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Airburst warning and response

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ABSTRACT

It is virtually certain (probability > 99%) that the next destructive NEO event will be an airburst. Planetary defense is usually assumed to have the primary goal of maximizing the number of lives saved, but it can be argued that more emphasis should be placed on maximizing the probability of saving lives. For the latter goal, it is far more effective to create an early warning and civil defense plan than a mitigation plan that involves deflecting a large NEO. Because early warning and civil defense will almost certainly be needed long before the first deflection is ever required, the credibility of the planetary defense community and its recommendations will be put to its first serious test by an airburst. Successful response to an airburst event will make it much more likely that recommendations for mitigation by deflection will be accepted by decision makers and the public. Focusing more attention on the second goal will, as a side effect, benefit the primary goal.

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1. Introduction

Airbursts are local events and unlikely to create international conflict if they have been predicted in advance, so early warning can generate goodwill and trust leading to cooperation for large NEO mitigation. If airburst recommendations save lives, those lives are very likely to be citizens of nations other than those responsible for the warnings. Conversely, if we ignore the airburst threat and there is an event with casualties, future mitigation recommendations are much more likely to be ignored. Moreover, if an imminent Tunguska-class impactor were observed but not recognized because of the insufficient observational resources or inadequate period between observations, the resulting criticisms and conspiracy theories could irreparably damage our credibility. Airburst "mitigation" by early warning and civil defense should be taken more seriously for that reason, if no other.

A reasonable approach would be to use computational models to generate "lookup tables," reduced-order models, or scaling laws to generate maps of damage on the surface and convolve with uncertainty footprints based on the astronomical observations and orbital dynamics projections. This method would be used only to issue warnings associated with airbursts that are virtually certain to happen ("8" on the Torino Scale or undefined if smaller than 20 m). Such an alert would provide the time, coordinates, and a scale number indicating maximum possible damage at the epicenter. Such a system could be implemented to provide maps showing contours based on the convolution. The system would need to be very fast and automatic, and therefore based on the simulation output that is linked to orbital output. The threat maps would be analogous to the National Hurricane Center's operational hurricane maps, which explicitly include uncertainty. Local authorities would then issue instructions based on the alert. Civil defense would be the responsibility of the target nation (just as foreign nations use the NHC alerts without requiring further US help).

The warning could also contain maps showing locations from which one could safely view the event, and

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where it would appear in the sky – even if over the horizon. This would create the opportunity to obtain images, video, and other useful data from smaller events, helping validate models and improving our understanding of the airburst process. It is highly likely that the first events with such warnings would not be threats at all, but opportunities for science and amateur astronomy. The optimal and most likely outcome would be a series of harmless 2008-TC3-class events, a few of which would be observable and documented. This would lead to positive media coverage, increased awareness of the threat, more confidence and respect for the predictive capabilities of our community, better response to subsequent serious civil defense warnings, more support for planetary defense activities, and ultimately more lives saved.

2. Low altitude airbursts

When a NEO deposits most of its kinetic energy in the lower stratosphere or troposphere, the resulting fireball continues to expand and descend toward the surface, driving a bow shock ahead of it that is reinforced by the explosion [1]. This directed nature of the burst enhances its destructive power relative to a point-source explosion of the same yield at the same altitude (which had been a tacit simplifying assumption for previous risk assessments based on the nuclear weapons effects data). Small crater-forming impacts are also accompanied by such airbursts. According to the latest NEO size distribution plot of Harris (personal communication, Fig. 1), a Tunguska-class airburst (about 4 Mt) has a mean recurrence interval of about 1000 years. Earlier estimates of the Tunguska yield were in the 10–20 Mt range, which would roughly correspond to a 1000-year event if the size distribution were defined by a constant power law. The recognition of a significant deficit in the number of NEOs in the airburst size range roughly compensates for the fact that they are more destructive than previously thought. Tunguska can still be considered to be a millennial event, even though its size has been downgraded.

For Tunguka-class events, the descending fireball stagnates before it reaches the surface, and then rises as a buoyant "mushroom cloud." The damage mechanism from Tunguska type airbursts is dominated by mechanical effects (high wind associated with the blast wave) and thermal radiation. More massive fireballs generated by larger NEOs can descend all the way to the surface and expand radially, leading to incineration of organic material and melting of alluvium and surface rocks. This is consistent with observations of Libyan Desert Glass from an event in the western desert of Egypt 29 million years ago. These can be called "Type 1" and "Type 2" airbursts, respectively (Fig. 2).

The basis for the "downgrade" in the Tunguska yield estimate is shown in Fig. 3. A set of computational experiments was performed, under various assumptions considered to be realistic for the event, using a 15-Mt impactor. In all cases, the fireball descended to the surface and the model event was consistent with a Type 2 airburst. The series of simulations for smaller NEOs was more in accord with the observations, including the shape of the treefall pattern (Fig. 3, center panel from Longo [2]), presence of an epicenter where there was no lateral component of the blast wave, lack of melt, and absence of evidence that organic material was immersed in the fireball and incinerated.

3. Relative risk assessment

Principles of probabilistic risk assessment can be applied to determine the relative threat from asteroids under various scenarios with different assumptions. Fig. 4 is an attempt to re-plot the information of Fig. 1 in a way that is more instructive for answering the questions: (1) What is the probability that the biggest event of a given decade will be an event of a given size? (2) How many people would die, on average, from an event of that size? (3) What is the total number of deaths per year from asteroids? The curves are labeled using the likelihood scale used by the Intergovernmental Panel on Climate Change, for purposes of comparison, to reinforce the fact that risk

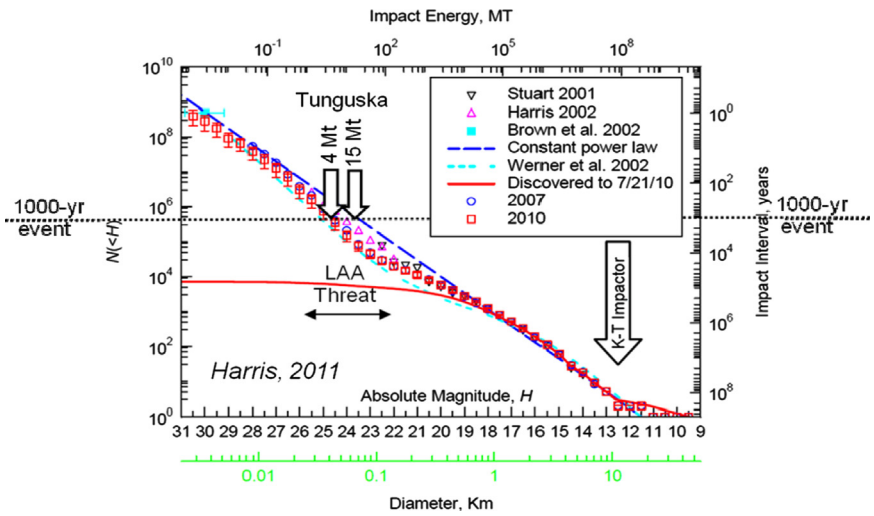

Fig. 1. Size distribution of Near-Earth objects (Harris, personal communication, 2011).

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is dominated by low-probability, high-consequence impact events. Analogous to the climate change threat, larger uncertainty in the future is associated with greater assessed threat. For the NEO problem, the uncertainty and assessed threat are reduced by survey efforts.

The best estimate for the largest object to collide with the Earth in the next decade is 6 m, almost certainly a harmless event. The probability density function (red) answers the first question, but a somewhat more intuitive curve is the complimentary cumulative probability (blue), which indicates the probability that the largest impact of the decade will be a given size or larger. The green "kill curve" is an estimate of the number of fatalities, on average, from an impact of a given size. The cyan curve is the product of the probability of an impact of a given size and consequences. The integral of this curve is the expected number of fatalities per year, for which extra significant figures are retained for intercomparison purposes (they are not significant in an absolute sense because of high uncertainty).

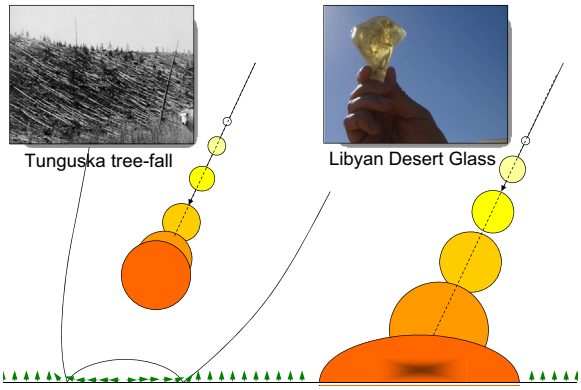

Fig. 2. Left: Type 1 airburst (Tunguska type). Right: Type 2 airburst (Libyan Desert Type).

The three panels in Fig. 5 show the same data on a different scale that includes asteroids greater than 1.5 km having the potential to exceed a global catastrophe threshold. The top panel is the pre-survey "original" risk assessment using data for current estimate of the population. The center panel shows current assessment (as of 2010), for which the tracked and catalogued objects have negligible probability of impact. The lower panel is a projection of what the statistical risk assessment will be for undiscovered objects after completion of the current survey, in which 90% of objects greater than 140 m are mandated to be discovered, which will result in the discovery of many smaller objects as well. These plots are based on estimates provided by Alan Harris (private communication, 2011). The lower end of the kill curve is based on simplified "point source" airburst model that underestimates the damage.

The same data are shown in Fig. 6, but with a kill curve that is increased for airbursts to include the damage enhancement due to the directed nature of airbursts. After the current survey is complete, the statistical risk from NEOs will be dominated by airbursts. Moreover, it is virtually certain (as this term is used by the climate change community) that the next damaging or fatal impact event will be an airburst. It can be argued that an objective measure of planetary defense would be to maximize the probability of preventing fatalities over some time period

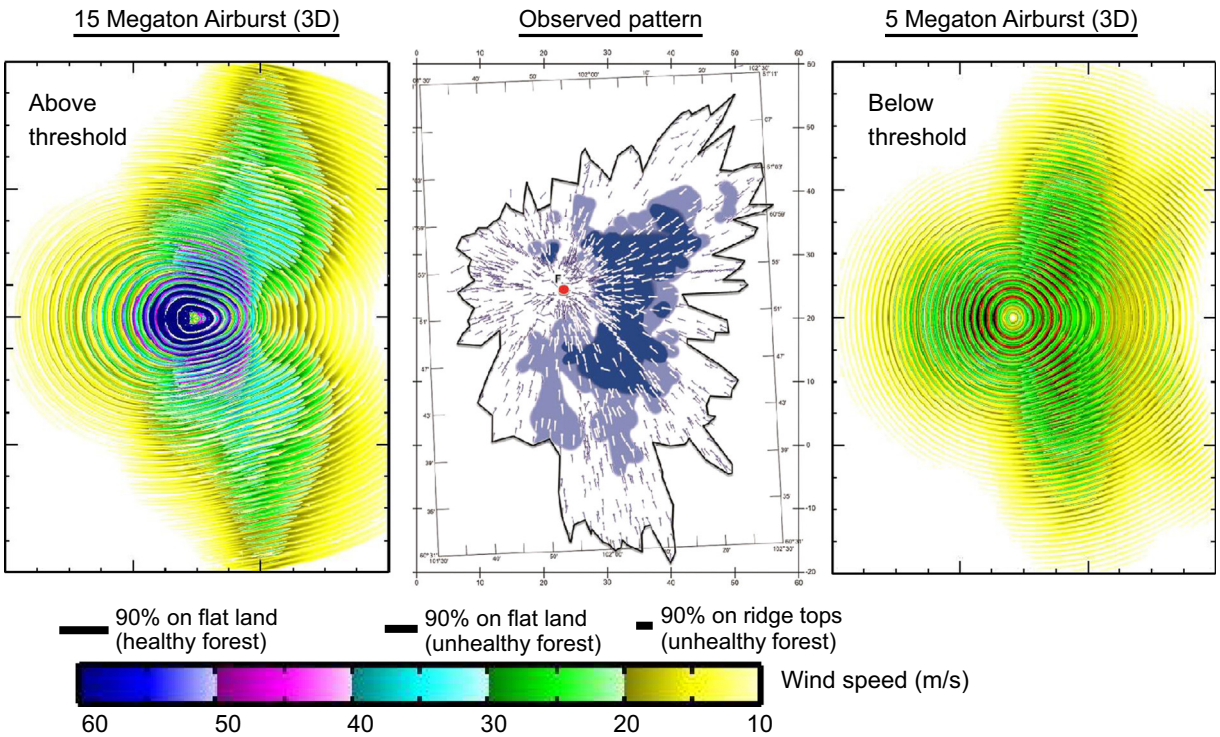

Fig. 3. 5-Mt burst (right) provides better match to Tunguska data (center) than 15-Mt burst (left).

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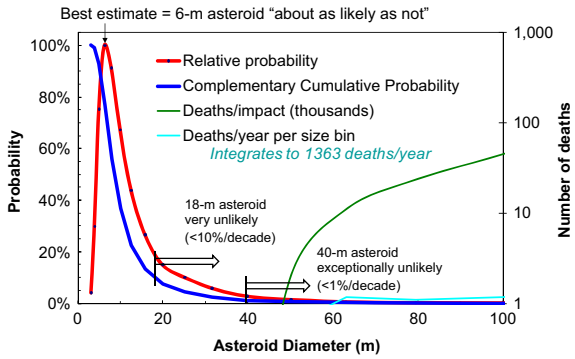

Fig. 4. Size distribution curve can be transformed to probability density function (red) for risk assessment. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

(a decade being realistic from a political and social perspective) rather than minimizing the number fatalities in the long run. The most effective means to accomplish this would be to focus on surveys and a civil defense (evacuation and shelter-in-place) as a mitigation component. A statistical argument can be made that the probability of an airburst disaster in the next decade is about 1%, but the probability that an object on a collision course that is greater than 140 m in diameter will be discovered in the next decade is only about 0.1%. The planetary defense community is much more likely to save lives on a socially relevant timescale by including small, short-warning impactors as a survey goal.

4. Short-warning objects

A finding of the 2010 NRC report *Defending Planet Earth* [3] was "It is highly probable that the next destructive NEO event will be an airburst from a <50-meter object, not a crater-forming impact." The associated recommendation was

> *"Because recent studies of meteor airbursts have suggested that near-Earth objects as small as 30 to 50 m 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."*

Based on the present work, it is reasonable to transition surveys toward short-warning objects on their "death plunge" into Earth's atmosphere. If an object is found within a few days of impact, lives could be saved through civil defense.

As side benefit, such a survey objective would inevitably discover many more non-threatening short-warning asteroids similar to 2008 TC3 that would provide opportunities for research, meteorite recovery, and even the potential for a novel form of "space tourism." Objects discovered far enough in advance could give outfitters an opportunity to operate adventure tourist-funded expeditions with piggy-backed scientific data collection. High-fidelity observational

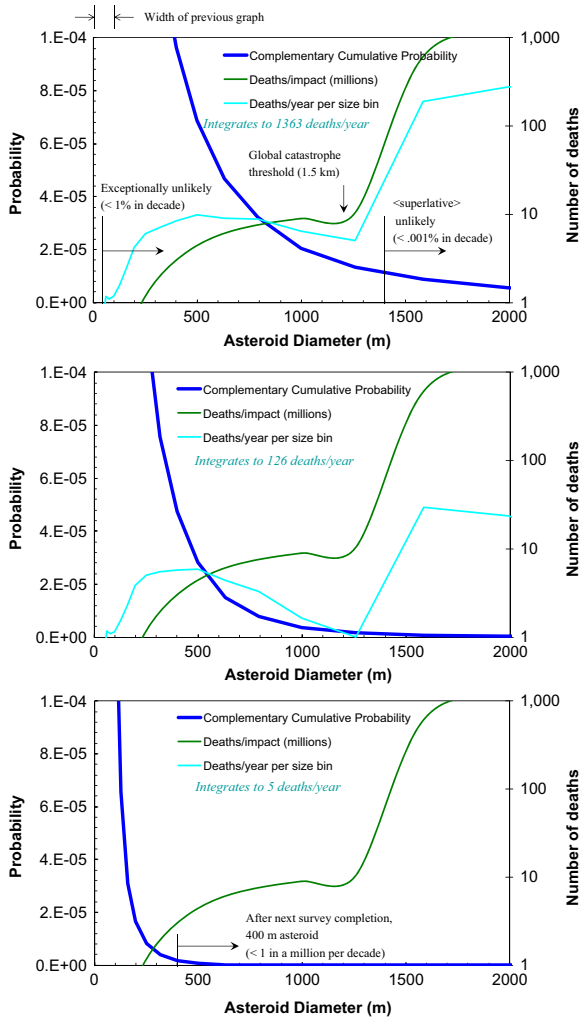

Fig. 5. Point-source airburst risk assessments. Top: pre-survey; center: current catalogue; bottom: post-survey.

data from high-altitude airbursts similar to the 2008 TC3 event could include high-resolution stereoscopic video, radiography, spectroscopy, seismology, barograph and infrasound measurements, and dust collection. Such a campaign would yield a panoply of 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.

5. Airburst response

One option for responding to short-warning airburst objects would be analogous to the National Hurricane Center, which provides regularly updated information to authorities who are responsible for evacuation or shelter orders. Like hurricanes, there would be many uncertainties associated with short-warning objects, but the nature of the uncertainties would be very different. The trajectory and impact location uncertainty would diminish very

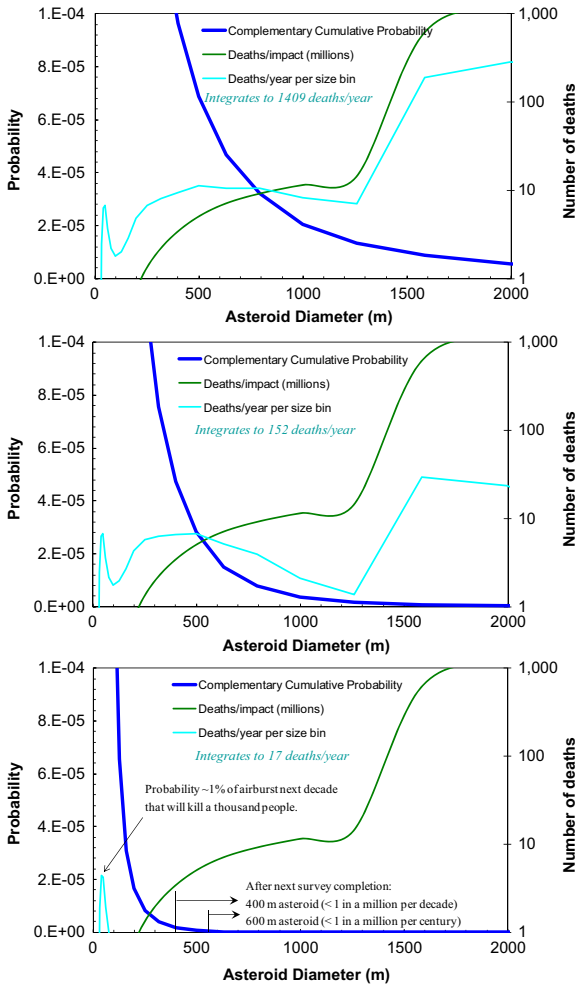

Fig. 6. Directed-source airburst risk assessments. Top: pre-survey; center: current catalogue; bottom: post-survey.

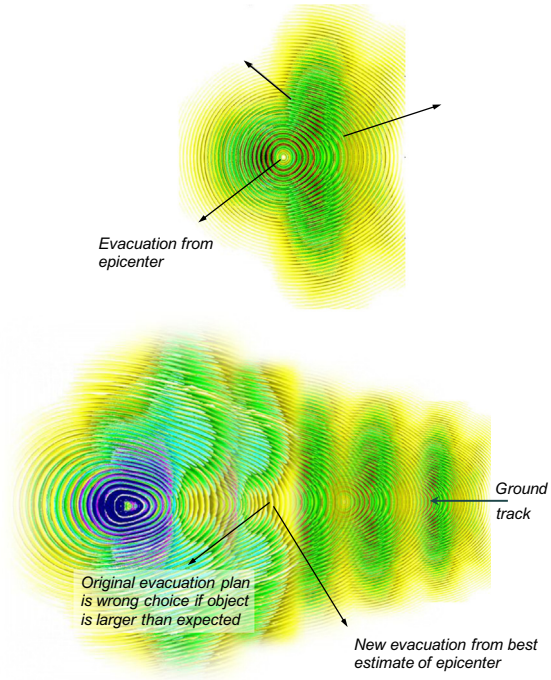

Fig. 7. Notional evacuation plans. Top: ideal case with no uncertainty; bottom: size uncertainty case.

quickly as the NEO is tracked, but the mass, strength, density, and other material properties that control burst altitude and destructive potential would remain uncertain and any civil defense measure would need to take this uncertainty into account.

Fig. 7 illustrates potential evacuation issues associated with uncertainty. The upper panel illustrates a hypothetical situation in which perfect knowledge is available, with a calculated damage map and the most efficient evacuation routes. In the lower panel size uncertainty is included and all the potential damage maps are shown together. By including uncertainty, potentially inappropriate evacuation instructions can be eliminated.

6. Proposed airburst warning scale

Finally, in keeping with previous efforts to develop simple and easy-to-understand scales to describe the NEO threat and communicate with decision makers and the public, an airburst scale based on the damage potential would be useful. A first attempt at defining a "Bucharest Airburst Scale" is provided below.

1. High-altitude airburst with no possible damage. Bright light in sky followed by sonic boom. No recommended action.
2. High-altitude airburst with minor damage. Possible hazard from broken windows and dust from sonic boom shaking of structures. Recommended action: avoid standing near windows and anticipate respiratory hazard from dust in buildings. 2008 TC3 would have probably been this class.
3. High-altitude airburst with major damage. Possible hazard from many broken windows and unsecured structures like trailers blowing down due to blast wave. Recommended action: take cover in basements or strong structures. Consider leaving area.
4. Low-altitude airburst with heavy blast damage: Tunguska-class event. Structures within blast zone destroyed. Recommended action: evacuate blast zone and take cover outside that zone.
5. Low-altitude airburst with heavy thermal damage: Libyan Desert Glass class event. Fireball zone surrounded by blast zone. Everything within fireball zone incinerated, everything within blast zone blown down. Recommended action: evacuate fireball and blast zones, and take cover outside those zones.

7. Conclusions

It is overwhelmingly likely that no large asteroid will be discovered on a collision course in the current survey, and that the survey will conclude by successfully reducing the statistical risk from undiscovered NEOs to a near-negligible

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level. The residual statistical risk will be dominated by airbursts for two reasons: (1) the vast majority of potential crater-forming objects will have been discovered, whereas the vast majority of smaller objects capable of producing a dangerous airburst will remain undiscovered, and (2) the destructive power of airbursts is greater than was previously recognized, because the energy is directed and not isotropic. As the current survey progresses, it will become increasingly more important, in a relative sense, to provide resources to discover small short-warning objects and develop a civil-defense-based mitigation plan.

Acknowledgments

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