoke Meteorite, both atmospheric and seismic signals were reliably recorded (Bayer and Jordan, 1967) as noted earlier. An equation similar to (5a) was developed earlier by E.M. Shoemaker (personal communication, 1971) using a similar data set, but with a different yield-period scaling law. As a result a great overestimation (by about 10 times) of the NEO influx was predicted by Shoemaker and colleagues in the late 1960's, just prior to the first U.S. manned landing on the Moon (Shoemaker and Lowery, 1967).

These results can be compared with those obtained more recently by Rabinowitz 1991), by Ceplecha (1992; 1994b) and by Chapman and Morrison (1994). Our data are in reasonable agreement with the values deduced by Rabinowitz and co-workers using the Spacewatch Telescope. For example, our least-squares result given in (5a) above, predict that about one 10 kt event will occur over the Earth in a year's time.

This is also in very good agreement with values of the influx determined using the DOD global satellite monitoring system (personal communication with R.E. Spalding, 1995). Ceplecha (1992) has combined several widely differing meteor and fireball detection techniques in order to determine the cumulative influx rate. His cumulative mass/year over the entire earth is about 1.7*10(8) kg (over the entire range from the micrometeoroids to the ten's of meters size range detected by satellite observing systems). This is also in reasonable agreement with our deduced value above (about 56 times higher), if we consider that we have probably not completely sampled all the types of compositional materials arriving as noted earlier and have also only sampled over a subset of the above size range.

Ceplecha (personal communication, 1995) has also recently refined the global mass influx on the basis of a new analysis of the Lost City meteorite (a bronzite chondrite) and its luminous efficiency in the presence of rotation. In the mass range which is relevant to the Air Force infrasound data set, this revision results in a predicted global mass influx which is smaller by about a factor of two compared to the earlier predictions. Also, in Ceplecha (1994), it was confirmed that for bodies larger than about 10 meters across the most probable arriving composition is of the Group IIIA/IIIB type (regular and weak cometary bodies). Such bodies are known in numerous studies not to penetrate the atmosphere very effectively and as such are far less likely to have been detected by the infrasonic global arrays.

Also, Chapman and Morrison (1994) adopted Shoemaker's cumulative flux curve which is based in part on crater counting statistics for the Earth and the moon and in part on the infrasonic data as well. Quite good agreement is found despite the fact that the acoustic-gravity wave estimate is likely to be deficient because of under sampling of the cometary part of the flux whose atmospheric end height typically is much larger than that corresponding to either chondritic materials of reasonable strength or of Nickel-Iron materials (ReVelle, 1979; ReVelle, 1980a; ReVelle, 1980b; ReVelle, 1985; ReVelle, 1993).

IV. Summary and Conclusions

A. Airwaves from Large Bolides

During the period from the early 1960's to the early 1980's a large body of acoustic-gravity wave signatures from large bodies entering through the atmosphere have been obtained by a number of research groups. The largest self-consistent dataset by far was taken by the U.S. Air Force from a global scale network operating for about 14 years. From this data we have been able to deduce the global influx rate of NEO's with the limitation that higher altitude cometary sources have probably not been detected by any of these networks. Despite this limitation, the influx rate determined by this method is in reasonable agreement with results obtained more recently by Rabinowitz (1992), by Ceplecha (1992; 1994b) and by Chapman and Morrison (1994).

B. Future Systems

In the near future the C.T.B.T. global scale effort for monitoring of explosive events will allow a great increase in the number of bolide events that can be observed annually. Since 60 to 75, 4 element arrays of broadband infrasound stations have been proposed as part of the International Monitoring System, the prospect for retrieving a revised estimate for the global influx rate of NEO's, at least of the deep penetrating part of the influx, i.e., chondrites and nickel-iron type materials, could be greatly increased.

V. Acknowledgements

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Table I. The meteoroid-atmosphere interaction spectrum.

Interaction Type	Local Knudsen Number	(*) α	Changes in Dimensionless Ablation Efficiency
i) Thermosphere Micro-meteoroid Regime	>> 1	>> 1	<< 1
ii) Free Molecule Regime	>> 1	>> 1	>> 1
iii) Transition Flow Regime	O(1)	> 1	>> 1
iv) Continuum Flow Regime	<< 1	O(1)	> 1
v) Impact Cratering Regime	<< 1	< 1	O(1)
vi) Explosive Cratering Regime	<< 1	<< 1	<< 1

(*) Surface pressure/modified ballistic entry parameter.

Associated Phenomena for each Regime:

i) Negligible mass loss and light production.
ii) Extensive mass loss and concomitant light production.
iii) Moderate to extensive mass loss; Diffuse shock wave formation and light curve flaring.
iv) Mass loss highly size and velocity dependent; Strong blast wave formation and propagation- hypersonic booms.
v) Low velocity and negligible mass loss with direct earth or oceanic impact. Bolide kinetic energy depletion height intersects the earth's surface. Blast wave interaction with the ocean/land interface; Electrophonic noise through interaction with the geomagnetic field.
vi) Climatic change effects, explosive cratering, tektites. Bolide kinetic energy > Atmospheric potential energy (3.8*10(23) J). Negligible mass loss with large atmospheric changes expected. Blast wave propagation, Surface fires; Tsunamis, Electrophonic noise.

Table II. Summary of Airwave Signal Velocity as a Function of Season, Based on Guiding Ozonospheric Winds from 30-50 km

Season	Date	Propagation Type	Propagation Direction (degrees)	Signal Velocity (m/sec)
Winter	10/16 to 3/14	Upwind	195-345	280
Spring	3/15 to 5/15	Fall/ Spring Type	-	300
Summer	5/16 to 8/14	Crosswind	15-320 and 165-220	306
Fall	8/15 to 10/15	Downwind	40-140	315

Table III. Summary of Basic Meteoroid Airwave Events Taken by the U.S. Air Force During the Period From 1960-1974.

Date	Source Location	Origin Time	Total Range	Source Energy (*)
1: 11/2/60	9N, 43E	0022 GMT	2488 mi.	10 kt
2: 9/26/62	30N, 35E	1545 GMT	688 mi.	20 kt
3: 9/27/62	32N, 60E	1529 GMT	518 mi.	30 kt
4: 8/3/63	51S, 24E	1645 GMT	7038 mi.	1100 kt
			8590 mi.	" "
5: 11/30/64	18N, 123W	0310 GMT	3243 mi.	10 kt
6: 1/3/65	21N, 68E	2151 GMT	2008 mi.	0.2 kt
7: 4/1/65	49N, 117W	0548 GMT	1552 mi.	0.24-2.4 kt (**)
			2173 mi.	" "
8: 6/12/66	51N, 164E	0905 GMT	4150 mi.	8 kt
			2750 mi.	" "
			1800 mi.	" "
			3000 mi.	" "
9: 1/8/71	30N, 40E	1826 GMT	8632 mi.	6 kt
10: 4/14/72	13S, 78E	1613 GMT	2300 mi.	14 kt
			2700 mi.	" "
			3400 mi.	" "
			4850 mi.	" "
			8000 mi.	" "
			8550 mi.	" "

(*) 1 kt TNT = 4.185*10(12) Joules; Assuming E_s = 2*Yield

(**) The average E_s of about 1.3 kt is from E.M. Shoemaker (personal communication, 1972) using a multi-modal analysis from Pfeffer and Zarichny (1963). E_s = 26 kt was used for the NEO influx calculations, but since equation (3) predicted 44.6 kt, our influx is likely to be too low. Also, in Table VIA. the E_s for Revelstoke was about 69 kt. Bayer and Jordan (1967) located the ground impact using infrasonic and seismic waves from multiple stations in the U.S. and Canada. A two gram carbonaceous chondrite was subsequently located in very rough terrain in the Canadian Rocky Mountains.

Table IV. Summary of Detailed Airwave Data Taken by the U.S. Air Force During the Period From 1960-1974 (Maximum values for all elements of all the arrays detecting the events).

Date	Maximum Peak Compress. Amplitude (microbar)	Lamb Period (sec)	Maximum Compression Period (sec)	Total Duration (min)
1: 11/2/60	2.4	ND(*)	11.1	18
2: 9/26/62	0.6	13.9	13.9	10+
3: 9/27/62	4.2	17.1	19.4	14+
4: 8/3/63	1.9	ND(*)	36.0	10+
5: 11/30/64	2.1+	13.3	10.0	6.0
6: 1/3/65	1.1	3.5	3.5	5.0+
7: 4/1/65	11.4	36.0	15.0	26
8: 6/12/66	2.1	15.0	10.0	13
9: 1/8/71	0.6	14.6	10.0	< 25
10: 4/14/72	4.3	34.5	13.5	27

(*) ND denotes no detection of the Lamb wave.

Table V. Summary of Meteoroid Airwave Data Taken by N.O.A.A. Wave Propagation Laboratory (Boulder), by the U.S. Geological Survey (Flagstaff) and by the University of Alaska.

Date	Maximum Amplitude (μbar)	Period at Max. Ampl. (sec)	Total Duration (min)	Total Range (km)
1: 4/01/65	4.0	16.0	20	1550
2a: 12/14/68-Flagstaff	0.25	4.0	12	134
2b: 12/14/68-Boulder	1.1	2.5	10	720
3: 9/17/66	1.25	54	34	2270
4: 12/19/69	2.3	12	> 12	327

(*)

1: Revelstoke Meteorite (Bayer and Jordan, 1967).

2a: Holbrook: Observed from Boulder, Colorado (Goerke, 1972)

2b: Holbrook: Observed from Flagstaff, Arizona (Shoemaker, 1972)

3: Kincardine Fireball/Meteorite (Chamberlin, 1968; Goerke, 1966)

4: College, Alaska Fireball (Johnson and Wilson, 1972)

Table VIA. Analysis of Table V. Meteoroid Airwave Data (from ReVelle, 1976).

Event	R_o (m)	Diameter (m)	Mass (kg)	Kinetic Energy (kt)
1:	518.6	13.7	4*10(6)	69.1
2a: (*)	177.4	5.01	2.0*10(4) to 2.0*10(5)	0.3-3.1
2b: (*)	54.1	1.53	5.6*10(2) to 5.6*10(3)	.01-0.1
3: (*)	1761	49.7	1.9*10(7) to 1.9*10(8)	285.7 to 2857.1
4: (*)	452	12.8	3.3*10(5) to 3.3*10(6)	4.76 to 47.6

(*) For these events the mass, diameter and energy estimates were made using V = 11.2 km/sec. For V= 20 km/sec, the energy estimates would all be lowered by a factor of four.

Table VIB. Comparison of Source Energy Estimates Using the Line-Source approach in ReVelle (1976) with the semi-empirical period and maximum amplitude method in III.C.

1: 55.3 kt -About 20 % < the average value in Table VIA.

2a: 0.54 kt -About 3.15 X < the average value in Table VIA.

2b: 0.11 kt -About 2 X > the average value in Table VIA.

3: 3.22 MT -About 2 X > the average value in Table VIA. (Alternatively using equation (4) this becomes 7.30 MT or 4.65 X > the average value in Table VIA.)

4: 21.2 kt -About 20 % < the average value in Table VIA.

Table VII. Other Higher Frequency Airwave Meteor Data:

Event	Maximum Amplitude (μbar)	Period at Max. Amplitude (sec)	Total Range (km)	Yield(*) (kt)
1:	9	1	250	2.63e-3 1.1e10 J
2:	6.6	0.5-1	240	1.01e-3 4.23e9 J
3:	1.4-2.3	0.21-.22	130	1.55e-5 6.51e7 J

1: Bedard and Greene, 1981. An independent estimate of the source yield was not available, but the event was certainly quite energetic since visual magnitudes from -5 to brighter than the full moon were estimated by ground and airplane observers on April 22, 1975. This event was detected by two arrays, 40 km apart (at Boulder and Fraser, Colorado). One array received signals from both the ozonospheric and the lower ionospheric sound channels while the other array only detected the ozonospheric return.

2: McIntosh, Watson and ReVelle, 1976. On December 14, 1974 the same Geminid meteor was also detected by a patrol radar at the Springhill Meteor Observatory with V_{inf}= 35 km/sec. The above infrasonic source energy (using equation (3) with E_s= 2*Yield) is 3.56 times greater at a period of 0.5 Hz than that computed by McIntosh et. al. for this event.

3: Kraemer and Bartman, 1981. In this case the infrasonic estimate of the doubled source yield is about 3.0 times greater than that deduced for the 320 gram (photometric mass) carbonaceous chondrite (Ceplecha and McCrosky fireball Group II.) traveling at a measured initial velocity of 16.5 km/sec. Due to the unusual geometry of this event relative to the ground, the initial signals recorded on May 24, 1975 were from the upper part of the meteor trail.

(*) Based on the period at maximum amplitude relation given in III. C. in equation (3).

Table VIII. Summary of U.S. Air Force, Global Microbarograph System of Airwave Detection Probability versus Yield and Season.

Season	Source Energy	Earth Coverage (%)
Winter	1 kt	11
(10/16-3/14)	3 kt	18
	10 kt	27
	30 kt	48
	100 kt	71
	300 kt	87
Summer	1 kt	6
(5/16-8/14)	3 kt	36
	10 kt	43
	30 kt	63
	100 kt	86
	300 kt	94