Earth Moon Planet (2008) 102:417–424
DOI 10.1007/s11038-007-9219-6

Meteoroids, Meteors, and the Near-Earth Object Impact Hazard

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Received: 15 September 2007 / Accepted: 14 December 2007 / Published online: 12 January 2008

Abstract In considering the modern-day hazard from infalling near-Earth asteroids and comets, the focus has shifted toward the smallest, most frequent impacts that can do damage on the ground, like the 1908 Tunguska aerial burst. There is considerable uncertainty about the potential for damage by objects in the range 20 to 100 m diameter. Since smaller, less dangerous, meter-sized meteoroids are part of a continuum of small interplanetary bodies, derived by a collisional cascade and Yarkovsky spin-up, research on such phenomena by meteor scientists can shed light on a vital question that will soon have great practical relevance as new telescopic searches for near-Earth asteroids come on line: what is the threshold size between harmless high-altitude airbursts and impacts that can cause lethal damage on the ground?

Keywords Asteroid · Impact hazard · Bolides · Meteoroids · Tunguska · Spaceguard Survey · Near-Earth asteroids

1 Introduction

The Earth has not only been bombarded by asteroids, comets, and their smaller pieces—meteoroids—over its history but continues to be struck today. During the last quarter-century, awareness has increased of the natural hazard posed by such cosmic projectiles. For a comprehensive review of the impact hazard, see Chapman (2004). The basic magnitude of the threat, in terms of time-averaged human fatalities in industrialized countries, is similar to that of individual kinds of natural disasters, such as hurricanes. However, as described by Chapman and Morrison (1994), by far the greatest fraction of the hazard resides in impacts by asteroids or comets larger than about 2 km diameter, where there is a significant risk of a sudden global climate crisis that could cause hundreds of millions of people or more to starve. Chapman and Morrison (1994) estimated the chances that an individual would die by near-Earth object (NEO) impact as 1-in-25,000. [NEOs are both comets and near-Earth asteroids

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Based on an Invited Talk at the "Meteoroids 2007" conference in Barcelona, Spain, 15 June 2007.

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(NEAs) whose orbits pass close to or cross the Earth's orbit; comets are believed to be responsible for a very small fraction of the overall hazard.]

During the past decade, the Spaceguard Survey (http://impact.arc.nasa.gov/intro.cfm) has detected about three-quarters of NEAs >1 km diameter, none of which will impact Earth during the next century, resulting in decreased chances for a large impact during our lifetimes. Moreover, bias correction and other analyses of these telescopic surveys suggest fewer numbers of 100-m-scale impactors than had been previously estimated (more on this below). The overall result is that the chance of dying from an NEA impact has been reduced by at least an order-of-magnitude. Harris (pers. comm. 2007) now considers the chances of dying by impact to be only 1-in-720,000, in the range of death by fireworks accidents or amusement park rides.

Most of the risk reduction has resulted from finding those NEAs that would kill millions or billions of people, but which strike only every million years or less frequently, and showing that they will not collide with Earth during the next century. Most of the remaining hazard resides in much smaller NEAs, 50–300 m in diameter, which strike much more frequently and for which there is a substantial chance (exceeding 1%) of one striking during our lifetimes. It is the cross-over region between these smallest-but-still-dangerous impactors and the still smaller but brilliant bolides, caused by meteoroids meters to a few tens of meters in size and studied by meteor researchers, that I emphasize in this article.

There have been reports of doubtful credibility from antiquity, as well as more recent anecdotes, of death by meteorite falls. While such an accident is certainly possible, there has been no confirmed, credible report of a human being dying from a meteorite strike. A human being was injured by a meteorite in 1954 and a dog was reportedly killed by a fragment of the Martian meteorite Nakhla in 1911, though this has been questioned. Confirmed strikes on automobiles and roof-tops reflect the greater cross-sectional areas presented by these larger, common targets. The Science Definition Team (2003) study suggests that much of the remaining impact hazard resides in Tunguska-scale events that would plausibly kill hundreds to thousands of people. Tunguska was the impact that happened one century ago in Siberia, with an estimated yield of $\sim$15 MT (megatons of TNT equivalent); I discuss Tunguska in greater detail below. Also very dangerous, and little addressed so far by the telescopic surveys, are somewhat larger NEAs 200–500 m in diameter, which could cause a tsunami rivaling or exceeding the Indian Ocean tsunami of 2004. However, it is plausible that there would be adequate warning for most people to evacuate, restricting much of the damage to infrastructure only.

2 Emphasis on More Frequent but Smaller Impacts

Consideration of the dangers of impacts by relatively small NEAs now dominates discussion of the impact hazard. This is partly because the original Spaceguard Survey, designed to address primarily NEAs >1 km diameter, is approaching completion of its ten-year goal to find 90% of such very large NEAs. And it is partly because both the social sciences and practical politics teaches us that people are more concerned about potential catastrophes that are more likely to affect themselves or their children or grandchildren, as distinct from extremely rare and unlikely catastrophes, even if the latter are much more lethal. Especially given the fact that an NEA impact can be prevented, by means of a space mission that would "nudge" the NEA away from its impact trajectory, it is relevant in practical terms to consider how we might address a potentially lethal NEA impact that has a few percent chance of happening this century...or how we must deal with the even more likely very-near-misses, predictions of dangerous impacts with temporarily high probabilities, or megaton-scale impacts that may explode too high to be dangerous but which could frighten people or even be mistaken for a nuclear attack.

Consider the case of Apophis (see also Sansaturio and Arratia 2007). For a few days around Christmas 2004, this 250–300 m NEA was given an official probability (by the Jet Propulsion Laboratory Sentry system and by the Univ. of Pisa NEODyS system) of about 3% of impacting Earth on 13 April 2029. The places on Earth that were at risk of being struck were central Europe, the Middle East, and populous regions in Asia such as the Ganges river valley. About a month later, radar echoes received by the Arecibo radar refined knowledge of Apophis' position and removed any chance of collision in 2029, although Apophis will still pass below the geosynchronous artificial satellites and will be visible to the unaided eye as a 3rd magnitude star rapidly crossing the sky. (There remains a 1-in-45,000 chance that Apophis will pass through a resonant-return "keyhole" in 2029, so that it impacts Earth on 13 April 2036.) News about this 3% possibility of an impact that would have destroyed a whole country or caused a tsunami rivaling the 2004 Indian Ocean disaster was pushed aside by the holiday and then by news of the *actual* Indian Ocean tsunami. Still, future NEO scares are certain to happen during the next decades, even though an actual impact is quite unlikely.

It appears probable that a new survey (informally called the Spaceguard Two Survey, as a follow-on to the original survey) will commence shortly, with the goal of finding 90% of NEAs >140 m diameter within the next 15 years or so. A U.S. law passed by Congress and signed by the President in late 2005 mandates that NASA conduct such a survey, although in a March 2007 report to Congress (NASA 2007) NASA claimed that it lacked funds to carry out such a survey. The large, wide-field telescope projects required for such a survey, however, are already well underway, with some under construction, and one telescope—the first of four PanSTARRs instruments—about to become operational. It is plausible, even without substantial support from NASA, that the observing programs of these telescopes will conduct a non-optimized search for small NEAs and largely meet the Spaceguard Two goals by around 2025.

3 The NEO Size Distribution

The size distribution of projectiles striking the Earth has traditionally been divided into at least two size ranges: (a) asteroids generally >100 m diameter that can be readily discovered by Earth-based telescopes and (b) meteoroids generally <few meters in size and interplanetary dust, whose flux is estimated by various techniques in meteor science and by dust counters on spacecraft (cf. Zolensky et al. 2006). The gap between the brightest bolides and the faintest NEAs has narrowed in recent years, due in part to the comprehensive analysis of infrasound and downward-looking satellite data (cf. Brown et al. 2002) and by the ongoing telescopic surveys (Fig. 1; Harris 2008). There is also new data on the frequency of very small impacts by meteorite-sized bodies on the lunar surface (Ortiz et al. 2006). The data are least certain near 10 m diameter, due to low-number statistics and because of uncertain systematic errors in bias corrections, luminous efficiencies, etc.

Until recently, it has been assumed that the size distribution is roughly linear on a log–log plot; i.e. that a power-law with a constant index fits the data over a wide span of sizes. Brown et al. (2002) concluded that a constant index fits data from 5 to 200 m, and the Science Definition Team (2003) concluded that a constant index adequately (though

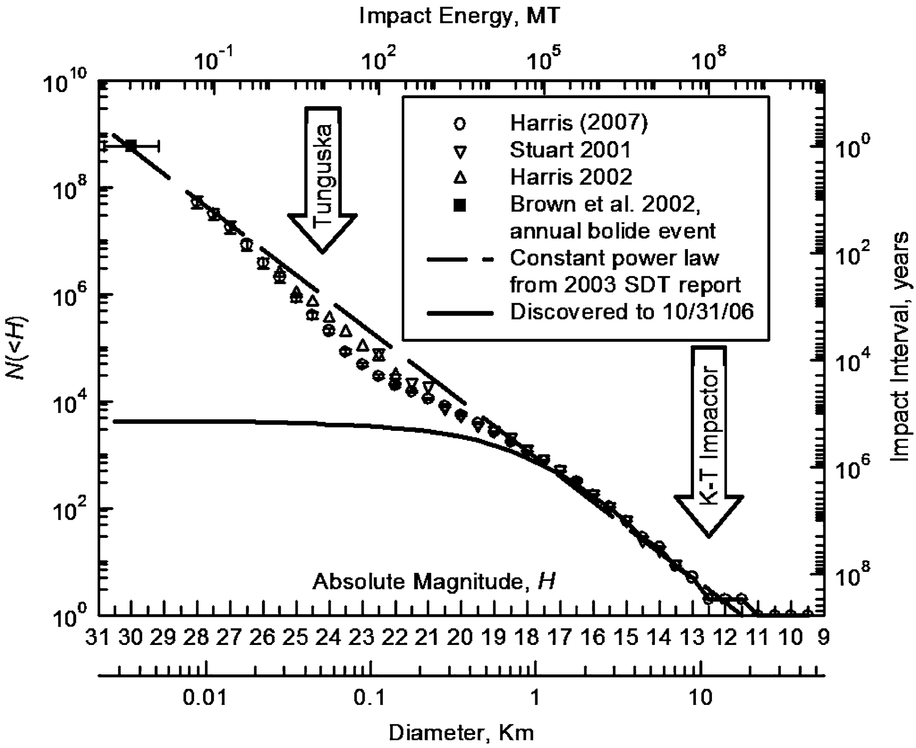

Fig. 1 This graph shows various estimates of the size vs. impact frequency of NEAs, including the most recent estimate of Harris (2008). Equivalent astronomical absolute magnitude and impact energy in megatons are shown. The solid curve shows the number actually known as of late 2006. Reproduced courtesy of Alan W. Harris (who retains the copyright)

not perfectly) fits data between about 3 and 10 km. The two indices are not exactly the same, however, indicating that the slope steepens somewhat toward smaller sizes; indeed, it steepens yet again at the smallest sizes (interplanetary dust; cf. Zolensky et al. 2006). In fact, it has long been known from the lunar cratering record (cf. Chapman and Haefner 1967) that the size-distribution of the projectile flux must be somewhat "wavy", at least averaged over the billions of years that the lunar surface has served as an impact counter. It has recently been re-recognized (cf. McEwen and Bierhaus 2006) that the dramatic steepening of the lunar crater size distribution at sizes <2 km diameter (made by projectiles <100 m diameter) is augmented significantly by secondary craters, as originally proposed by Shoemaker (1965); nevertheless, it is apparent that the NEA/meteoroid size distribution also steepens somewhat over this range.

Harris (2008) has recently emphasized that the previously uncertain deficit (relative to the constant power-law) of NEAs between 20 and 500 m diameter seems to be real and somewhat larger than previously estimated. The deficit is fully a factor of 3 below the power-law near 100 m diameter. This result contributes to a reduced hazard from Tunguska-sized impacts, as noted earlier. On the other hand, the reduction in frequency of 10 MT events to about 1 every 3,000 years seems to be increasingly incompatible with the fact that Tunguska itself struck only 100 years ago. (Indeed it struck on land and comparable explosions over the ocean might not have been recognized until recent decades; so there could have been more than one Tunguska-scale impact in the past couple hundred years.)

4 Tunguska and the Transition from Harmless Bolides to Dangerous Impacts

Most interpretations of phenomena associated with Tunguska place the energy in the 10–40 MT range, favoring lower values around 15 MT, making it about a 1-in-4,000 year event. However, Boslough and Crawford (1997) argue that the Tunguska devastation might have been caused by a 3 MT explosion, or about a 1-in-700 year event according to Fig. 1. Boslough (2007) has recently discussed reasons why the damage from such small impactors might be amplified beyond what previous calculations have shown. Nevertheless, to be a once-in-200 year event, an impact <1 MT is required, which would be caused by an impacting projectile (at typical velocities and with stony composition) only 20 to 25 m across (Fig. 1). Most calculations suggest that bodies that small explode far too high in the atmosphere to cause significant damage on the ground, let alone the devastation over 1,000s of sq. km represented by Tunguska. (One co-author of the Science Definition Team (2003) report has said that he would run *toward* such an impact, to observe it, rather than run away to escape what he believes would be a negligible chance of damage on the ground.) With a contrary perspective, Bland and Artemieva (2003) present calculations showing that atmospheric fragmentation of incoming small NEAs is more effective than previously modeled; they argue, opposite to Boslough, that ground damage is greatly reduced from previous estimates.

Of course, small metallic objects do penetrate the atmosphere, with only modest fragmentation, resulting in nearly all of the known impact craters on Earth <1 km diameter (e.g. the Henbury crater cluster in Australia). But only a few percent of NEAs, and a few percent of meteoroids striking the top of the Earth's atmosphere, are believed to have metallic strengths. If the fraction of metallic meteoroids several meters to several tens of meters in size is larger than has been estimated, then surface destruction would be greater than is currently being inferred from the NEA size distribution.

Currently, analyses of mortality from the impact hazard (e.g. Science Definition Team 2003) assume negligible effects from NEAs <50 m diameter. If dangerous effects, including mortality, were caused by NEAs only half as big (25 m), then dangerous events would occur almost a factor of ten more often. To put the issue in a practical context, what should the response be of national and international emergency management officials to a prediction that a 35 m NEA will strike a populated country a decade in the future? Following current interpretations, we would simply tell people near ground-zero to stay inside and not look directly at the high-altitude explosion. But if objects of that size could cause Tunguska-like damage, we might not only evacuate people for 100 km surrounding ground-zero but we would certainly consider a space mission to move or blow-up the threatening NEA. A major issue that must be thoroughly evaluated with high priority concerns the damage, on the Earth's surface, caused by explosions of various sizes at different altitudes in the Earth's atmosphere. Much of what we currently believe is based on bomb tests from nearly half-a-century ago (Glasstone and Dolan 1977). We now have tools to examine these matters that do not involve actual explosions in the real world. We must better understand the range of possible effects of large atmospheric explosions on the environment, on artificial structures, and on human beings.

It is because of all of these uncertainties that it is vital to learn about the numbers and natures of objects in the upper end of the range of bolides, studied chiefly by military assets, and in the lower end of the range of NEAs accessible to telescopes (optical, infrared, and radar). Since these transitional NEAs are part of a continuum—a collisional cascade spreading over a large range of sizes—the attributes of meter-sized objects are related to the larger, tens-of-meters sized objects in the transition region. Not only are many of the meter-size projectiles fragments of these larger objects, but their numbers—both in near-Earth space and in the main asteroid belt from which most of them come—govern the rates of catastrophic disruption and hence the numbers and impact frequencies of these larger objects. Hence the properties and numbers of the largest bolides studied by meteor specialists are directly relevant to establishing the hazardous effects of threshold-sized NEAs.

5 Related Issues and Conclusion

It is worth considering now what the implications will be of the Spaceguard Two Survey, described above, once it gets underway in the next few years and by the time it is concluded in the mid 2020s. The discovery rate for 10 m NEAs will go up by more than a thousand times! By the end of the search, even though it is focused on bodies >140 m, the search will have found more than half of the 50 m (Tunguska-sized?) NEAs. We will then be tracking 1–2 million 30 m bodies; even though impact damage *may* be small or negligible, any threatening NEA of such size will command attention. By the end of the survey, we should know the orbits of a quarter-million meteoroids 5 m in size: think of the implications for meteoroid researchers! At a minimum, we will be able to check and correct for the existing uncertainties in luminous efficiencies, bias corrections, etc. that affect both the telescopic data and interpretations of actual bolides, because the issue of small-number statistics will have been erased.

We should re-think the issue of the danger of meteorite falls—those events like Sikhote-Alin that shower the landscape with "rocks falling from the skies." In the past, the hazard from creation of such strewn fields has been negligible because of the much lower population density of human beings during past decades, centuries, and millennia. The population density of the world is now about seven times what it was in 1,800, when meteorites were first recognized as being rocks from interplanetary space. And it averaged about four times less than that during the previous millennium. So the chances of human fatalities from meteorite falls during the 21st century are greater than the cumulative chances during all of recorded human history. In fact, if Bland and Artemieva (2003) are correct in asserting that NEAs up to 200 m in size are generally fragmented in the atmosphere, then falls of tens-of-centimeter to ten-meter scale meteorites may be more common than previously estimated.

Our picture of the physical nature of small NEAs is rapidly changing. It is now realized that about a fifth of NEAs are binaries, or asteroids with satellites, and another fifth are probable contact binaries. How these statistics vary with size is uncertain. Almost all NEAs >200 m in diameter are believed to be "rubble piles", composed of multiple pieces held together loosely by gravity. Since Yarkovsky forces tend to spin up small NEAs, they are likely to disaggregate into their constituent pieces when their spin periods become shorter than about 2 h. The spins of most NEAs <100 m in size are so fast that they must be coherent monoliths, with appreciable tensile strength; perhaps many of them were previously constituents of rubble piles that have since come apart.

One dramatic case of a rapidly spinning NEA, exchanging mass with its nearby satellite, is 1999 KW4 (Scheeres et al. 2006). This developing picture of the physical nature of small NEAs is in rapid flux, and puzzles remain. For example, the astronomical evidence suggests that nearly all binary NEAs are either in contact or separated by just several radii from the larger body. Yet the frequency of double craters on the Earth and Venus (Cook et al. 2003) imply that about 15% of NEAs are much more widely separated binaries (the common close binaries would form a single crater). Obviously, observations pertaining to the properties of projectiles that cause large bolides, which may be fragments of either catastrophic collisional disruption of larger bodies *or* the disintegration of rubble piles under Yarkovsky spin-up, can potentially help us understand the processes that shape the physical properties of NEAs and meteorites. Are meteoroids that cause bolides also binary objects? Are apparently paired meteors telling us something about the forces affecting meteoroids as they approach the Earth? Is there correspondence between inferred properties of bolide-producing meteoroids and the astronomical evidence that about half of NEAs are either C-type asteroids or dormant comets, which are increasingly suspected of having very low bulk densities?

Finally, although the specialties of meteor science, meteoritics, and asteroid astronomy lie within the physical sciences, we must remember that these scientific specialties—like no others within astronomy besides research on the Sun and its influence on Earth—have very practical implications. Social science research has already predicted that the NEA hazard may have societal and political consequences beyond its “objective” impact (Slovic 2007). And the realities of the news media and political decision-making processes force us to acknowledge that an NEA impact (predicted or actual) with lethal consequences similar to the effects of a large earthquake, flood, or typhoon may stimulate psychological and political reactions far out-of-proportion to the fact that such an impact is roughly two-orders-of-magnitude less likely to happen than one of these familiar natural disasters. And even smaller, more frequent events—which are sure to happen during the next few decades—could have unfortunate consequences; for example, if an unusually large (but not unexpected) airburst were to occur over a war zone and be misinterpreted, thus triggering a nuclear response. The chances for such misinterpretation have been reduced since the scenario was first raised (Shoemaker 1983). But with the imminent frequent discovery of innumerable small NEAs during the next decade, as Spaceguard Two comes on line, it becomes vital to understand those smallest meteoroid impacts that can be lethal *or* that may be *perceived* as significantly threatening or dangerous.

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