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Updated Population and Risk Assessment for Airbursts from Near-Earth Objects (NEOs)

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***Abstract*—We present a new analysis of airburst risk based on updated estimates for the population of undiscovered NEOs, taking into account the enhanced damage potential of directed airbursts. We define airbursts as events in which small (meters to tens-of-meters in diameter) asteroids deposit most of their energy in the atmosphere as large bolides and where the total energy is comparable to or greater than small nuclear explosions (>0.1 kilotons of TNT). Our tens-of-meter population estimate from optical surveys is now much closer to bolide frequency estimates, resolving most of an earlier discrepancy. Our Tunguska-class (~40 meters) population estimate has doubled, and Chelyabinsk-class (~20 meters) has increased by a factor of 2.6. Uncertainty in this population remains quite large, and can only be unambiguously reduced by expanded surveys focused on objects in the tens-of-meters size range. The assessed risk from this population is also increasing for two reasons. First, airbursts are significantly more damaging than assumed in the original risk assessments, because for typical impact geometries they more efficiently couple energy to the surface than nuclear explosions of the same energy. Second, the greater numbers mean that they are more frequent than previously thought. We review the evidence that asteroid airbursts are more damaging than nuclear explosions, and provide arguments that such events are more frequent.**

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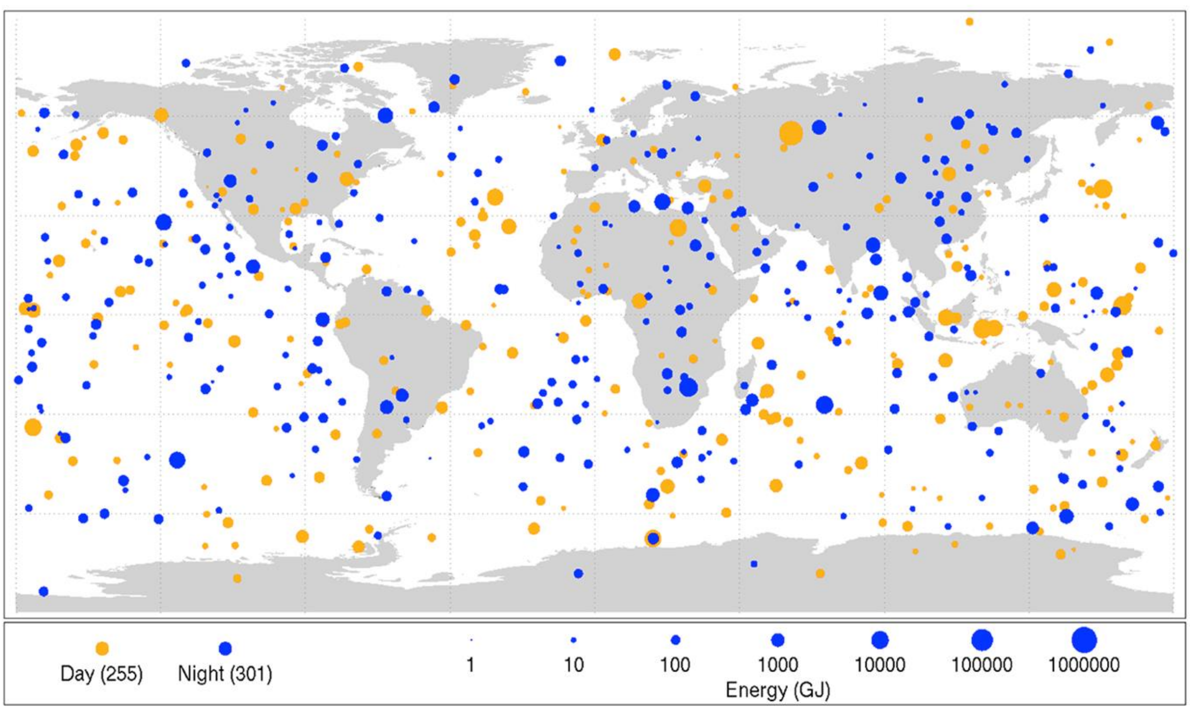

Figure 1 – Bolide events (1994-2013) detected by US government sensor data (NASA Near-Earth Object Program Office).

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1. INTRODUCTION

Last year's half-megaton airburst over Chelyabinsk, Russia, appeared to challenge the notion that such events are extremely rare. To address this question, Brown *et al.* [1] carried out an analysis of cosmic airbursts—including Chelyabinsk—with energy releases of a kiloton or more. They concluded that the number of objects in the ten-meter diameter range could be considerably greater than previously thought. They included a new analysis of US government sensor data (Figure 1), which shows the registered optical energy assuming 6000 K blackbody emission, in which the total airburst energy is roughly ten times as large. They included recently-published synthesis of decades of infrasound bolide data by Silber *et al.* [2], as well as the 1908 Tunguska event which has been thought to be an extreme outlier.

The first and most widely-referenced probabilistic risk assessment for NEOs was published by Chapman and Morrison [3], who concluded that the largest asteroids (> 1 km diameter) dominate the hazard, even though they represent a tiny fraction of the population. The power-law size distribution means that large impacts are low-probability events. Despite this, the potential for global catastrophe also means that their contribution to the risk is highly disproportionate. This conclusion led to the Spaceguard survey, which focused on detection of km-sized and larger asteroids, and which has now catalogued nearly 90% of these objects, none of which is on a collision course. The survey has reduced the assessed risk from this fraction by more than an order of magnitude because completion is highest for the largest and most dangerous. The *relative* contribution to the assessed risk from airbursts due to collisions of objects with diameters in the tens-of-meters range is therefore increasing.

Compared to what was previously thought, megaton-scale airbursts are (1) significantly more damaging on average [4] and (2) probably more frequent [1]. We therefore conclude that the *absolute* risk from airbursts is also greater than previous assessments concluded.

The first argument for increased risk is our improved understanding of airburst physics, which is reviewed in Section 2. In Section 3 we summarize what we learned from the 2013 Chelyabinsk airburst and why it pointed toward the possibility that we have underestimated the population of objects in the tens-of-meters size range. In Section 4 we provide statistical data on bolides that supports the assertion of higher flux. Astronomical observations of asteroids are re-evaluated in Section 5, and are shown to be in reasonable agreement. We combine the upgrade in both damage and frequency in Section 6 to provide and discuss a quantitative reassessment of risk, and in Section 7 we suggest strategies for reducing the uncertainty in our risk assessments.

2. AIRBURST PHYSICS

The 1993 discovery of Comet Shoemaker-Levy 9 (SL9), and the impact of its multiple fragments into Jupiter at 60 km/s the following year, led to the first high-fidelity three-dimensional computational simulations of an atmospheric airburst. Jupiter is a gas giant, having no solid surface. Without the possibility of a solid crater-forming impact, the objects' kinetic energy had to be dissipated as they passed through the hydrogen/helium atmosphere. One of the most salient and unexpected phenomena that was predicted [5], and then observed [6], was associated with the directionality of the resulting explosion: the towering plumes that rose 3000 km above Jupiter's cloud tops. Prior to the SL9 simulations, our best attempts at describing the aerial explosion of a comet or asteroid was based on an appeal to the only class of airburst that had been observed—atmospheric nuclear tests. What the simulations showed, and the observations validated, was that collisional airbursts cannot be approximated as point-source explosions. The deposition of energy (through drag) and mass (through ablation) into the atmosphere of a planet takes place over a distance of many scale heights, creating a long and narrow wake of high-pressure, high-temperature, low-density vaporized cosmic material that must expand as it maintains a large fraction of its initial velocity and momentum that continues to drive a bow shock ahead of it. The outward expansion is also faster than the speed of sound in the atmosphere, so it drives an outward shock that reinforces the downrange bow shock, creating an anisotropic explosion with an effective yield that approximates its initial kinetic energy. Because this yield is similar (or larger) than that of a nuclear explosion, we often use units of kilotons or megatons which refers to the chemical energy content of the equivalent mass of TNT (where 1 ton $\equiv 4.184\times10^9$ J).

The built-in anisotropy of the linear wake creates a low-density, high-pressure pathway upward from the impact and back into space. As soon as the impactor descends below a given altitude, the wake immediately behind it begins to expand in all directions. However, when the impactor descends another increment it leaves more wake material at slightly higher pressure and density, causing the mass above it to slow down, stop, and finally reverse direction. This leads to a "backfire" effect by generating a long slug of cosmic vapor and high-temperature air that moves up the wake to be launched into space where it can expand freely during free fall, before collapsing back on top of the atmosphere. On Jupiter, this was observed as a high-altitude plume followed by high-intensity thermal infrared radiation as it compressed the atmosphere by falling back, followed by an asymmetric pattern of fallout that appeared as a dark spot oriented along the direction of impact with a Coriolis rotation as it slid [7].

The largest fragments to strike were probably about a kilometer in diameter [8], and would have penetrated the atmosphere intact and formed a large crater if they had collided with the Earth. To first approximation, however,

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the physics of airbursts is scale-independent when no solid surface is involved. Thus, the understanding of airburst physics gleaned from modeling and observations of SL9 can be applied to asteroid airbursts in Earth's atmosphere when the object is too small to reach the ground. Boslough and Crawford [7] modeled the 1908 Tunguska explosion over Siberia and determined that it would have formed a similar plume that would rise hundreds of kilometers into space before falling back, provided the impact angle was sufficiently steep. They also determined that such a plume would generate a reaction force that would couple more momentum into the ground than would come from the explosion itself, suggesting that the previously-accepted size of the explosion (10-20 megatons, based on nuclear explosion data) had been overestimated. They downgraded the yield to 3-5 megatons, implying that the explosion was caused by an asteroid about 40 meters in diameter.

Previous work incorporating the "pancake model" by Chyba *et al.* [9] had equated the airburst height to the altitude of maximum energy deposition, and estimated the damage on the ground by assuming it would be the same as that from a nuclear explosion at that altitude. Risk assessments by Chapman and Morrison [3] considered the contribution due to airbursts to be negligible and focused on crater-forming events up to and above a presumed global catastrophe threshold.

Boslough and Crawford [7] also suggested that the high altitude plume from such an airburst, if it were to take place today, would endanger satellites in low-Earth orbit, adding another component to the risk assessment. The reaction force and dynamic increase of surface pressure from a Tunguska-scale airburst is a potential tsunami-generating mechanism that has never been modeled. This may be analogous to the inertia-gravity waves on Jupiter that were driven by the impact of SL9 and suggests that a similar physical mechanism generates meteotsunami on Earth as another contributor to airburst risk.

Boslough and Crawford [4] also reevaluated the damage potential of low-altitude airbursts, showing that the effective height of burst for many impact scenarios is much lower than the altitude of peak energy deposition because the downward transport of energy due to remaining momentum as the mass of the object forms a jet of debris that continues along the impact trajectory. For many situations, this leads to much more severe damage at the surface than would be estimated using the pancake model and assumptions of Chyba *et al.* [9]. They also showed that there are situations for which the jet of high-temperature descends all the way to the surface, leading to a damage mechanism that had not been previously considered. They interpret the Libyan Desert Glass to be a product of surface ablation. This type of airburst has the potential to completely incinerate a large area, adding another mechanism to the risk equation.

Prior to 2013, computational models of airburst mechanics generally treated scenarios for which the downward velocity was a significant component. Even with less than the most probable impact angle of 45°, the Tunguska entry was at a steep enough angle (35° gives the best agreement between simulated and observed damage maps) to carry the jet downward to a much lower effective height of burst. The Chelyabinsk airburst asteroid, on the other hand, entered the atmosphere at only 17° from the horizontal. As a near-grazing encounter, it was therefore not a typical airburst in terms of the effects on the ground. A brief summary of what we know about the physics of the Chelyabinsk airburst is reviewed in the next section.

3. The Chelyabinsk Airburst

On Feb. 15, 2013, an asteroid entered the Earth's atmosphere at 19 km/s and exploded about 40 km south of Chelyabinsk, Russia. Because of its shallow entry angle (17° from the horizontal) it traversed hundreds of km of low-density air before it descended to a height (~40 km) and density capable of generating sufficient drag to cause it to break apart, vaporize, and explode. The fireball was observable for a full 16 seconds and was widely recorded by many digital dashboard video cameras, from which an enormous amount of data were extracted, providing the basis for detailed quantitative analysis [1,10,11]. By combining seismic, infrasound, US government sensor, and video-derived lightcurve data, Brown *et al.* [1] provided a robust yield estimate of about 500 kilotons.

Two key findings of Brown *et al.* [1] have implications for risk assessment. First, they showed that "…a widely referenced technique of estimating airburst damage does not reproduce the observations, and that the mathematical relations based on the effects of nuclear weapons—almost always used with this technique—overestimate blast damage." Second, they reviewed global data on large (greater than a kiloton) airbursts (including Chelyabinsk) and found that "…the number of impactors with diameters of tens of meters may be an order of magnitude higher than estimates based on other techniques."

The first Chelyabinsk finding, if generalized, would contradict the previous work of Boslough and Crawford [4] who claimed the opposite: that estimates based on nuclear weapons effects *underestimate* the damage. Moreover, it would imply that—for a given airburst event—the risk has been overestimated, not underestimated. The explanation is due to the fact that the relatively shallow impact angle of Chelyabinsk is not common. The distribution of impact angles on earth can be approximated by assuming that asteroids are randomly distributed and isotropic in space. The probability of an impact coming from a given elevation angle (θ) is proportional to $\sin(2\theta)$, and the cumulative impact probability is $\frac{1}{2}(1-\cos(2\theta))$. More than 90% of impacts arrive at steeper angles than Chelyabinsk. The conclusions of Boslough and Crawford [4] were based on simulations showing that the exploding jet continues along the initial path. For shallow entries this carries the energy primarily downrange along the ground track, and for steep

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entries it carries it mostly downward. For shallow entries, energy is deposited at higher altitude and is distributed over a larger area but is less intense directly beneath the burst, whereas the opposite is true for steep entries. We have not yet performed a sufficient number of simulations to determine the parameter domains that define when a given airburst is overestimated or underestimated by a nuclear explosion of the same yield. This will be a necessary component of future risk assessments.

The second Chelyabinsk finding—that objects tens-of-meters in diameter could be an order of magnitude more frequent—appeared to contradict the astronomical data. The primary purpose of this paper is to improve risk assessments by resolving this discrepancy, which is the subject of the following two sections.

4. Airburst Observation Statistics

The contemporary rate of terrestrial airbursts (corresponding roughly to meter-sized and larger impacts) occurring on the Earth is constrained directly from a number of different techniques. These techniques use the electromagnetic signals (usually in the form of visible radiation) as well as the shocks produced by airbursts to systematically record airbursts. In addition, observations of smaller impacts in the atmosphere (fireballs) from ground-based surveys and lunar impact flashes can be extrapolated upward to estimate airburst frequency at the small energy end. Various surveys, described below, are plotted in Figure 2. Diameters are computed using the assumptions given by Brown *et al*. [1]. The grey curve is a power-law fit to the Brown *et al.* [14] data.

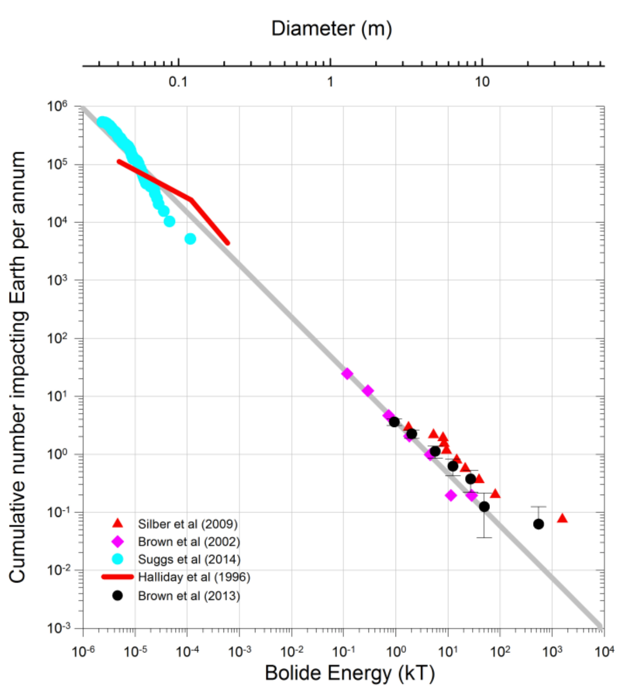

Figure 2 – Energy distribution of bolide events.

At small sizes, Halliday *et al.* [12] used data from the Meteorite Observation and Recovery Project (MORP), which ran from 1971 to 1985 in Western Canada, to perform a clear-sky survey of fireball frequency. This remains the only controlled flux survey of in-atmosphere fireball detections covering the mass range from a few tens of grams to a few tens of kilograms. Despite operating for almost 14 years, the integreated time-area product of the survey was less than one full day of equivalent global coverage. The largest recorded event in the survey was just over one metric ton and hence well below meter-size. A pronounced change in the slope also occurs at masses of a few kilograms, probably associated with changes in meteoroid population/origin between shower dominated cm-sized meteoroids and non-shower/asteroidal objects at larger sizes.

Recently, analysis of lunar impact flashes provided by Suggs *et al.* [13] shows absolute flux numbers to be a factor of several lower in the kilogram range compared to Halliday *et al.* [12] and differing slopes. However, the lunar impact flash survey and the MORP fireball survey have significantly different assumptions built into their estimates for mass/energy and hence uncertain relative mass scales which may be the cause of this difference.

Atmospheric fireball and lunar impact flux measurments do not have the time-area coverage to provide useable statistics for meter-sized impacts (which occur roughly once every two weeks over the entire Earth). From space-based sensor systems, Brown *et al.* [14] reported an 8-year study of over 300 multi-meter sized meteoroids The resulting cumulative number of impacts per year (N) as a function of energy (E) —in units of kilotons where 1 kiloton = 4.185×10^{12} J — was found to follow a power law of the form $N = 3.7\,E^{-0.9}$. This fit is appropriate to energies of 0.1 – 10 kT which corresponds to objects with diameters ranging from 1 to 6 m. The recent extension to this survey by Brown *et al.* [1] found similar values at these energies, but evidence for fluxes above the power-law curve at larger sizes. In the Brown *et al.* [1] survey, almost 20 years of bolide data restricted to energies above 1 kT were examined. At the lower energies, the flux values were similar to those found earlier [14], but inclusion of the very large Chelyabinsk event of Feb 15, 2013 raised the apparent flux at tens of meter sizes to ~5 times the Brown *et al.* [14] power-law extrapolation. However, since the flux of Chelyabinsk-sized asteroids was based on a single event during the 20-year observation period, it is not statistically significant by itself.

Silber *et al.* [2] used acoustic records provided by the Air Force Technical Applications Centre (AFTAC) of airwave events over a 14 year period which were attributed to bolides [15]. Their fluxes are systematically higher than the power law curve from Brown *et al.* [14] but in agreement within uncertainty with the revised values at larger sizes (>6 m) from Brown *et al*. [1]. As with the Brown *et al.* [1] study, a single event occurring on Aug 3, 1963 near the Marion Islands south of Africa significantly skews the high

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end flux if the survey time of 14 years as recorded is used. This event was detected at two distant acoustic stations and had very long acoustic periods (of order 40 sec), consistent with nuclear detonations in the megaton range.

5. ASTEROID OBSERVATION STATISTICS

The first asteroid discovered that fit the present definition of "Near-Earth Asteroid" (NEA)—with perihelion distance from the sun q less than 1.3 AU—was (433) Eros, in 1898. The first asteroid discovered that actually crossed the Earth's orbit ($q < 1.0$) was (1862) Apollo. It was not found until 1932, and was promptly lost until 1973. Serious surveys for NEAs, to assess the population, were begun in 1973, using small (~0.5 m) telescopes and photographic emulsions. These were capable of reaching only to about visual magnitude 15, and yielded only modest numbers over the next two decades. Larger (~1 m) telescopes using large format CCD detectors began operation in the mid-1990s, and have yielded ever increasing rates of discovery for nearly twenty years now. At the start of the CCD era, only about 400 NEAs had been discovered; the rate quickly reached 200 per year by about 1997, and 2013 saw slightly over 1,000 new discoveries. The rate of discovery has increased almost linearly over that interval, thus the cumulative number known has increased about quadratically, to 11,500 as of October, 2014.

Early attempts to estimate the total population versus size of objects (size-frequency distribution) were based on "controlled surveys", which are single surveys with a known sky coverage, limiting magnitude, and other parameters that would allow estimating the "volume" of sky surveyed and thereby allow one to "bias correct" to estimate the total population. But over time, the surveys have evolved and multiplied, so no one survey with a constant set of "control" parameters has discovered more than a small fraction of the total known. D'Abramo *et al.* [16] suggested a method of estimating total population based on "re-detection ratio." The completion at a given size should be roughly equal to the ratio of the fraction of detected objects of that size in a trial interval that were already known objects to the number of total detections, re-detections plus new discoveries. For example, if the total number of detections in a given size range was ten, of which five were already known objects, then the re-detection ratio would be 0.5, and to first order, one would infer a completion of 50%, and a total population of twice the total number already known.

If all asteroids were equally easy to discover, so that detections are random events, this would be true. But all asteroids are not equally easy to discover, some are easier than others due to orbital geometry and such, and one expects the easier ones tend to be discovered first, so in fact, the re-detection ratio will always be greater than the actual completion. To carry the analysis to the next level, we turn to computer simulations of surveys, using a large population of synthetic orbits chosen to match as closely as possible the actual distribution of NEA orbits (see Harris [17] for a description of the survey simulation algorithm and an evaluation of NEA surveys at the time). In these survey simulations, we use a parameter $dm = V_{lim} - H$, where V_{lim} is the limiting magnitude of the survey and H is the absolute magnitude of the asteroid. By "filtering" the same file of asteroid sky positions for different values of dm, one can construct a completion curve versus the parameter dm. This can be interpreted as a curve of completion versus survey limiting magnitude for a single size of asteroid H, or a curve of completion versus absolute magnitude for a fixed survey limiting magnitude V_{lim}. It is noteworthy that within a wide range of survey parameters, the relative completion curve versus dm resembles the same form. If the computed completion is 50% at some value of dm, it will be about 27% at one magnitude fainter (dm – 1), 12% at two magnitudes fainter (dm – 2), and so forth. Furthermore, at very small values of dm (very faint, small asteroids), detections occur only very near the Earth so detection geometry can be treated as sort of "particle in a box" to arrive at an analytic expression for relative completion, extending down to arbitrarily small size [17]

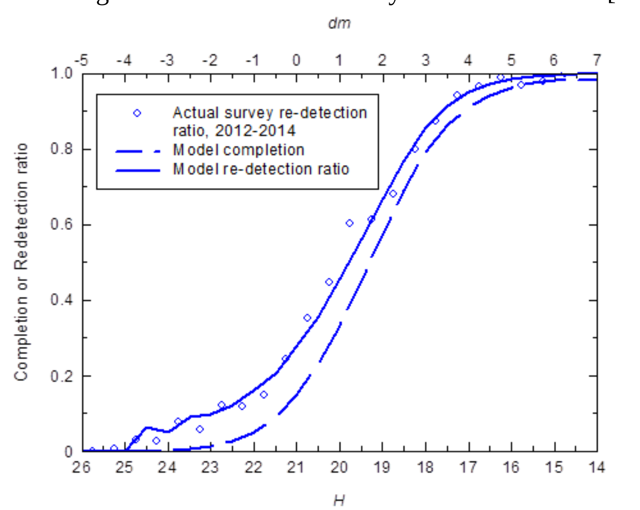

Figure 3 – Simulated completion and re-detection ratio.

Unlike a real survey where we can only count up the re-detection ratio in each size range (we choose half-magnitude intervals of H), in a computer simulation we can score both re-detection ratio and completion, because we know how many objects are in the complete population (100,000 objects in the current simulations). We run a simulation for an interval of time comparable to the current real surveys, most recently we have chosen 20 years, and also we have introduced a variable depth-of-survey (dm) over time to match more or less the rate of discoveries of the real survey over the 20 year period. Figure 3 is a plot of the results of that survey simulation, and also includes the re-detection ratio of the actual surveys fitted to match the computed re-detection ratio. The curves are the computer model completion of a simulated 20-year NEA survey and the re-detection ratio during the final 2 years of the survey simulation period, both versus the parameter $dm = V_{lim} - H$ (top scale). The open circle plots symbols are the re-detection ratios of the actual NEAs surveys for each half-

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magnitude interval of *H* (bottom scale). The two scales have been adjusted horizontally to achieve the best fit of the model re-detection curve to the actual survey data.

Once so "calibrated," the completion curve can be taken to represent completion versus *H* of the actual surveys. Obviously, the re-detection ratio is only well determined over a rather narrow range of *H*, or even *dm* in the 100,000 object simulation. At the large size range, most everything has been discovered and there are insufficient new discoveries to be statistically useful, and at the small end, almost no objects are re-detected, so again the re-detection ratio is poorly determined. But once "calibrated", the completion curve can be extended over a much larger range, to near 100% completion at the large end, down to arbitrarily small objects using the analytical extension, even below completion of 10^{-5}, where the survey simulation records not even one detection, let alone any re-detections.

Once the completion function, $C(H)$, has been determined, the differential population, $n(H)$, can be calculated simply as $n(H) = n_{disc}(H)/C(H)$, where $n_{disc}(H)$ is the number in the size bin of *H* that have been discovered. Figure 4 is the plot of the number discovered, $n_{disc}(H)$, as of August, 2014, and the estimated population, $n(H)$, derived using $C(H)$ from Figure 3.

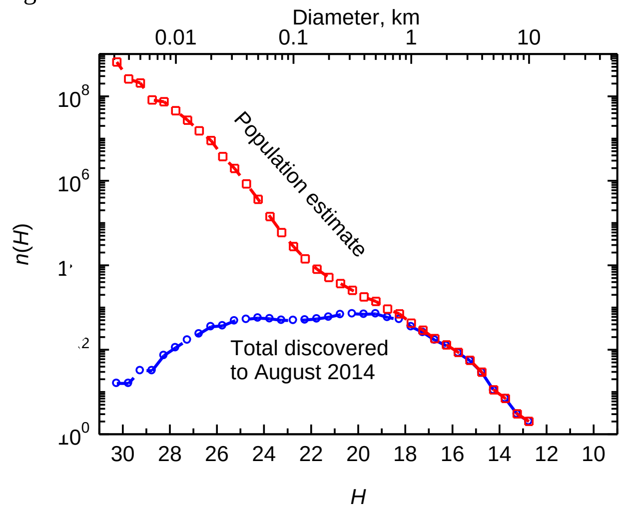

Figure 4. Differential population estimate based on discovered objects up to August, 2014.

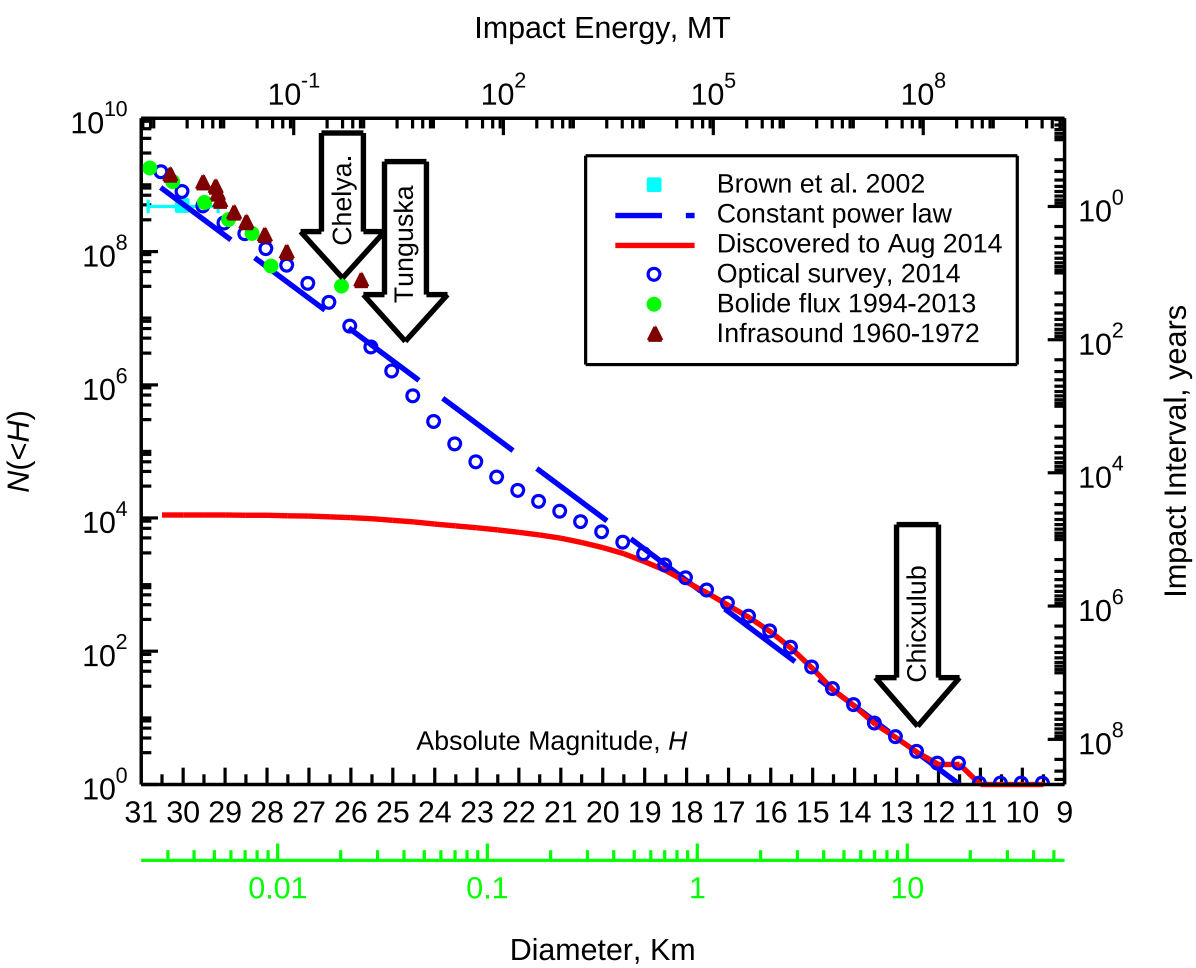

Figure 5 – Estimated cumulative population of NEAs.

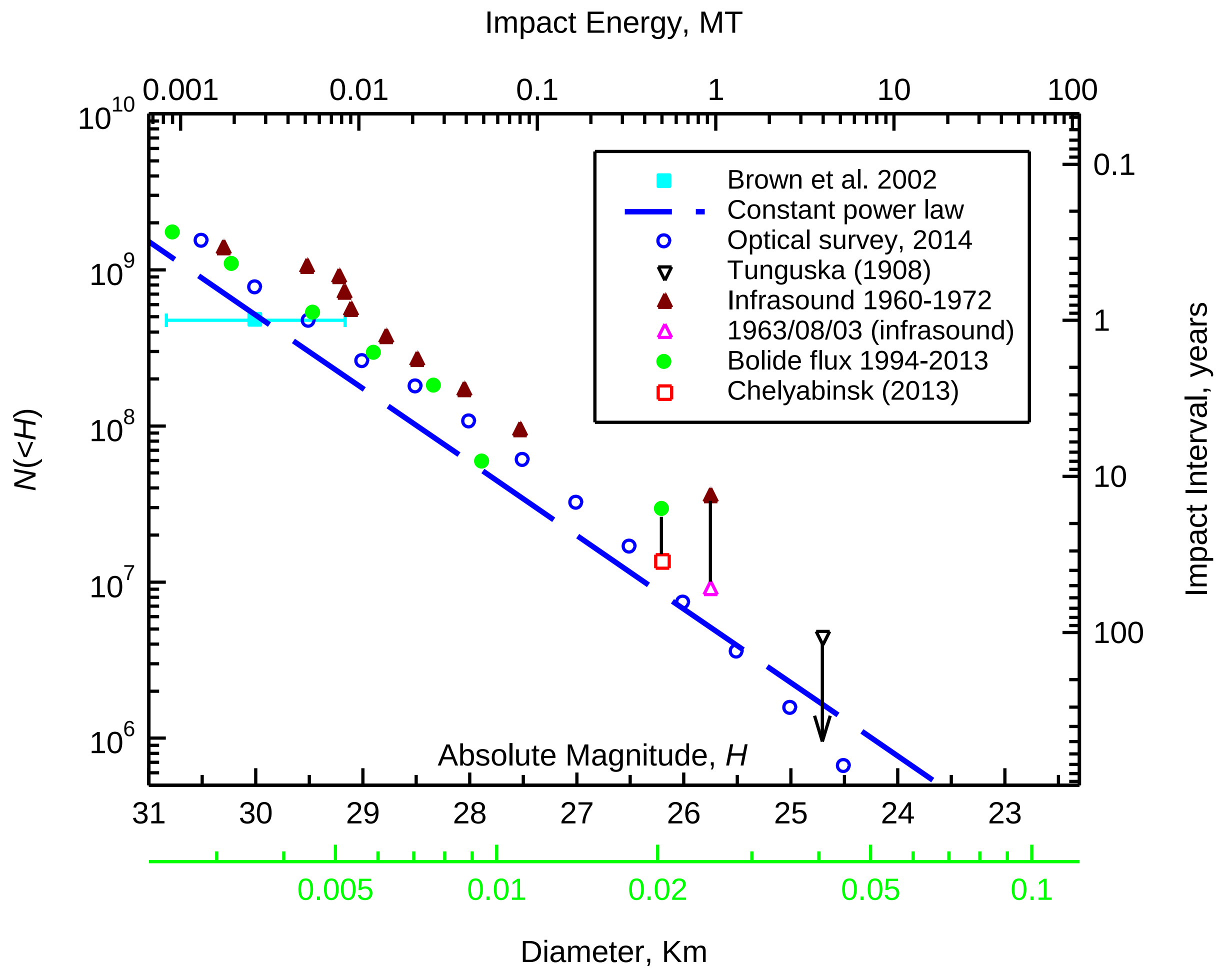

Figure 6 – Estimated cumulative population of small NEAs.

The final step is to derive the cumulative population, *N(<H)*, which is just the running sum of *n(H)* starting from the largest size (lowest *H*). Figure 5 is that plot, with some ancillary scales. The energy in megatons assumes RMS impact velocity of 19.45 km/sec and an impactor density of of 2.5 gm/cc. This gives a *D* = 1 km impactor a kinetic energy of to 59,000 megatons. *D* = 1 km is equated with *H* = 17.75, implying a mean albedo of 0.14. The impact interval is (474 million years)/*N(<H)*. Additional data was also added to provide estimated cumulative population of NEAs, with sizes of the Chicxulub impactor, Tunguska, and the recent Chelyabinsk bolide indicated. Also included are two estimates of bolide population taken from Figure 2, and a straight-line power law population model that was used for impact frequency estimation in the 2003 NASA report on NEA hazard and surveys [18].

Following the Chelyabinsk bolide event of February 15, 2013, Brown et al. [1] pointed out that the then-current estimate of population from optical surveys through 2012 [19] fell well below the populations estimated from bolides and infrasound signatures. This triggered a thorough re-evaluation of the re-detection models and algorithms in order to model the most recent, 2012-2014 redetection statistics from the surveys. The 2012 population estimate may have been somewhat of a statistical fluke, even using the old ten-year survey simulation model with the 2012-2014 redetection data yielded a higher population in the smaller size range. To more accurately model the real survey, we generated a 20-year simulation with variable depth of coverage as described above. The improved model resulted in a much better fit over the full magnitude range to the observed re-detection ratios, and resulted in a population estimate in even closer agreement with the bolide and infrasound data. The new population estimate puts the Chelyabinsk size as a 50-year event. The even larger event of 1963 August 3 (here called "Marion Island") still stands out as a modest anomaly, although there is some question of the accuracy of the energy or even if it was actually a bolide event [2]. Tunguska stands out even more—the current population makes it a five-hundred-year event—yet there is no reasonable doubt it was a cosmic airburst, and the energy is very likely within a factor of two of so of the 4 megatons. Any reasonable size-frequency distribution that is consistent with better-determined smaller and larger size ranges will leave Tunguska standing out as a statistical outlier.

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It is difficult to plot the two largest bolide events (the 2013 Chelyabinsk event and the 1963 Marion Island event), along with the 1908 Tunguska event, in a meaningful way because the sparse observations of these rare events lacks statistical significance. Marion Island and Chelyabinsk can be plotted in Fig. 2 because they were observed by well-defined surveys of known duration. They were the only events observed during their respective survey time, so they are plotted as if the survey duration is their recurrence interval. Tunguska was not observed as part of a defined survey, and is therefore not drawn as a data point.

Whereas this is a rigorously-defined method of plotting the data, we argue that it is not meaningful for rare events and leads to population overestimates. For events with mean recurrence intervals that are short relative to the observation duration, this is not a problem. There are likely to be many events observed and if the observation period is doubled then the number of events also doubles.

Chelyabinsk was a half-megaton event observed during a 20-year period, but it is very likely that a similar event, anywhere in the world, would have been detected even many years prior to that. Likewise, the Marion Island event was the largest in the 13-year infrasound observational period, but would have certainly been observed by US government sensors in past 20 years as well as previous years.

For purposes of this analysis we employ a heuristic based on the argument that, in the last 106 years, there are 3 events have been recorded that are greater than ~0.5 megatons (defined by Chelyabinsk), two that are greater than ~0.9 megatons (defined by Marion Island) and one that is ~4 megatons (defined by Tunguska). Since our curves are cumulative, we must include all larger events within the relevant period when plotting the data. Therefore we plot Chelyabinsk at 35 years, Marion Island at 53 years, and Tunguska at 106 years in the of Figure 6.

We admittedly chose our "frame" after the fact, in order to contain Tunguska in our 108-year window. However, it is almost certainly true that 108 years is an *over* estimate of the observational window. The Tunguska event took place over a remote part of the planet, but was only recognized because of eyewitness observations and the long-term damage recorded in the fallen forest that were not explored until nearly 20 years after the event. If it had happened over a remote ocean, desert, or polar region with no witnesses or long-term record, we would probably not know about it. Nevertheless, it is very likely to be an outlier. It is the only point on our graph that is based on a single event. Significantly, if it had not happened, we would not be required to plot Marion or Chelyabinsk much differently.

It is also worth noting that Chelyabinsk is the only event of these three with a well-defined yield. The best estimate of Marion Island is 0.93 megatons, but it could have been as small as 0.3, in which case it would not be an outlier. Likewise, there are many estimates of Tunguska's yield. We used the midpoint of the estimate by Boslough and Crawford [4] that it was 3-5 megatons, but that is the lowest published estimate and is based primarily on the comparison of computational simulations of dynamic pressure at the surface in comparison to the pattern of tree-fall. It is still possible, with refined simulations, that the yield estimate could change again. However, it is difficult at this point to see, with any realistic assumptions, how Tunguska could be anything but a statistical fluke. It is accordingly drawn in the lower panel of Figure 5 as an upper bound.

6. RISK ASSESSMENT

Boslough [20] used principles of probabilistic risk assessment to determine the relative threat from asteroids under various scenarios with different assumptions. The conclusion of that paper was that the residual statistical risk after the current survey (in which 90% of objects greater than 140 meters in diameter are to be catalogued) will be dominated by airbursts. If the current survey is successful, most of the NEOs large enough to form craters will be known. By contrast most of the dangerous airburst-class (tens of meters in diameter) will remain undiscovered. That assessment took into account the fact that the destructive power of airbursts is greater than was previously recognized. For the present analysis, we also include our estimate of the greater frequency of impacts in that size range.

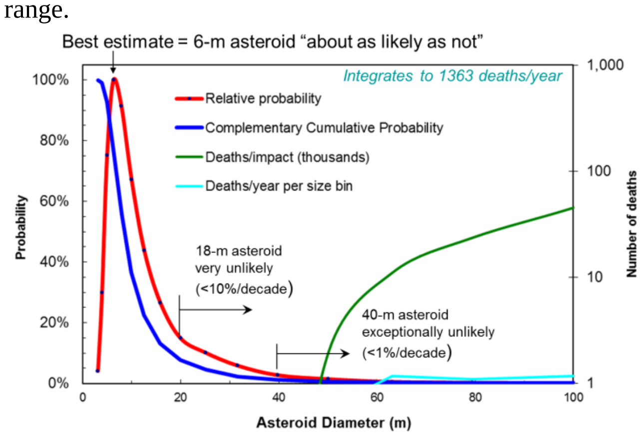

Figure 7—Pre-survey probability density from 2011 population estimate.

The red curve in Figure 7 is a probability density function (PDF) calculated by Boslough [20] and based on the 2011 version of the population curve shown in Fig. 5. This PDF is a graph of the probability that the biggest event in the next decade would be an event of a given size, based on the assumption that the remaining undiscovered NEOs (as of 2011) are in completely random orbits. The cumulative probability density function is shown in blue. The risk assessment is based on an estimate of how many people would die, on average, from an event of a given size (the green "kill curve"). By weighting this measure of impact consequences by probability of impact, the total number of impact deaths per year can be derived (area under cyan curve). Such an estimate is highly uncertain and is not very

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trustworthy in absolute terms. Nevertheless, when comparing various survey options and threat reduction alternatives, it is useful to compare relative risk. For example, the fact that nearly 90% of the largest and most dangerous asteroids have been discovered—and none are on a collision course for at least a century—means that the assessed risk has been reduced by about an order of magnitude, even if the average absolute number of deaths from a given event can never be verified. For the risk assessment illustrated by Figure 7, the kill curve is based on the old assumption that airburst act as point-source explosions, and uses estimates based on nuclear weapons effects [21]. As such, it underestimates fatalities for asteroids in the tens-of-meters size range.

For purposes of discussion and intercomparison, we have adopted the likelihood scale used by the Intergovernmental Panel on Climate Change. This reinforces the fact that impact risk is dominated by low-probability, high-consequence events and draws on the analogy with global warming that larger uncertainty in the future is associated with greater assessed risk. The most effective means of reducing this uncertainty (and the resulting assessed risk) is through continued survey efforts. Every asteroid that is discovered that is not on a collision course for the next century reduces the probabilistic risk during that time period. However, there is always a chance that an asteroid will be discovered that is in an orbit that will lead to an impact. In such a case, mitigation of the risk would require deflection or disruption in the case of a large asteroid, or by civil defense measures (evacuation and/or shelter-in-place) in the event of a small asteroid.

Using optical survey-derived population data, Boslough [20] estimated that a 6-meter asteroid was about as likely as not to be the largest object to collide with the Earth in the next decade. Since this would almost certainly be a harmless event, it does not contribute to the bottom line of the assessment (a probability-weighted consequence of zero adds nothing to the risk). The only contribution to the risk is the low-probability tail of larger asteroids on the right-hand side of the PDF.

When the new population (Figure 5) is used, it yields a PDF that peaks at 12.5 meters (Figure 8). Even though the size of the most likely largest impact of the next decade is greater, it is still nearly certain to be a harmless event, and still does not add to the risk. However, the portion of the tail of the curve corresponding to dangerous airburst events has significantly higher probability, by a factor of about 2 for a Tunguska-class event. Therefore the probability-weighted contribution to the overall risk from objects of this size would increase by a factor of 2 for the same kill curve.

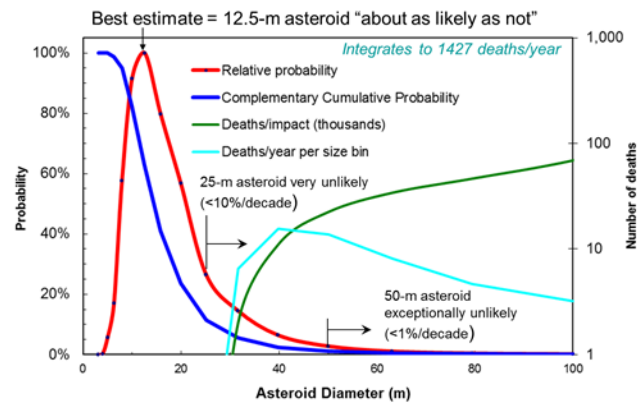

Figure 8—Pre-survey probability density from present population estimate.

For the present analysis, we also shifted the kill curve to smaller asteroids to account for the increased destructive paper of directed airbursts. The net effect of both the increase in our estimate of population and damage potential of airbursts only increases the pre-survey assessed risk by about 5%, from 1363 to 1427 fatalities per year as the long-run average (where extra significant figures do not imply precision, but are preserved for intercomparison). The same graph is shown at an expanded scale in Figure 9, revealing that most of the area under the pre-survey probability-weighted kill curve is above the global catastrophe threshold, estimated here to be for objects greater than 1.5 km in diameter.

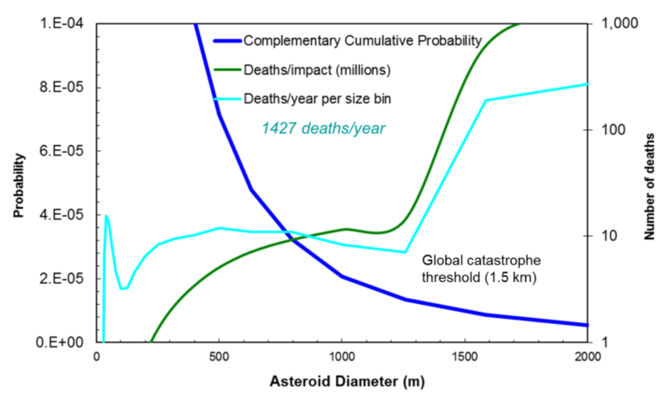

Figure 9—Pre-survey probability density from present population estimate.

The current survey is nearly 90% complete for objects greater than 1 km, which means the contribution from global catastrophes has been reduced by about an order of magnitude. Most of the objects in the catalogue are actually smaller than 1 km, but as size goes down the survey is progressively less complete. Figure 10 shows the probability and risk curves for the current survey completion, as of August, 2014.

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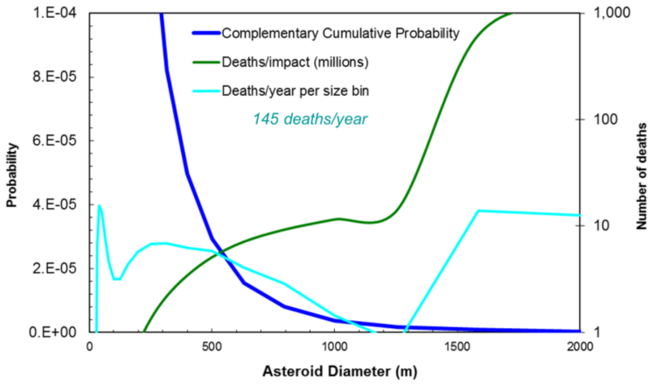

Figure 10—Current probability density from present population estimate of undiscovered objects.

The NASA appropriations bill of 2005 has mandated that the next survey should discover and track all NEOs greater than 140 meters in diameter. Using the same kill curve and current population, corrected for the expected discovery rates at various sizes, yields Figure 11 and an average death rate of 36/year. This compares to 5/year using the 2011 population and point source airburst damage estimate, and to17/year using the 2011 population and directed source airburst damage estimate [20]. After survey completion (if nothing is discovered on a collision course) the statistical risk will be dominated by airburst-sized NEOs and the risk reduction strategy will likely shift to short-warning surveys and civil defense.

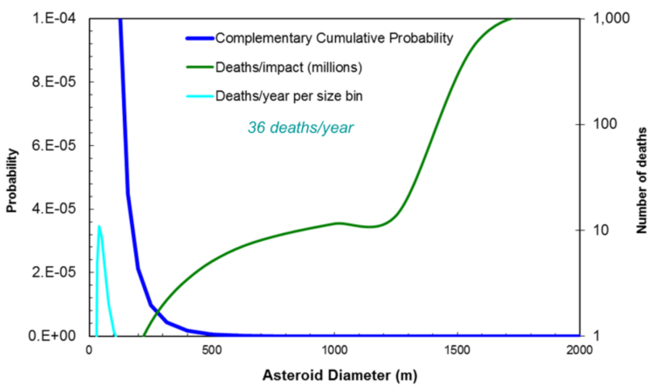

Figure 11—Future probability density from present population estimate after completion of current survey.

The present analysis reinforces the conclusions of Boslough [20], that it is virtually certain (using this term as defined by the climate change community) that the next damaging or fatal impact event will be an airburst.

7. Uncertainty Reduction Strategies

The uncertainty in NEO population is greatest for Chelyabinsk and Tunguska-scale objects, which are tens of meters in diameter, because they are too small and numerous for good optical counting, but still too rare for statistically-significant bolide counting. After the current survey is complete, they will dominate the risk. We argue that future surveys should address this uncertainty and reduce the associated risk.

It has long been a working assumption of the planetary defense community that the appropriate risk metric is the long-term "actuarial" estimate measured in fatalities per year, and that the primary goal should be aimed at reducing this risk. However, it could be argued that another goal of planetary defense would be to maximize the probability of preventing *any* fatalities over some prescribed time period. From a political and social perspective, one decade would be a realistic time scale. Short-warning surveys and a civil defense (evacuation and shelter-in-place) would provide the best means. Statistically, the probability of an airburst disaster in the next decade is about 1%, whereas the probability that surveys will discover an object on a collision course that is greater than 140 meters in diameter in the next decade is only about 0.1%. To save lives on a socially-relevant timescale, inclusion of small, short-warning impactors should be an additional survey goal.

The NRC report *Defending Planet Earth* [22] stated in its findings that "It is highly probable that the next destructive NEO event will be an airburst from a <50-meter object, not a crater-forming impact." This finding led to the following recommendation:

> *"Because recent studies of meteor airbursts have suggested that near-Earth objects as small as 30 to 50 meters in diameter could be highly destructive, surveys should attempt to detect as many 30- to 50-meter objects as possible. This search for smaller-diameter objects should not be allowed to interfere with the survey for objects 140-meters in diameter or greater."*

This reinforces the notion that, in addition to pursuing the current survey goal, it would be appropriate to augment capability to provide early warning (days or weeks) of objects on their "death plunge" into Earth's atmosphere rather than only discovering large objects with sufficient time (many years or decades) to launch a deflection mission. Early warning of an imminent impact would give authorities time to issue evacuation or take-cover instructions in circumstances for which there would be no time the prevent the impact.

An early-warning system, such as the ATLAS project [23] which has plans to come online in 2015, would have many additional benefits optimized to discover imminent impactors. First, it would provide an additional means to improve the population estimates of airburst-scale objects (tens of meters in diameter) allowing NEOs making close passes to be counted in statistically significant numbers. For example, there are about 25 times as many objects of a given size that pass within the distance of geosynchronous orbit than collide with the earth, and 2000 times as many pass within a lunar distance (accounting for gravitational focusing). An asteroid the size of the Cheylabinsk impactor

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(~20 m) could potentially be observed within geosynchronous orbit every two years and within lunar orbit nearly once a week. A Tunguska-sized asteroid (~40 m) passes within a lunar distance several times a year. A survey optimized to discover and count these objects would rapidly reduce the uncertainty in their populations.

Second, as pointed out by Boslough [20], short warning survey would also discover non-threatening imminent impactors like 2008 TC3 and 2014 AA. The ability to observe asteroids in space and predict the time and place of their atmospheric entry would provide opportunities for research, meteorite recovery, and even for adventure tourism. This suggests a financial incentive for private enterprise to support short-warning surveys. Advance warning surveys would potentially allow outfitters to operate tourist-funded expeditions that could also carry scientific instruments and devices such as high-resolution stereoscopic video cameras, radiometers, spectrometers, seismometers, barographs, radar, infrared trackers, infrasound, and dust collectors. High-fidelity observational data collected from airbursts would provide information on the dynamic properties of asteroids that would be useful for impulsive deflection design, as well as for better understanding of the physics of airbursts for improved risk assessment and to further our knowledge of meteoritics by linking meteorite types to astronomical asteroid observations and orbits.

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BIOGRAPHY

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