GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 2, PAGES 191-194, JANUARY 15, 1998

Monitoring the Comprehensive Test Ban Treaty: Possible ambiguities due to meteorite impacts

Christopher F. Chyba
Lunar and Planetary Laboratory, University of Arizona, Tucson

Gregory E. van der Vink, and Christel B. Hennet
IRIS Consortium, Washington DC

Abstract. For seismic magnitudes in the range of monitoring interest for the Comprehensive Test Ban Treaty, hypervelocity meteorite impacts will be detected about once every decade. Such detections could cause concern if they were difficult to distinguish from explosions and were associated with potential terrorist activity or treaty violations.

Introduction

The Comprehensive Test Ban Treaty (CTBT) calls for a global network of seismic monitoring stations intended to detect, locate, and characterize seismic events suggestive of nuclear testing. According to the Director of the U.S. Arms Control and Disarmament Agency [*Holum*, 1996], the network's detection capability "will be significantly below a seismic magnitude of four, or roughly one kiloton fully-coupled in hard rock. For many places on the globe, the event detection threshold for the prototype system is routinely about seismic magnitude three . . . ." For the range of magnitudes that could be of concern for treaty monitoring, we determine how often meteorites of the corresponding impact energy will strike the Earth's surface. As demonstrated by a recent event in Western Australia [*Hennet et al.*, 1996, 1997], such detections may cause concern if they are difficult to distinguish from explosions and are associated with potential terrorist activity or treaty violations.

Magnitude-Yield Relations

Teleseismic body wave magnitude m_b is known as a function of yield Y for underground nuclear explosions over a broad range of yields and source media. The data are fit by a linear relationship between m_b and log Y, adjusted for the seismological characteristics of particular geological regions. For a stable tectonic setting with low seismic attenuation, such as eastern North America and Central Asia (including the former Soviet test sites near Semipalatinsk and on Novaya Zemlya), the appropriate relationship is [*Ringdal et al.*, 1992, *Murphy*, 1996]:

$$m_b = 4.45 + 0.75 \log Y, \quad (1)$$

Paper number 97GL03586.
0094-8534/98/97GL-03586$05.00

where Y is in kilotons of high-explosive equivalent. However, for areas of high seismic attenuation, such as the Nevada Test Site in the Western United States or the French Sahara test site, the appropriate equation is [*Murphy*, 1981]:

$$m_b = 3.92 + 0.81 \log Y. \quad (2)$$

These equations should bracket the range of analogous relationships of interest for most of the world. Both these equations are fits to data for yield energies in the range 2 kt to 200 kt; we will assume them to hold for Y < 2 kt as well.

To apply eqs.(1) and (2) to impacts, we must take into account that the coupling efficiency of yield energy into seismic waves for nuclear explosions differs from that of impacts. Underground nuclear explosions with yields in the range 1 kt to 19 kt partition their energy into seismic waves with a typical efficiency of about $\varepsilon_n = 5 \times 10^{-3}$ [*Pomeroy*, 1963].

The seismic coupling efficiency factor ε_i for impacts is smaller than ε_n. Laboratory impact experiments for plastic projectiles fired at hypervelocities into bonded sand (target density 1.6 g cm^{-3}) give seismic coupling efficiencies ε_i ranging from 2×10^{-5} to 1.3×10^{-4}, with an average value $\varepsilon_i = 6 \times 10^{-5}$ [*McGarr et al.*, 1969]. Values of 10^{-5} have been derived from missile impacts at the White Sands Missile Range [*Latham et al.*, 1970]. Partitioning of energy into the target increases for higher impactor densities [*O'Keefe and Ahrens*, 1982; *Chyba et al.*, 1990] so missile impacts and experiments with plastic projectiles may underestimate the efficiency of coupling into the target for an iron impactor. For the iron meteorites that will prove to be of interest here, we take $\varepsilon_i \approx 10^{-4}$, a choice also suggested [*Toon et al.*, 1997] for large asteroid impacts into crustal rock. Further experimental work or simulations would be valuable for increasing the reliability of this estimate.

Modified for impacts, eqs.(1) and (2) therefore give:

$$m_b = 4.45 + 0.75 \log[E_i/(\varepsilon_n/\varepsilon_i)], \quad (3)$$

and

$$m_b = 3.92 + 0.81 \log[E_i/(\varepsilon_n/\varepsilon_i)], \quad (4)$$

where E_i is the meteorite impact kinetic energy and $(\varepsilon_n/\varepsilon_i) \approx 50$. Uncertainties in the ratio $(\varepsilon_n/\varepsilon_i)$ are difficult to quantify due to potential systematic errors arising in generalizing from limited experiments to a global average. Moreover, these coupling factors may be expected to vary regionally; the values used here should therefore be viewed as approximations that must serve until these factors may be regionalized. By eqs.(3) and (4), a seismic event of magnitude 4, corresponding to a nuclear yield in the range 0.25 to 1.25 kt by eqs.(1) and (2), requires an impactor with a kinetic energy in the range 12.5 to 62.5 kt. A magnitude 2.5 event, corresponding to an equivalent high explosive yield in the range 2.5 to 18 tons of high explosive, requires an impactor with a kinetic energy in the 0.125 to 0.90 kt range.

Impact Frequencies

We must therefore determine how often the Earth is struck by meteorites with energies in the 0.1 kt to 100 kt range. Observations of small Earth-crossing asteroids [*Rabinowitz*, 1993], taking into account their median impact velocity at the top of the Earth's atmosphere of 13.3 km s^{-1} [*Chyba*, 1993], give Earth-impact frequencies in agreement with lunar cratering data. Cumulative impact frequency F vs. kinetic energy E for these data [Toon et al., 1997] are well-fit by the equation

$$F = 12.6\,E^{-0.86}, \tag{5}$$

where F is in yr^{-1} and E (in kt) is the object's kinetic energy at the top of Earth's atmosphere. However, the terrestrial atmosphere filters out non-iron meteors entering the atmosphere with energies below about 2 megatons (Mt); these weaker objects typically explode in the atmosphere [*Chyba*, 1993; *Toon et al.*, 1997]. Small craters on Earth are invariably formed by iron or stony iron bodies [*Grieve*, 1991]. Some small objects or object fragments (e.g., carbonaceous and stony meteorites) do reach the ground, but with energies too small to generate appreciable seismic signals. Many larger non-iron meteors also detonate at altitude; stony asteroids will not begin to reach the surface intact unless they have initial kinetic energies above about 30 Mt, although Tunguska-like explosions [*Chyba et al.*, 1993] of 10-30 Mt objects may occur low enough in the atmosphere to generate seismic waves [*Ben-Menahem*, 1975]. Tunguska, a 10-15 Mt atmospheric explosion at about 10 km altitude [*Chyba et al.*, 1993], excited an Earthquake of magnitude five [*Ben-Menahem*, 1975]. Tunguska-like explosions will, by eq.(5), occur in Earth's atmosphere about once every 300 yr. A variety of data suggest that iron objects comprise about 5% of the small impactors striking Earth [*Chyba*, 1993]; the uncertainty in this factor is perhaps a factor of 2. Assuming that impacts into oceans (which cover 70% of the Earth's surface) produce a negligible seismic signal (though the possibility of observable hydroacoustic signals from such events should be considered), eq.(5) gives

$$F = 3.8\,f\,E^{-0.86}, \tag{6}$$

where F is in yr^{-1} and f=0.05 is the fraction of total meter-size impactors that are iron objects.

However, iron objects entering the Earth's atmosphere at hypervelocities will be both ablated and decelerated, so that an object entering the top of the atmosphere with a given energy E will strike the surface with substantially less impact energy E_i. Thus, the frequecies of events to be expected are lower than those given by eq.(6). To calculate the importance of this effect, we employ a numerical simulation of the ablation, deceleration, and catastrophic disruption of small impactors in Earth's atmosphere. This simulation has been previously used successfully to model the Tunguska and Revelstoke meteorite explosions [*Chyba et al.*, 1993]. We adopt the parameter choices for iron meteors used in that study, with the following modifications [*Lyne and Tauber*, 1995]: (1) We take the drag coefficient to be that appropriate to a blunted ellipsoid (C_D = 1.2) rather than that for a flat-faced cylinder (C_D = 1.7); (2) We take as a constant shock layer temperature 20,000 K (rather than 25,000 K); and (3) We adopt the formalism for the heat-transfer rate suggested by *Lyne and Tauber* [1995]. For all simulations, we choose the most probable impact entry angle, 45°, and the median small-asteroid initial velocity at the top of the atmosphere of 13.3 km s^{-1} [*Chyba*, 1993]. Of course, both these parameters vary over some appropriate range. However, the uncertainties already present in this problem argue that the further level of detail in the impact simulations represented by incorporating angle and velocity distributions is unwarranted.

Detection Frequencies

Iron meteorites entering the atmosphere with kinetic energies of 100 kt, 50 kt, and 1 kt (corresponding to iron objects with radii in the range from 5 to 1 meters) impact the surface with energies of only 75 kt, 35 kt, and 0.2 kt, respectively. That is, the frequency of impactors with the latter energies on Earth's surface in fact corresponds to the frequency of impactors with the former energies at the top of Earth's atmosphere. The atmosphere exerts a stronger effect on the smaller objects than on the larger. The result of these simulations over the energy range corresponding to seismic magnitudes ranging from 2 to 4, using eqs.(3), (4), and (6), are shown in Fig. 1.

For seismic magnitude detection thresholds around 3, hypervelocity impacts of meter-scale iron meteorites will be

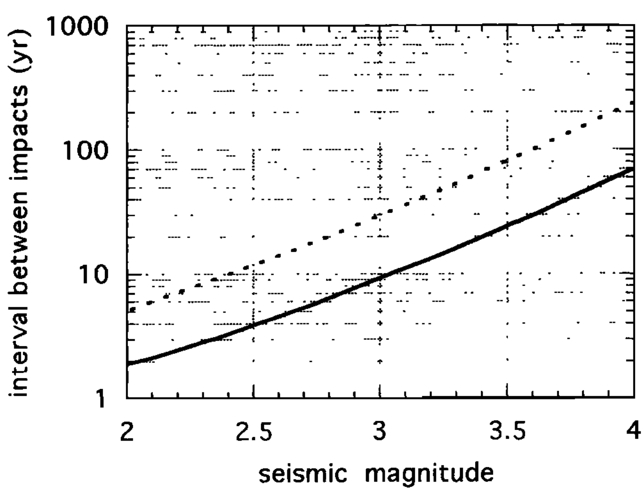

Figure 1. The typical interval between meteorite impacts leading to seismic events of a given magnitude should, for most of the globe, fall between the solid and dotted curves (corresponding to the magnitude-yield relationships of eqs.(3) and (4), respectively). Impact-triggered seismic events within the range of monitoring concern occur on roughly decade timescales, depending on seismic magnitude.

detected with timescales of decades between events. Magnitude 4 impacts will occur on century timescales. It is doubtful that conclusions about event frequencies more precise than these order-of-magnitude statements can reliably be made, given present uncertainties due to local geology, the coupling of impact energy into seismic waves, and in the m_b-Y relationship at energies below ~1 kt.

For nuclear monitoring, the task will be not only to detect such an event but also to distinguish it from the background of naturally occurring earthquakes (as well as mining explosions). With decreasing magnitude, the number N of earthquakes per year increases exponentially according to $\log N = 7.47 - 0.9\, m_b$ [*Ringdal*, 1985]. While a meteorite impact may create a discernable seismic signal (magnitude 2 or larger) every few years, each year there are over 10^5 naturally occurring earthquakes of corresponding magnitude. Although there are no known broadband digital seismic recordings of meteorite impacts, this suggests that the current seismological data archives include meteorite impacts that have been mistakenly categorized as earthquakes.

The official monitoring system for the Comprehensive Test Ban Treaty is only one of a number of facilities that have the potential to record seismic signals of interest. For many areas of the world, the dense coverage of regional seismic networks developed for earthquake monitoring provides a detection capability down to magnitudes of 3.0 to 2.0. From a monitoring perspective, events detected by these regional networks will be of concern if they occur in areas under the control of a nuclear weapon state or a potential proliferator. A magnitude 2.5 event, for example, could correspond to the muffled seismic signal emanating from a 1-kiloton nuclear explosion that was seismically decoupled in a large underground cavity [*van der Vink*, 1995].

Finally, the potential identification of a given seismic event with a specific impact can benefit from data in addition to seismic recordings. Both defense satellite observations [*Tagliagerri et al.*, 1994; *McCord et al.*, 1995] and infrasound detection [*Revelle*, 1997] might be available to test an impact hypothesis. In addition, an impact event should leave a discernable crater. The diameter D of a terrestrial crater is related to the impact energy E_i according to [*Shoemaker and Wolfe*, 1982; *Shoemaker et al.*, 1990]:

$$D = 86.3\, E_i^{0.29}, \tag{7}$$

where crater diameter D is in meters and E_i is in kt. Eq.(7) may then be combined with eqs.(3) and (4) to give impact crater diameter D (in meters) as a function of detected seismic magnitude m_b:

$$D = 1.6\, (\varepsilon_n/\varepsilon_i)^{0.29} \times 10^{0.39\, m_b}, \tag{8}$$

and

$$D = 3.3\, (\varepsilon_n/\varepsilon_i)^{0.29} \times 10^{0.36\, m_b}. \tag{9}$$

Here $(\varepsilon_n/\varepsilon_i)^{0.29} = 3.1$ for $(\varepsilon_n/\varepsilon_i) = 50$. Therefore, for example, a detection of a magnitude 3 event should correspond to a crater of diameter 100 ± 30 m. Localization of the event will clearly be critical to discovering such direct evidence for an impact. Such craters might prove difficult to find were they to occur in a remote area and the seismic event were poorly located; currently, even magnitude 4.0 events have a location error of about 10^4 km^2 [*Harvey*, 1996].

In this regard, it is noteworthy that the magnitude 3.6 event in Western Australia in 1993, of concern due to its possible association with the Aum Shinrikyo terrorist group, could have been caused by a meteorite impact [*Hennet et al.*, 1996, 1997]. This identification is consistent with eyewitness reports. Western Australia is an area of very low seismic attenuation, so that eq.(3) should be applicable. A magnitude $m_b = 3.6$ therefore corresponds to an impact energy of 3.7 kt with $(\varepsilon_n/\varepsilon_i) = 50$, so $D \approx 125$ m. A crater of this size may be difficult to identify; it is not surprising that it has not been found by the preliminary searches conducted so far. A 3.7 kt impact energy corresponds to an iron meteor about 1.9 meters in radius that enters the top of Earth's atmosphere with a kinetic energy of about 7.5 kt. By eq.(6), such objects impact on land about every 30 years.

The percentage of land area worldwide currently accounted for by urban areas has been estimated to lie below 6% [*Weissman*, 1994], so that impacts corresponding to seismic events in the range of monitoring interest would not be expected to have occured in urban areas. Spectacular impacts of iron objects have been observed this century; for example, the 1947 Sikhote-Alin meteorite fall excavated nearly 100 craters with diameters between 1 and 27 m [*Krinov*, 1963]. The largest of these craters, however, corresponds by eqs.(8) and (9) to a seismic event with magnitude m_b below 2.

Acknowledgments:. We are grateful for discussions with J. Murphy, T. Wallace., and D. Wood. C.F.C. is grateful for the hospitality of the Center for Energy and Environmental Studies and the Department of Geosciences at Princeton University where this work was begun, and acknowledges support from the NASA Exobiology program and a Presidential Early Career Award for Scientists and Engineers.

References

Ben-Menahem, A., Source parameters of the Siberian explosion of June 30, 1908, from analysis and synthesis of seismic signals at four stations, *Phys. Earth planet. Int.*, 11, 1-35, 1975.

Chyba, C.F., Thomas, P.J., Brookshaw, L. & Sagan, C., Cometary delivery of organic molecules to early Earth, *Science*, 249, 366-373, 1990.

Chyba, C.F., Explosions of small Spacewatch objects in the Earth's atmosphere, *Nature*, 363, 701-703, 1993.

Chyba, C.F., Thomas, P.J. & Zahnle, K.J., The 1908 Tunguska explosion: Atmospheric disruption of a stony asteroid, *Nature*, 361, 40-44, 1993.

Grieve, R.A.F., Terrestrial impact: The record in the rocks. *Meteoritics*, 26, 175-194, 1991.

Harvey, D., Comparative seismic detection and location capabilities of IRIS and GSETT-3 stations within Central Asia, *IRIS Newsletter* 15(3), 5-7, 1996.

Hennet, C.B., van der Vink, G., Harvey, D. & Chyba, C., IRIS assists Senate in investigation of international terrorist group, *IRIS Newsletter* 15(3), 13-15, 1996.

Hennet, C.B., can der Vink, G., Harvey, D. & Chyba, C., Seismic mystery in Western Australia: Earthquake, meteorite impact or nuclear blast? *EOS Tans. Am. Geophys. Union*, 78(17), S215, 1997.

Holum, J.D., Comments to the seismological community, *IRIS Newsletter*, 15(3), 18-19, 1996.

Krinov, E.L., The Tunguska and Sikhote-Alin meteorites, in *The Solar System, Vol. IV: Moon, Meteorites and Craters*, edited by B. Middlehurst and G.P. Kuiper, pp. 208-234, University of Chicago Press, Chicago, 1963.

Latham, G.V., McDonald, W.G. & Moore, H.J., Missile impacts as sources of seismic energy on the Moon, *Science*, 168, 242, 1970.

Lynn, J.E. & Tauber, M., Origin of the Tunguska event, *Nature*, 375, 638-639, 1995.

McCord, T.B., Morris, J., Persing, D., Tagliaferri, E., Jacobs, C., Sperling, R., Grady, L. & Schmidt, R., Detection of a meteoroid entry into the Earth's atmosphere on February 1, 1994., *J. Geophys. Res.*, 100, 3245-3249, 1995.

McGarr, A., Latham, G.V. & Gault, D.E., Meteoroid impacts as sources of seismicity on the Moon, *J. Geophys. Res.*, 25, 5981-5994, 1969.

Murphy, J.R., P wave coupling of underground explosions in various geologic media, in *Identification of Seismic Sources--Earthquake or Underground Explosion* , edited by E.S. Husebye and S. Mykkeltveit, pp. 201-205, D. Reidel, Dordrecht, 1981.

Murphy, J.R., Types of seismic events and their source descriptions, in *Monitoring a Comprehensive Test Ban Treaty* , edited by E.S. Husebye and A.M. Dainty, pp. 225-245, Kluwer, The Netherlands, 1996.

O'Keefe, J.D., and Ahrens, T.J., Cometary and meteorite swarm impact on planetary surfaces, *J. Geophys. Res.*, 87, 6668-6680, 1982.

Pomeroy, P.W., Long period seismic waves from large, near-surface nuclear explosions, *Bull. Seis. Soc. Am.*, 53, 109-149, 1963.

Rabinowitz, D.L., The size distribution of the Earth-approaching asteroids, *Astrophys. J.*, 407, 412-427, 1993.

Revelle, D.O., Historical detection of atmospheric impacts by large bolides using acoustic-gravity waves, in *Near-Earth Ojbects: The United Nations Conference* , edited by J. Remo, pp. 284-302, New York Acad. Sci., New York, 1997.

Ringdal, F., Study of magnitudes, seismicity and earthquake detectability using a global network, in *The Vela Program: A Twenty-Five Year Review of Basic Research* , edited by A.U. Kerr, pp. 611-624, Defense Advanced Research Projects Agency, Arlington, Virginia, 1985.

Ringdal, F., Marshall, P.D. & Alewine, R.W., Seismic yield determination of Soviet underground nuclear explosions at the Shagan River test site, *Geophys. J. Int.*, 109, 65-77, 1992.

Shoemaker, E.M. & Wolfe, R.F., Cratering time scales for the Galilean satellites, in *Satellites of Jupiter*, edited by D. Morrison, pp. 277-340, University of Arizona Press, Tucson, 1982.

Shoemaker, E.M., Wolfe, R.F. & Shoemaker, C.S., Asteroid and comet flux in the neighborhood of Earth, in *Global Catastrophes in Earth History*, edited by V.L. Sharpton and P.D. Ward, pp. 155-170, Geol. Soc. Am. SP 247, Boulder, CO, 1990.

Tagliaferri, E., Spalding, R., Jacobs, C., Worden, S.P. & Erlich, A., Detection of meteoroid impacts by optical sensors in Earth orbit, in *Hazards Due to Comets and Asteroids*, edited by T. Gehrels, pp. 199-220, University of Arizona Press, Tucson, 1994.

Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P. & Covey, C., Environmental perturbations caused by the impacts of asteroids and comets, *Rev. Geophys.*, 35, 41-78, 1997.

van der Vink, G.E., Seismology and the test ban: A new era, *Rev. Geophys. Suppl., U.S. Nat. Rep. to Int. Union of Geodesy and Geophysics*, pp. 269-273, 1995.

Weissman, P.R., The comet and asteroid impact hazard in perspective, in *Hazards Due to Comets and Asteroids* , edited by T. Gehrels, pp. 1191-1212, University of Arizona Press, Tucson, 1994.

C.F. Chyba, Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA (e-mail: chyba@lpl.arizona.edu)

G.E. van der Vink and C.B. Hennet, IRIS Consortium, 1200 New York Ave., NW, Suite 800, Washington DC 20005, USA (e-mail: gvdv@iris.edu)

(Received August 27, 1997; accepted November 10, 1997.)