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1. Duley, W. W. & Williams, D. A. *Mon. Not. R. astr. Sec.* **196**, 269 (1981).
2. Leger, A. & Puget, J. L. *Astr. Astrophys* **137**, L5–L8 (1984).
3. Allamandola, L. J., Tielens, A. G. G. M. & Barker, J. R. *Astrophys. J.* **290**, L25–L28 (1985).
4. Szczepanski, J. *et al. J. phys. Chem.* **96**, 7876–7881 (1992).
5. Szczepanski, J., Vala, M., Talbi, D., Parisel, O. & Ellinger, Y. *J. chem. Phys.* **98**, 4494–4511 (1993).
6. Szczepanski, J., Vala, M., Talbi, D., Parisel, O. & Ellinger, Y. *J. phys. Chem.* (to be submitted).
7. Szczepanski, J., Chapo, C. & Vala, M. *Chem. Phys. Lett.* **205**, 434 – 439 (1993).
8. Shida, T. *Electronic Absorption Spectra of Radical Ions* (Elsevier, Amsterdam, 1988).
9. Birks, J. B. *Photophysics of Aromatic Molecules* (Wiley, New York, 1970).
10. Salama, F. & Allamandola, L. J. *Nature* **358**, 42–43 (1992).
11. Andrews, L., Kelsall, B. & Blankenship, T. A. *J. Am. chem. Soc.* **86**, 2916–2926 (1982)
12. Jourdain de Muizon, M., d'Hendecourt, L. B. & Gabelle, T. R. *Astr. Astrophys.* **227** 526-541 (1990).
13. Zavagno, A., Cox, P. & Baluteau, J.P. *Astr. Astrophys.* **259**, 241–251 (1992).
14. Pauzat, F., Talbi, D., Miller, M. D., DeFrees, D. J. & Ellinger, Y. *J. phys. Chem.* **96**, 7882–7886 (1992).

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Explosions of small Spacewatch objects in the Earth's atmosphere

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RECENT observations with the Spacewatch telescope indicate that the flux of Earth-crossing objects with diameters below about 50 m is some 10–100 times higher than predicted by simple extrapolation from the known main-belt asteroid population[1,2]. This might seem to imply[3] a significantly greater terrestrial hazard from atmospheric explosions such as those that occurred over Revelstoke or Tunguska[4,5]. Here I show that explosions due to Spacewatch objects with diameters less than 50 m (having kinetic energies below about 10 megatonnes high-explosive equivalent) typically occur too high in the atmosphere to cause substantial surface damage. Exclusive of relatively rare iron objects, no comet or asteroid with an energy below ~2 megatonnes threatens the Earth's surface. The high flux of small Earth-crossing objects identified by Spacewatch therefore does not imply a greater terrestrial hazard.

Table 1*a* lists the 12 Spacewatch objects with diameters below ~50 m discovered so far (ref. 2 and D. Rabinowitz, personal communication). The semimajor axes (a), eccentricities (e), and inclinations (i) of these objects are also listed. From these orbital elements, I have calculated the probability and velocity of collision with Earth for each object, using Öpik's[6,7] equations, modified[8] to account for orbits that are not fully Earth-crossing. Table 1*a* also gives approximate diameters for each object, assuming[2] spheres of albedo 0.0945, the geometric mean between the albedos of S-type and C-type asteroids (0.186 and 0.048, respectively[1,2]; these values are taken below to correspond to stony and carbonaceous compositions).

The Öpik equations used here[7,8] incorporate the Earth's orbital eccentricity, but break down for Earth-crossing objects with extremely low inclinations[7]. The remarkable object 1991 VG has an inclination of only 0.25°, leading to the exceptionally high probability of impact with the Earth of 4,200 per thousand million years (Gyr^{-1}). (Impact probabilities vary as $(\sin i)^{-1}$; the mean probability[9] for an Earth-crossing object to collide with the Earth is ~4 Gyr^{-1}.) The equations are valid provided[7] the ratio of the Earth's gravitational capture radius $R_E[1+(V_{esc}/V_\infty)^2]^{1/2}$ to $a_E \sin i$ is «1, where R_E= 6,371 km is the Earth's physical radius, V_{esc} = 11.2 km s^{-1} Earth's escape velocity, a_E Earth's semimajor axis, and V_∞ is the object's velocity at infinity. This ratio lies in the range 10^{-4}–10^{-3} for all objects in Table 1*a*, except 1991 VG, for which it is 0.06.

1991 VG entirely dominates the characteristics of "typical" terrestrial collisions by Spacewatch objects. For example, a 'typical' terrestrial collision velocity for these objects—weighted appropriately by collision probabilities—would simply be 11.4 km s^{-1}. It has been speculated, although not demonstrated, that 1991 VG is a human artefact[2]. Excluding 1991 VG, the median, average and root-mean-square terrestrial impact velocities for the Spacewatch objects are 13.3, 14.3, and 14.4 km s^{-1}, respectively, compared with impact velocities for the previously known Earth-crossing asteroids of 15, 17 and 18 km s^{-1} (ref.10).

The mean impact probability for the objects in Table 1*a* (excluding 1991 VG) is 29 Gyr^{-1}, a factor of ~7 higher than that for the other Earth-crossing asteroids. Therefore the higher flux of near-Earth objects discovered by Spacewatch does not necessarily require a much higher population of these objects than previously estimated. The flux is enhanced simply because the objects are in unusually Earth-like orbits.

Rabinowitz's analytical estimate of cumulative impact rates[1], as a function of object mass, was made before the Earth-like nature of the Spacewatch objects' orbits was evident[2], and assumed a terrestrial collision velocity of 20.1 km s^{-1}. Beginning instead with the median velocity of 13.3 km s^{-1} calculated above, these collision fluxes may be recalculated, then cast in terms of the frequency of impacts of a given energy. With these modifications, the analytical estimate yields one 680 kilotonne (3.2×10^7 kg) impact per 21 years, and[3,4] 21-kton (1.0×10^6 kg) impacts per year. (Note, however, that Rabinowitz's preferred numerical flux estimates are a factor ~2 higher than his analytical estimates at these masses.) These results may be

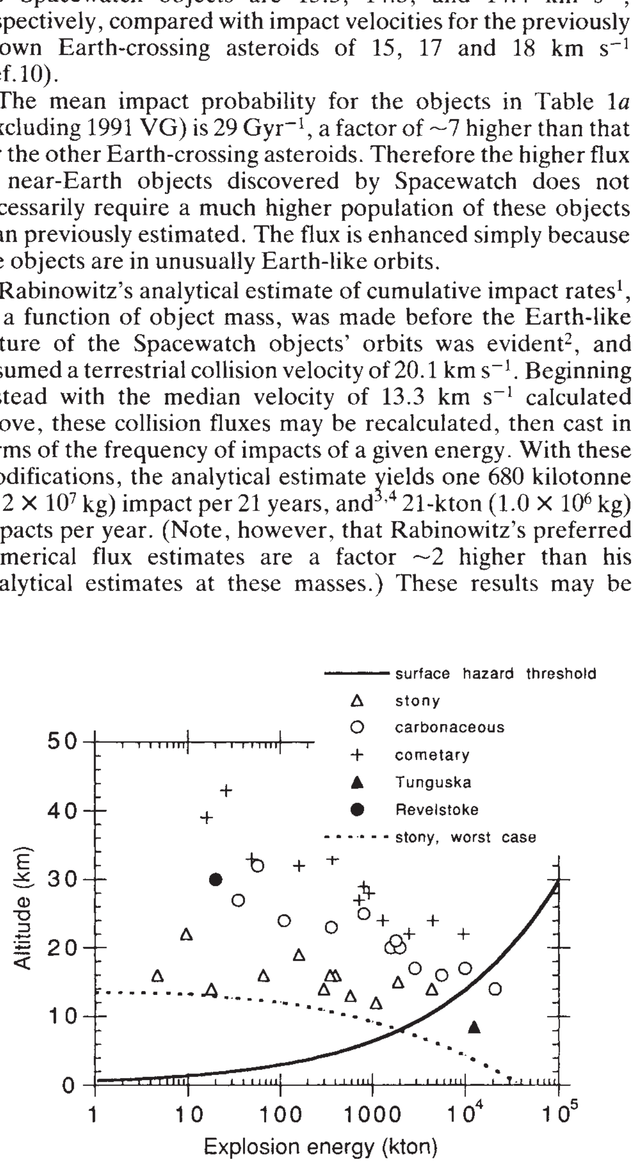

FIG. 1 Explosion altitude in the terrestial atmosphere as a function of energy, for small Spacewatch asteroids. The Tunguska and Revelstoke explosions are plotted for comparison. Explosions occurring above the solid 'surface hazard threshold' line do not pose a significant threat at the Earth's surface. Exclusive of iron objects, no asteroid or comet of a given energy will explode below the 'worst case' line, which indicates the deepest possible atmospheric penetration for a stony asteroid of a given energy.

TABLE 1 Details of small Spacewatch objects

1*a*, Impact velocities and probabilities

Object	*a* (AU)	*e*	*i* (deg)	Diameter* (m)	Impact velocity (km s^{-1})	Impact probability (Gyr^{-1})
1991 BA	2.24	0.68	1.96	7	21.2	7.1
1991 TT	1.19	0.16	14.8	28	13.9	49
1991 TU	1.42	0.33	7.68	8	13.7	11
1991 VA	1.43	0.35	6.52	17	13.9	11
1991 VG	1.05	0.08	0.25	13	11.4	4,210
1992 DU	1.16	0.18	25.1	44	17.8	7.2
1992 JD	1.03	0.03	13.6	44	13.3	115
1992 YD3	1.17	0.14	27.8	55	18.6	6.8
1993 BD3	1.62	0.37	0.9	28	15.7	59
1993 DA	0.94	0.09	12	36	12.9	46
1993 FA1	1.42	0.29	21	26	16.5	2.6
1993 HP1	1.97	0.61	7.9	18	19.3	2.4

b, Airburst energy and altitude

Object	Stony asteroids			Carbonaceous asteroids			Comets†	
	Radius‡ (m)	Energy (kton)	Altitude (km)	Radius (m)	Energy (kton)	Altitude (km)	Energy (kton)	Altitude (km)
1991 BA	2.5	9.6	22	4.9	57	32	26	43
1991 TT	10	300	14	20	1,600	20	720	27
1991 TU	2.9	4.7	16	5.6	35	27	16	39
1991 VA	6.1	66	16	12	360	23	160	32
1991 VG	4.6	18	14	9.1	110	24	49	33
1992 DU	16	1,900	15	31	10,000	17	4,500	24
1992 JD	16	1,100	12	31	5,600	16	2,500	22
1992 YD3	20	4,400	14	39	21,000	14	9,600	22
1993 BD3	10	400	16	20	2,000	20	920	28
1993 DA	13	580	13	25	2,900	17	1,300	24
1993 FA1	9.3	350	16	18	1,800	21	810	29
1993 HP1	6.4	160	19	13	810	25	370	33

*These diameters assume[2] an albedo of 0.0945, the geometric mean between a spherical S-type asteroid and a C-type asteroid, with albedos of 0.186 and 0.048, respectively.

†Comet radii are taken to equal those of C-type asteroids (albedos assumed equal).

‡These are radii for spherical objects. The airburst model used here[4] treats objects as initially 'cubical' cylinders; I take these objects to have masses (hence, explosion energies) identical to those listed (and therefore slightly different cylindrical radii). Radii and explosion energies are given here to two significant figures for the different models considered; however, fundamental uncertainties (such as whether the object is S-type or C-type) guarantee an overall uncertainty of a factor of at least ~2 in radius, and ~2 in energy.

compared to the Spaceguard Survey's estimate[5] of one 20-kton impact per year.

The latter estimate is derived from the lunar cratering record[11], which shows an excess of craters at sizes corresponding to objects in the size range where Spacewatch finds an enhanced flux. But this flux was found[1] to be higher than implied by the lunar extrapolation. With the lower impact velocities determined here, mass estimates from lunar cratering increase by a factor of ~1.6, bringing the Spacewatch and lunar flux estimates into closer agreement.

The Spacewatch results seem to suggest a considerable terrestrial threat due to sub-megatonne impacts. On the other hand, they must be reconciled with the apparent fact that human civilization does not suffer frequent surface explosions in the 10–1,000-kton range. If most Spacewatch objects were small comets[1], they might dissipate their kinetic energy too high in the atmosphere to cause surface damage[3]. I demonstrate here, however, that this conclusion holds if the Spacewatch objects are stony or carbonaceous asteroids as well, as these objects will catastrophically disrupt too high in the atmosphere to cause ground damage. Using a code successfully employed to model the Tunguska and Revelstoke atmospheric explosions[4], I have simulated the entry of the Spacewatch objects into Earth's atmosphere, assuming iron, stony, carbonaceous and cometary compositions. All objects are taken to be incident on the atmosphere at the most probable impact angle of 45°. The results of these simulations are given in Table 1*b*. The altitude at which an object is taken to explode is that at which, once disrupted, it deposits maximum kinetic energy per unit distance[4]. The explosion energy is taken to be that deposited by the object after it has flattened out to twice its initial radius, typically within 10% of its incident kinetic energy. Iron objects, discussed further below, typically crater the terrestrial surface.

The albedos of the Spacewatch objects are not known. Table 1*b* derives object radii based on the choices[1,2] of S- and C-type albedos. Comets are assigned C-type albedos. Following ref.4, densities are set to 3.5, 2.2 and 1.0 g cm^{-3}, and material strengths are taken to be 10^8, 10^7 and 10^6 dyn cm^{-2}, for stony, carbonaceous and cometary objects respectively. These choices of albedo (and hence radii) lead to the C-type and cometary candidates being more energetic than their stony counterparts.

Figure 1 plots explosion energy against altitude for the 12 objects in Table 1*b*. Possible stony, carbonaceous and cometary compositions are indicated. The Tunguska and Revelstoke explosions are shown for comparision. In addition, two important thresholds for surface destruction are shown.

Hills and Goda[12] present a formula for the radius r_4 at the ground below an explosion of energy E at altitude h out to which the resulting overpressure will exceed 4 p.s.i. (2.8×10^5 dyn cm^{-2}). This is the overpressure at which trees will be felled and substantial damage to buildings will occur[12]. Wood frame houses are destroyed at overpressures of 5 p.s.i. (ref. 13). Lower overpressures may also cause some damage; overpressures of 0.5–1 p.s.i. will break glass windows[13], and an overpressure of 2 p.s.i. is the threshold at which these fragments will begin to be propelled with sufficient velocity to cause serious injury[14]. Nevertheless, 4 p.s.i. seems an appropriate choice as a definition of a 'substantial' surface hazard posed by an air explosion.

Citing an unpublished analysis of atmospheric nuclear tests by J. Solem, Hills and Goda[12] give $r_4 = 2.09\,h - 0.449\,h^2\,E^{-1/3} + 5.08\,E^{1/3}$, with E in megatonnes explosive equivalent and h in kilometres. This equation consistently relates treefall observations at the Tunguska site with microbarograph and other evidence (ref. 4 and refs therein) for a 10–20-Mton explosion at 8–9 km altitude, provided r_4 refers to the central circular treefall zone, excluding the lobes of the observed 'butterfly' pattern (perhaps caused by the ballistic wave from the terminal motion of the Tunguska object, before it exploded[15]). The altitude h above which an airburst does not threaten the surface is given by setting $r_4 = 0$, or $h = 6.42E^{1/3}$, shown as the solid curve in Fig. 1. Airbursts occurring above this line pose no substantial threat to the ground.

The above equations were derived for nuclear weapons, where ~50% of the explosion energy is lost to thermal radiation or other energy sinks apart from shock production. Lower-temperature bolide explosions may produce shock waves more efficiently; one simulation[16] finds only 12–25% of bolide explosion energy lost to radiation. As energy enters the above expression only to the 1/3 power, however, the resulting uncertainty is small.

Figure 1 shows that Spacewatch objects with energies below ~10 Mton (at 13.3 km s^{-1}, a stony asteroid ~32 m in radius) do not threaten the surface. Carbonaceous and cometary objects of a given energy always pose less of a threat than stony ones, as they explode higher in the atmosphere because of their lower strengths and densities. What is the lowest energy stony object that can threaten the surface? For a given energy, deepest penetration into the atmosphere occurs for the lowest possible velocity (as catastrophic disruption begins at a pressure proportional to ρv^2, where ρ is atmospheric pressure and v is bolide velocity), or 11.2 km s^{-1} on Earth, and for normal incidence. The dotted line in Fig. 1 shows altitude as a function of energy for a series of such 'worst-case' stony asteroid explosions in the terrestrial atmosphere. No stony (and of course no carbonaceous or cometary) asteroid with kinetic energy below ~2 Mton will cause significant ground damage.

It is not known what fraction of the small Spacewatch objects are composed of iron. Iron–nickel meteorites constitute only ~8% of observed meteorite falls, and probably a much smaller fraction of the meteoritic bodies incident on the atmosphere[17]. However, iron objects make up about 6% of observed main-belt asteroids[18], and about an equal fraction (though the statistics here are poor, and these percentages ignore selection effects) of Earth-crossing asteroids[19].

Each of the Spacewatch objects in Table 1, if of iron composition, would crater the ground. Those with velocities above ~14 km s^{-1} would experience ρv^2 pressures sufficient to cause disruption before impact, possibly yielding a crater-strewn field such as that left by the ~10-kton Sikhote-Alin explosion in 1947 (ref. 20). If 6% of the Spacewatch objects were iron, globally there would be one ~20-kton explosion every ~5 years, and one ~700-kton event every ~350 years. If the former are really occurring, they clearly pose no hazard, as nearly all evidently pass unnoticed. The latter would excavate one ~500-m crater on land every 1,400 years, and the ocean impacts would not cause appreciable tsunamis[12]; again this threat seems small.

On the other hand, if Spacewatch objects originate as, for example, lunar impact ejecta (possibly accounting for their Earth-like orbits), iron objects would be entirely absent. Indeed, limited spectral observations suggest that Spacewatch asteroids are distinct from known asteroid types[2]. It would be of considerable interst to make spectral comparisons of Spacewatch objects with lunar and martian meteorites.

The Spacewatch discovery[1,2] of a higher flux of small Earth-crossing objects does not imply a significantly higher terrestrial impact hazard, despite the prediction of several or more 20-kton impacts every year. But even if these explosions are not felt at the ground, it is at first startling that they could be occurring so frequently in Earth's atmosphere virtually unnoticed. A number of United States (and, presumably, former Soviet) defence satellites are capable of detecting atmospheric events above a certain luminosity threshold, although most such detections are discarded as irrelevant for defence purposes. The Spacewatch results lend urgency to the declassification of the relevant defence data, as well as to efforts to improve the reporting performance of existing satellites[21]. □

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1. Rabinowitz, D .L. *Astrophys. J.* **407**, 412–427 (1993)
2. Rabinowitz, D. L. *et al. Nature* **363**, 704–706 (1993).
3. Ceplecha, Z. *Astr. Astrophys.* **263**, 361–366 (1992).
4. Chyba, C. F., Thomas, P. J. & Zahnle, K. J. *Nature* **361**, 40–44 (1993).
5. Morrison, D. *et al. The Spaceguard Survey* (NASA, 1992).
6. Öpik, E. J. *Proc. R. Irish Acad.* **A54**, 165–199 (1951).
7. Öpik, E. J. *Interplanetary Encounters* (Elsevier, New York, 1976).
8. Shoemaker, E. M. & Wolfe, R. F. in *Satellites of Jupiter* (ed. Morrison, D.) 277–339 (Univ. of Arizona, Tucson, 1982).
9. Shoemaker, E. M., Wolfe, R. F. & Shoemaker, C. S. in *Global Catastrophes in Earth History* (eds Sharpton, V. L. & Ward, P. D.) 155–170 (Geol. Soc. Am spec. publ 247, Boulder, 1990).
10. Chyba, C. F. *Icarus* **92**, 217–233 (1991).
11. Shoemaker, E. M. *Rev. Earth planet. Sci.* **11**, 461–494 (1983).
12. Hills, J. G. & Goda, M. P. *Astr. J.* **105**, 1114–1144 (1993).
13. Broyles, A. A. *Am. J. Phys.* **50**, 586–594 (1982).
14. Glasstone, S. & Dolan, P. J. *The Effects of Nuclear Weapons* (Dept of Defense, Washington DC, 1977).
15. Zotkin, I. T. & Tsikulin, M. A. *Sov. Phys. Dokl.* **11**, 183–186 (1966).
16. Korobeinikov, V. P., Chushkin, P. I. & Shurshalov, L. V. *Acta astronaut.* **9**, 641–643 (1982).
17. Wetherill, G. W. & Shoemaker, E. M. in *Geological Implications of Impacts of Large Asteroids and Comets on the Earth* (eds Silver, L. T. & Schultz, P. H.) 1–13 (Geol. Soc. Am. spec. Publ 190, Boulder, 1982).
18. Gaffey, M. J., Bell, J. F. & Cruikshank, D. P. in *Asteroids II* (eds Binzel, R.P., Gehrels, T. & Matthews, M.S.) 98–127 (Univ. of Arizona, Tucson, 1989).
19. McFadden, L., Tholen, D. J. & Veeder, G. J. in *Asteroids II* (eds Binzel, R. P., Gehrels, T. & Matthews, M. S.) 442–467 (Univ. of Arizona, Tucson, 1989).
20. Passey, Q. R. & Melosh, H. J. *Icarus* **42**, 211–233 (1980).
21. Jacobs, C. & Spalding, R. in *Con. Abst. Hazards Due to Comets and Asteroids* (ed. Gehrels, T.) 45 (Univ. of Arizona, Tucson, 1993).

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