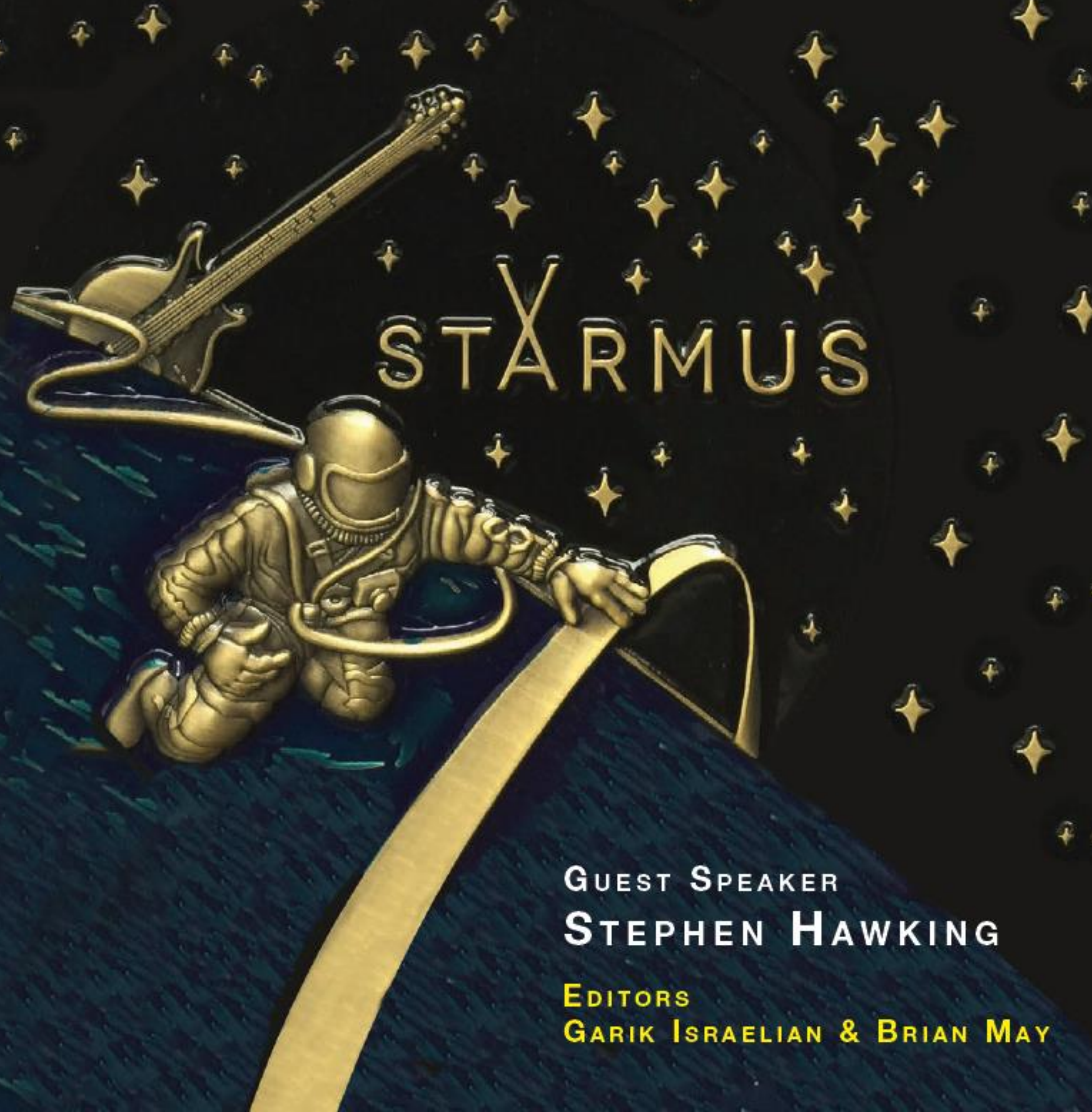
ORIGINS OF THE COSMOS



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Defending the Only Home That We Have Ever Known

Mark Boslough

> *On a sleepy endless ocean when the world lay in a dream*
> *There was rhythm in the splash and roll, but not a voice to sing*
> *So the moon shone on the breakers and the morning warmed the waves*
> *Till a single cell did jump and hum for joy as though to say*
> *This is my home*
>
> Dave Carter, "Gentle Arms of Eden"

Starmus II brought together speakers who expressed views spanning the complete range of opinion on how the universe came into being, how our home planet formed, how life started, and finally, how we ourselves evolved. On one side physicist Stephen Hawking, evolutionary biologist Richard Dawkins, paleoanthropologist Katerina Harvati, and several Nobelists applied the naked laws of physics and nature to lead the way in forging our evidence-based scientific understanding. In the opposite corner, Apollo astronaut hero Charlie Duke and some delegates embraced a faith-based belief in creation by an all-powerful God. For purposes of this essay, I want to set aside these differences to focus on one point of agreement: we all love our home planet and are in awe of the force that created it, whether we credit it to an almighty God or the marvelous laws of nature.

Love and awe — both religious and naturalistic —have inspired scientists, explorers, poets, and musicians throughout history. Starmus is a gathering of such people, and I write in this spirit:

> *This is my home, this is my only home*
> *This is the only sacred ground that I have ever known*

Everyone alive today has been blessed with a fruitful and abundant planet that seems customized to support us. But it has not always been so. The dinosaurs, at some level, may have felt equally secure on the planet that had nurtured their own existence without interruption for many millions of years. If they ever looked at the sky in wonder they might have seen points of light — the stars. If they had the capacity to observe and think, they would have noticed that some of those points wandered through the heavens relative to the others. In the final centuries or millennia of their existence, they might have noted one particular point that occasionally became very bright as it passed near Earth in an intersecting orbit.

Then they had a very bad day. Without warning, Earth was no longer hospitable after the point grew to a monstrous stone and plowed into a shallow sea near North America, releasing its unfathomable kinetic energy in the form of heat and pressure in an explosion at would dwarf a global thermonuclear war. Debris rained down over the entire planet, turning the atmosphere into a giant convection oven and filling it with hot debris condensed from asteroid and rock vapor. A firestorm raged and then darkness, cold, and deprivation descended on the beasts. They did not survive.

Surely the dinosaurs loved their home as much as we do, at least in their own lizardesque way. If they'd had the science and technology that we do, could they have defended it? And if they'd had the means would they have had the will? Or would they have squabbled over politics of who pays the costs and who gets the benefits and how to distribute risk among the various species?

The rules of planetary motion were exactly the same 66 million years ago as they are now. Even before Newton worked out the classical physics of gravity that governs orbital mechanics, Johannes Kepler was able to predict the movement of those wandering bodies. If the dinos had their equivalent — say, *VelociKepler* — could they have known of the impending catastrophe? If they had a *SaurIsaacNewton*, would they have figured out that the asteroid could be deflected by generating a force? If they had their own *VonBraunasaurus*, could they have developed the rocket technology to intercept it? And could they have generated an explosion to push on it with help from technology conceived by a *TriceritOppenheimer*?

Fortunately, we humans don't have to worry about being wiped out by a 10-km-diameter "extinction-class" asteroid. We have been surveying the heavens for Earth-crossing asteroids for two decades now. If such an object existed on a collision course, we would have discovered it already. When it comes to smaller objects that still have the capacity to cause a major climate change and ecological collapse, killing billions of people and bringing down civilization, there are still some out there. Many people would agree that any risk of global catastrophe — no matter how small — is unacceptable.

Astronomical surveys are the first line of defense. We can't protect our home from something we don't know about. If the searches were to turn up an asteroid on a collision course, then planetary defense would require the technology to intercept it and prevent it from impacting. This could be done by changing its trajectory — by changing its speed just enough so that it misses Earth.

In principle, we already have the technologies: interplanetary rockets and nuclear explosives. In practice, these tools have never been used together in deep space and we have very limited experience with intercepting asteroids. If we were lucky, we might discover the offending asteroid far enough in advance to have one chance. Such a mission would require many years or even decades to successfully pull off, so it is urgent business to rapidly discover as many asteroids as possible.

Recognizing this, Starmus II contributors Grigory Richters and Brian May, along with astronomer Martin Rees, created the Asteroid Day declaration which has been signed by 200 scientists, astronauts, luminaries, and scholars. It calls for the following action:

1. Employ available technology to detect and track Near-Earth Asteroids that threaten human populations via governments and private and philanthropic organisations.
2. A rapid hundred-fold acceleration of the discovery and tracking of Near-Earth Asteroids to 100,000 per year within the next ten years.
3. Global adoption of Asteroid Day, heightening awareness of the asteroid hazard and our efforts to prevent impacts, on June 30, 2015.

I am pleased to have been asked to lead the Asteroid Day Expert Panel (ADXP), which was formed to ensure that Asteroid Day's activities and statements are scientifically accurate.Increasing the rate of discovery by 100 times is no small task and I was initially skeptical that it was even possible. It would require investment in at least one space-based infrared telescope as well as a massive expansion of Earth-based optical telescopes, costing hundreds of millions of dollars.

The justification for spending resources on planetary defense comes from probabilistic risk assessment, a tool that was developed to quantify and compare risk associated with high-consequence failures of engineered systems like airplanes, spacecraft, nuclear power plants, and weapons. It is essentially a method of cost/benefit analysis that includes uncertainty, allowing us to determine the benefit of lowering a risk compared to the cost of doing so. It helped get us get our astronauts to the Moon and back.

The method begins to break down when it comes to preventing highly improbable global catastrophes that could lead to human extinction. What is the value of the planet, of civilization, or of the human race? One could argue that the value, at least to us, is infinity. If the probability of losing these things is infinitesimal but nonzero, shouldn't the justifiable cost of saving them also be infinite? Is it worth going into debt and breaking the economy to prevent a catastrophe that almost certainly won't ever happen? Such questions make quantitative arguments difficult.

Stepping back from this question of extremes, we can still perform an analysis with realistic numbers using the same methods that have been used to quantify the risk from climate change. There is no scientific debate about the reality of global warming and the fact that human burning of fossil fuels is the dominant (if not the only) cause. Still, there is significant uncertainty about the magnitude of future warming and even more uncertainty about how much we will suffer from side effects such as sea level rise, storm intensity, drought, ecosystem and agriculture loss, and extinction. One way to describe uncertainty is to use the concept of climate sensitivity, defined as the equilibrium rise in global mean surface temperature forced by an equivalent doubling of atmospheric carbon dioxide. Probabilistic risk assessment allows the climate threat to be quantified even when we don't know for sure how much warming will take place. This methodology provides a template by which we can assess the impact risk in the face of similar uncertainty and limitless but unquantifiable consequence.

Figure 1 shows a bar chart of a thought experiment designed to put probabilistic risk assessment into concrete and dramatic terms, Suppose you are the subject of a laboratory test, in which a mad professor of risk assessment wants to find out how people make individual safety decisions in the face of uncertainty. She brings three revolvers. Gun A has a bullet cartridge (round) in each of its six cylinders. If you pull the trigger, the probability that it will fire is 100 percent. Gun B has three of its cylinders loaded, and the odds that it will fire are 1 in 2 for a 50 percent chance. Gun C has only one round in a random cylinder so the odds are 1 in 6 for a probability of 16.7 percent.

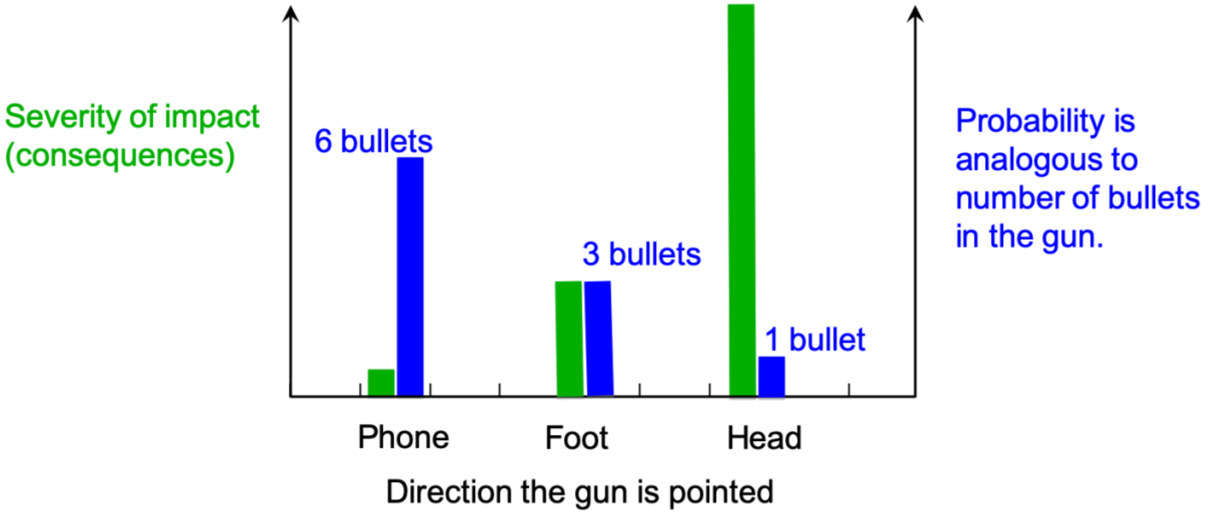

Fig. 1. Risk = Sum of probability × *consequences*

The researcher then tells you that she is going to point the guns at three different objects in the room but you have to decide which trigger to pull. Will your decision depend only on probability, or will it also depend on where the guns are pointed (which will determine the consequences)? Suppose Gun A is pointed at your expensive smart phone, Gun B is pointed at your foot, and Gun C is pointed at your head. Now there is a trade-off between probability and consequences. Do you risk killing yourself to avoid the loss of your precious telecommunications device? Or do you consider a crippling but non-fatal injury?

What if she gives you the option of taking one round out of one gun and then pulling that gun's trigger? Based strictly on the numbers, the best way to minimize total risk would be to take the single round out of Gun C, pointed at your head, and pull the trigger. There is zero chance of shooting yourself in the head, so the risk is zero. But how many people would do this? Even the

National Rifle Association (not noted for having a risk-averse philosophy) teaches students in gun safety classes to never ever EVER point a gun at anyone, let alone pull the trigger. Why? Because empirical data show that many people have been killed by guns that the shooter thought to be unloaded.

If you are 99.999 percent certain that the gun is unloaded, there is still a nonzero probability that it will fire a bullet. If your life is worth a billion dollars (to you) then the risk (probability multiplied by consequences) is still greater than the cost of a new phone. I suspect most people would rather shoot their phone than take that risk.

In the case of Gun C with the ammunition removed the statistical probability might calculate to zero, but there will always be uncertainty due to a possible lack of knowledge. How carefully did you watch the experimenter unload? Do you know for sure that she's not truly evil and good at sleight of hand? Did you look in the chamber and all the other cylinders? Are you confident that you really understand how revolvers work? This problem illustrates the difference between aleatory and epistemic uncertainty. Aleatory uncertainty is used to quantify the risk that can be expressed as random events, like rolls of dice, firing of partially-loaded guns, and asteroid impacts. Epistemic uncertainty is used to quantify risk associated with lack of knowledge, like whether a pair of dice is honest or rigged, how many rounds are actually in a gun, our how many undiscovered asteroids are in Earth-crossing orbits.

Taking the thought experiment one step further illustrates how to arrive at total risk. Real-world risk problems are better illustrated by a protocol in which the all three triggers must be pulled. In this case the risk must be summed over all possibilities. Total risk is equal to the probability multiplied by consequences of all three events. Determining the optimal method for reducing the risk becomes a cost-benefit exercise. Under the total risk protocol, the trigger pulls are not up to you. However, the experimenter now gives you the option of unloading however much ammo you want, but you have to pay. If you can only afford to remove one round, it would be foolish not to remove the one from Gun C. Paying to remove that single round will remove any risk of death (except the small epistemic component), even though the probability of such a catastrophe is only 16.7%. Most people would accept that guarantee before trying to lower the risk of a crippling shot to the foot, or the certain loss of their treasured mobile device.

The planetary defense community has made the same calculation. The population of asteroids is very much like the number of rounds in the thought experiment, but now the consequences depend on the size of the asteroid rather than where the gun is pointed. The largest asteroids have the greatest consequences — up to and including extinction (as the dinosaurs discovered). But the consequence estimate is also very uncertain. How big does an asteroid have to be to wipe out the human race? 5 kilometers? 10 km? How big does it have to be to cause an ecological collapse and loss of agricultural production that leads to the end of civilization? 1 km? 3 km? This calculation is difficult because we do not understand all the damage mechanisms and the Earth system is complex and nonlinear.

There is evidence that the 10-km-diameter asteroid that wiped out the dinosaurs also completely altered Earth forever, first by direct impact effects — the excavation of a massive crater and ejection of debris. The explosion transferred some of its 100 million megatons of energy to the atmosphere, heating it up by an unknown amount. The atmosphere was loaded with so much dust and debris that it became opaque, leading to a years-long impact winter and a permanent change in its composition. The result was a mass extinction, but the exact mechanism is still debated and may never be fully understood.

Fortunately, impacts by asteroids of that size only happen once every 100 million years or so, and there is currently no risk of one because it would be large enough to have been discovered (however, there is still a nonzero possibility of a large comet impact). And while there is little evidence that any of the other four prehistoric mass extinctions were caused by impacts, we are now creating a sixth great extinction of our own.

A 5-km asteroid is half the diameter of the dinosaur killer, but has only 1/8 the mass because volume is proportional to the cube of the diameter. The mass is a better measure of "size" than diameter, so it is really only an eighth as big and an impact would deliver about one-eighth the destructive energy. However, there are many more of them so Earth suffers more frequent impact from objects of this size (once about every 30 million years). Earth doesn't experience mass extinctions on that time interval, so there is no evidence that such impacts exceed the extinction threshold — at least not every time. But based on the energy released (about 10 million megatons) and the amount of debris produced, a 5-km asteroid impact would lead to certain global catastrophe, killing billions of people.

Much like the partially-loaded-guns thought experiment, the number of asteroids continues to increase as the size (and consequences) go down. There are sound physics arguments, backed by evidence in the geological record, that smaller impacts can have local, regional, or even continental-scale consequences without leading to a significant climate disruption or global catastrophe. That means there is a size threshold for global catastrophe, even though we don't know what it is. Moreover, the threshold is not definite. An asteroid plowing into one part of the planet might release a lot of planet-warming CO_2 or cause firestorms leading to impact winter, whereas if it fell into the deep ocean it might not affect climate as much. The global catastrophe threshold is not only poorly known, it is fuzzy.

In 1994, Clark Chapman and David Morrison published the first comprehensive probabilistic risk assessment for asteroids. For small asteroids, they based their consequence estimates on the damage that a nuclear burst with the same explosive yield would have, which we know from atmospheric weapons test data and physics-based scaling laws. For larger asteroids the scaling laws break down as global effects come into play. They heuristically extrapolated the curve up to a global catastrophe threshold asteroid size between 1.5 and 3 km in diameter, above which they assumed a quarter of the world's population would die. For purposes of approximate risk assessment, this provided a reasonable "kill curve" that could be used to decide how to begin reducing the danger.

The impact risk is completely analogous to the threat of global warming. The Intergovernmental Panel on Climate Change (IPCC) created a schematic representation of how this risk quantification method works (Figure 2), by showing a graph of probability distribution of the magnitude of some event or effect (black), the degree of associated consequences (red) and the resulting risk (blue), which is area under the curve representing the product of the other two curves. The left-hand graph uses consequences that increase nonlinearly with the size of the event or effect. It shows that the most likely event or effect (the best estimate, or peak in the black curve) is not the primary determinant of risk. This is because risk is proportional to the area under the blue curve and is more heavily weighted by the lower probability, higher consequence part if the distribution. The right-hand graph illustrates the case where there is a threshold in which global warming or asteroid size leads to global catastrophe and the loss of billions of lives. The area under the blue curve, and therefore the total risk, is much greater when the possibility of global catastrophe is not eliminated.

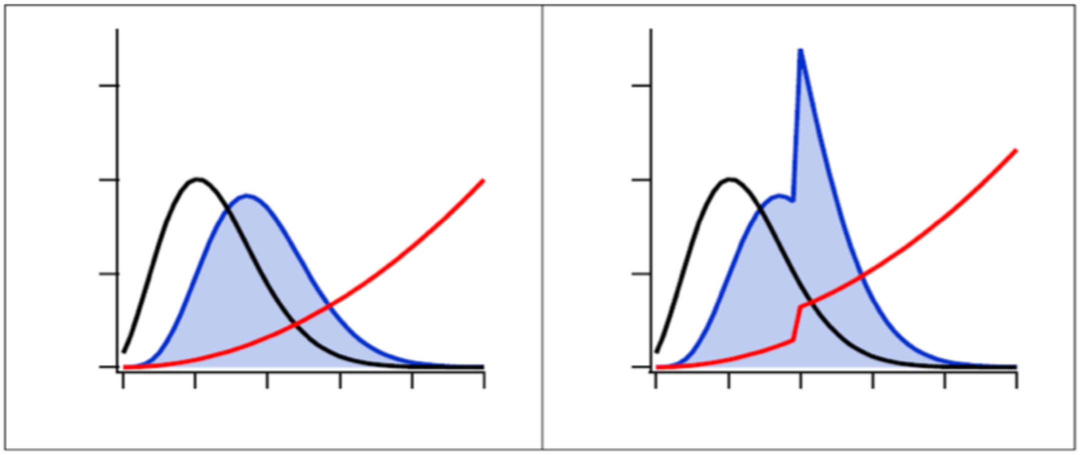

Fig.2. Source: Intergovernmental Panel on Climate Change

Unlike the gun thought experiment, with discrete numbers of bullets for three different scenarios, there is a continuous distribution of asteroid sizes and possible climate sensitivity. If we were truly wicked gods with an arbitrarily large number of Earths to experiment with, we could use these distributions to generate a statistically significant number of experiments by repeatedly destroying our creation and smiting large numbers of our children. For the impact threat we could hit the earth with random impacts in numbers proportional to the size distribution of the population, and add up the numbers of fatalities. For the climate threat we could change the amount of CO_2, altering the atmospheric chemistry and opacity, and see what happens. The equivalent option for a benign and mortal researcher would be to perform ensembles of Monte Carlo computer simulations, which is a standard risk assessment method. However, the killing potential of both asteroids and global warming is complicated and poorly understood. The asteroid calculation is especially uncertain for water impacts because there is no consensus on the efficiency of impact tsunami generation. There is even more uncertainty for the global warming threat and for asteroid impacts leading to climate-changing global catastrophes because climate is a nonlinear dynamic system with unknown thresholds and feedbacks. But the larger the uncertainty, the greater the assessed risk.

For the global warming problem, climate sensitivity can also be transformed to a graph of expected greenhouse warming this century for a given realistic assumed rate of atmospheric CO_2 increase. It can be expressed as a probability density function, but the uncertainty is and always will be epistemic because a lack of knowledge remains — especially about the feedback associated with clouds, analogous to uncertainty in the number of rounds in the gun you are holding to your head in the thought experiment. The global warming probability density function can be graphed as a smooth curve just like the bar graph of bullet cartridges in a gun (Figure 3). The shape of the curve is an expression of uncertainty.

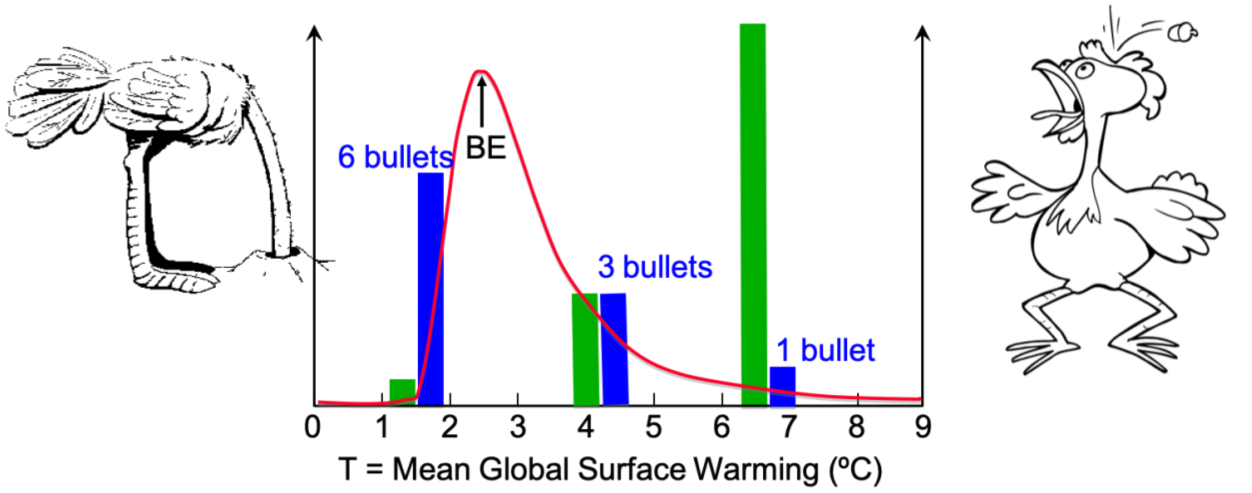

Fig.3. Discrete and continuous probability density functions

The science has long been settled about the reality of human-caused global warming, but scientists are still debating the magnitude of warming and how rapidly it will proceed. The IPCC has been focused on the best estimate, “BE,” but as Figure 2 illustrates, the risk is dominated by non-zero probability of large warming. Those who do not accept this uncertainty are rightly characterized as “deniers” who claim that global warming is a hoax and “alarmists” who claim that global catastrophe is certain. When actual uncertainty is calculated, it does not include zero warming as a possibility. But it does include global catastrophe, so alarm is justified.

There is not even a complete consensus on the actual shape of the curve. Nevertheless, virtually all distributions show a high-sensitivity tail. That means there is a significant probability of greatly exceeding the 2º C threshold for dangerous climate change. Alarmingly, there is also a significant probability of exceeding a threshold for global catastrophe. Even though (as with the impact problem) we can only guess what that threshold is, all the curves extend above 10º C, which would arguably be as catastrophic as the 10 km diameter asteroid that wiped out the dinosaurs.

For the impact problem, we can convert the estimated asteroid size distribution curve to a probability density function that expresses the likelihood of an impact of a given size in a given period of time and to multiply it by a heuristic “kill curve” like the one derived by Chapman and Morrison. This is done by dividing the curves up into discrete size bins. We can create a table where one column might be the of the number of expected impacts by asteroids with diameters between 1 and 1.5 km in an interval of time, and the average number of people an impact of that size would kill (over all possible scenarios). We can sum the product of the two numbers for each column, and the resulting number is in units of fatalities per year.

Chapman and Morrison estimated a risk of a few thousand fatalities per year. This result is counterintuitive, because nobody has ever been killed by an asteroid as far as we know. The reason it seems wrong is because the risk is dominated by low-probability, high consequence events. An event that happens once every million years, but kills a hundred million people, would contribute 100 fatalities per year to the risk, so it might be easier to think of it as an event that has one-in-a-million odds of happening in a given year.

Fatalities-per-year is not the only possible way to quantify risk, and may not even be the best, but it has become the *de facto* metric for the planetary defense community’s risk assessments. It is useful for intercomparison of the contributing factors and for performing cost-benefit analyses of risk-reduction methods. The Chapman and Morrison analysis led to an obvious policy recommendation: catastrophe avoidance. Take all the ammo out of the gun that is pointed at your head. The best way to reduce risk is to prevent large impacts, and the first necessary step toward such prevention is to find them. This analysis led directly to the Spaceguard Survey, with the mandate of discovering 90 percent of near-Earth objects (NEOs) greater than 1 km in diameter. As luck would have it, this was also the easiest solution. There are only about a thousand NEOs of that size — and they are the biggest, brightest in the sky, and easiest to find. Unfortunately, the global warming problem does not have such an easy solution. The only certain way to “remove the ammo” and eliminate the possibility of global catastrophe is to radically reduce the rate of CO_2 production.

The principle of astronomical NEO surveys is the same as looking both ways before you cross the street. The act of looking doesn’t change the actual probability of impact. For any object in a deterministic orbit the actual probability of a collision is either zero or one. Looking allows you to take a preventive action to mitigate the risk of something you discover on a collision course. In the case of street crossing, you can change your own course by waiting until the car passes. In the case of the asteroid, it is easier to change the object’s course than Earth’s — so asteroid deflection is the preventive option of choice.

Nevertheless, the act of discovering asteroids reduces the assessed risk. If there are a thousand kilometer-sized NEOs in unknown orbits the risk is aleatory because the orbits can only be assumed to be random. Once they are known (and found not to be on a collision course) they can be removed from the random population for purposes of risk assessment. The assessed risk goes down, but the actual (unknown) risk is unchanged — a given asteroid is either on a collision course or it isn't regardless of whether or not it's been discovered. But since assessed risk is all we know, policy and actions must be based on that. And if something is discovered to be on a collision course, we can do something about it.

Fortunately, the NEO survey has been a tremendous success, having surpassed its goal of 90 percent of objects greater than 1 km diameter and still accelerating the discovery of smaller objects. The assessed risk of an asteroid apocalypse in our time as virtually been eliminated. The risk of a continental-scale catastrophe has been greatly diminished, and the overall risk (measured in average fatalities per year) had been reduced by an order of magnitude, to about a hundred. But there is still work to be done to remove the remaining risk. Because the distribution of asteroids follows a power law, with many more small (dim, and difficult to find) asteroids than large bright ones that have already been discovered, it won't be easy.

Asteroid diameter	Effects	Energy (TNT equivalent)	Recurrence period (mean)
5 m	Bright fireball, boom	~10 kilotons	~3 years
25 m	Local damage	~1 megaton	~200 years
50 m	Local destruction	~10 megatons	~2,000 years
140 m	Regional destruction	~300 megatons	~20,000 years
300 m	Continental destruction	~2,000 megatons	~70,000 years
600 m	Continental destruction	~20,000 megatons	~200,000 years
1 km	Global destruction	~100,000 megatons	~700,000 years
3 km	Global catastrophe	10 million megatons	~30 million years
10 km	Mass extinction	100 million megatons	~100 million years

Source: Asteroid Day expert panel

In NASA's 2005 authorization act, the United States Congress mandated a "George E. Brown survey" that discovers 90 percent of NEOs greater than 140 meters in diameter — big enough to wipe out a large metropolitan area or small country if one were to score a direct hit. This will require surveys of an entirely different scale, including the construction of a space-based infrared telescope if it is to be accomplished in the next decade or so. And this brings us back to Asteroid Day, which has the goal of insuring that survey is successful.

There are three possible outcomes of a successful George E. Brown survey. The most likely result by far is that no asteroids large enough to warrant deflection will be discovered on a collision course in our time (the next century or so). Much less likely is that an object will be found and observed with enough precision to calculate a chance of impact, but not well enough to be certain. It is possible that such an ambiguous object will not return to visible range until it is on its final approach toward an impact or near miss. Third and least likely is that an object will be discovered that we will know for certain we have to deflect or destroy. After we have catalogued all the near-Earth asteroids big enough to discover in advance, an impact threat will remain: destructive impacts and airbursts with little or no warning. This was the subject of my 2014 Starmus presentation, “Death Plunge!”

To appreciate the idea of a death plunge event, it is important to understand that traditional planetary defense relies on discovering asteroids many years or decades in advance. This is because it would take many years to design a deflection mission, build the hardware, launch it, wait until it arrives at the asteroid and nudges it, and then wait for the asteroid to gradually drift away from its original collision course so that it misses the Earth. During this time, both the Earth and the asteroid will orbit the sun multiple times.

Fig 4. Source: Nature Magazine *Fig 5. Source: Physics Today*

Computational simulations by Mark Boslough, rendered by Brad and Andrea Carvey

The discovery of an asteroid on its last orbit before the collision, on the other hand, would not provide sufficient time to prevent an impact. There is no nuclear-tipped interplanetary rocket waiting to be launched in such an event (an idea that would never satisfy any cost/benefit analysis even if it were politically viable). When this happens, our planet is going to take the hit. That’s why an accelerated survey is needed now, but it’s also why the planetary defense community will need a new “business plan” after completing the catalogue of all asteroids big enough to require deflection.

The worst kind of death plunge would be like the one that the dinosaurs experienced because it spelled death for the beasts along with that of the asteroid. Their first awareness of the impact was when the sky lit up. That’s true for almost every other impact in history, including the 1908 Tunguska explosion over Siberia and the 2013 Chelyabinsk event, both of which appeared in the sky with no warning whatsoever. (See Figures 4 and 5.)

Tunguska has been a touchstone for the planetary defense community because it is the biggest known Earth impact event in human history and its spectacular effects are well documented. For many years, researchers were puzzled because the asteroid exploded in the air and did not actually reach the ground or form a crater. Most of the damage was caused by an air blast that descended from the sky, blowing down trees spanning an area of about 2000 km^2. The heat from the explosion charred trees and ignited fires. Figure 6 shows a rendering by space artist Don Davis based on computer simulations I performed for the centennial anniversary of that event.

Fig 6. 1908 Tunguska explosion, Source: Don Davis

By interviewing witnesses, mapping the pattern of tree fall, and analyzing crude seismic and air pressure measurements, scientists were able to paint a rough picture of the event. They concluded that when an object descended into the atmosphere the dynamic pressure caused it to slow down, creating a strong shock wave that dissipated its kinetic energy, converting it into thermal energy. This vaporized the entire body, generating a ball of hot gas that expanded and exploded, much like a nuclear detonation (but with no ionizing radiation).

Based on measured damage from atmospheric nuclear weapons tests during the cold war, scientists estimated the explosive yield to have been 10 to 20 megatons, corresponding to an asteroid about 60 meters in diameter. More recent hydrocode modeling includes the asteroid's mass and momentum, showing that it acts as a "directed energy weapon" and does more damage at the surface than a nuclear explosion of the same yield. This led to a "downgrade" of the Tunguska yield estimate to 3 to 5 megatons, consistent with an asteroid about 40 meters in diameter. The same simulations suggest that above some threshold, the exploding fireball of hot vapor would reach the surface of Earth and would melt and ablate soil and rock. This may be the best explanation for the enigmatic Libyan Desert Glass of in the Sahara Desert. Figure 7 shows a piece of glass I found in Egypt during the 2006 filming of the BBC documentary Tutankhamun's Fireball.

Fig 7. Libyan Desert Glass, Photograph: Mark Boslough

Only three natural death-plunge objects have ever been found in advance. The discovery of Comet Shoemaker-Levy 9 was announced on March 25, 1993. Co-discoverer Carolyn Shoemaker first identified the comet on damaged film, polluted with glare from Jupiter, from an image taken just before clouds prevented further observations that night. According to David Levy, she remarked, “I don’t know what this is, but it looks like a squashed comet.”

It looked deformed because it had recently broken into about 20 fragments after its last close pass with the gas giant it was orbiting. By the time it was discovered, the fragments were drifting away from the planet in an elongated orbit that was quickly determined to intersect with Jupiter on its next pass. Just over a year later — in July 1994 — the surviving fragments of Shoemaker-Levy 9 slammed, one by one, into Jupiter's atmosphere with the energy of millions of nuclear explosions. It was one of the most spectacular celestial displays ever witnessed and led to a shift in scientific and public opinion about the danger of impacts to our home planet.

Fig 8. 2008 TC3, Photograph: Unattributed

It would be more than 15 years before the next death-plunger would be discovered. Alarmingly, this one, designated 2008 TC3, was headed for Earth, but fortunately it was so small (a few meters in diameter) that it was no danger. It was discovered on October 6, 2008, only 19 hours before its impact over northern Sudan. This provided sufficient time for more telescope observations to gather astrometric measurements that would accurately pin down its location and provide an orbit with such precision that the impact time and location could be calculated in advance to the nearest second and nearest kilometer.

Because of the remoteness of the impact, over the Nubian Desert, there was no time for observers to travel to the site and document its entry. Nevertheless, the flash was seen by pilots in a commercial flight over Africa, and it appeared in a weather satellite image. One lucky observer was able to photograph a pre-dawn debris cloud that resulted from the entry and explosion (Figure 8). Several weeks later a search party of Sudanese students found the meteorites, subsequently dubbed Almahata Sitta, guided by the orbital calculations that defined its entry path. It was the first and only asteroid to be observed in the sky and then seen entering the atmosphere, picked up off the ground, and analyzed in the laboratory. It was like a self-delivering “sample-return mission.”

Remarkably, the third death plunge object was discovered by the same astronomer, Richard Kowalski, with the same telescope as part of the Catalina Sky Survey five years later (on January 1, 2014). Unfortunately, there were insufficient follow-up observations for that one. Infrasound (very low frequency acoustic wave) evidence points to a landing in the Atlantic Ocean so it was never recovered. Nevertheless, these most recent death-plunge events, taken together, suggest that with the proper equipment and observing methods, death plunge discoveries could become routine.

The best documented and most spectacular death plunge took place over the Russian city of Chelyabinsk on Feb. 15, 2013. It was not discovered in advance, because it came from the sunward direction and no telescope could have seen it. However, it happened to appear in the sky during dawn rush hour in a country where dashboard cameras are common, leading to a wealth of videos and photographs. The flash was also observed and quantified by satellites, and the blast generated seismic and infrasound signals. This serendipitously collected data set was combined to determine the trajectory, understand the physics, and estimate the size of the explosion (about a half megaton, corresponding to an asteroid about 20 meters in diameter).

What if the Chelyabinsk asteroid had been discovered in advance? Based on my Starmus presentation, I offered a fanciful vision of how differently the event would have unfolded, in the July 2015 issue of Astronomy Magazine:

> *Much to the delight of scientists and technicians, the frigid sky over the snow-covered Siberian fields and villages remained clear as dawn approached. The February stars put on a dazzling show as they revolved about Polaris, higher in the sky than many of the foreign visitors were used to seeing it. The frequency of sporadic meteors increased as the night grew long, as if providing a warm-up act.*

> *Charter flights were already in the air, filled with business tycoons and celebrities, and rumor even had it that Russian President Vladimir Putin was on one. The planes could be seen in all directions except in the special airspace dedicated to cooperative research flights by the Russian Federal Space Agency, the European Space Agency, and NASA, and in the restricted airspace directly beneath the asteroid's projected path. In order to keep light pollution from interfering with the observations, the nearby city of Chelyabinsk was in blackout. Everyone waited at the ready for the meteor event of the century…*
>
> *In that fictional world, by the time the southeastern sky began to glow with faint hints of light, scientists had been up all night calibrating and testing their equipment. The weeks of planning meant they had time to spare, and they spent it photographing the stars, drinking coffee or tea, fidgeting, and (except for the North Americans) smoking cigarettes. High-definition cameras, telescopes, radiometers, radar dishes, spectrometers, and optical pyrometers all pointed at a spot above the eastern horizon. The instruments were mounted on gimbals so they could rapidly slew at just the right rate to track the fireball. Even with advanced warnings, there would be no second chance.*
>
> *Researchers already had deployed arrays of seismometers, geophones, microphones, infrasound detectors, microbarographs, anemometers, and dust collectors. Now, just before sunrise, they launched drones and balloons to get precise readings of atmospheric conditions and to record the characteristics of the blast wave in three dimensions.*

Advance warning of a death plunge would not only allow the collection of detailed data by calibrated scientific instruments designed for the purpose, but it would also prevent loss of life and property. Much like hurricane or tsunami alert systems, warnings could be issued for citizens to evacuate, take shelter, or simply board up their windows.

The vast majority of death plunges into earth's atmosphere are too small to be dangerous (like 2008 TC3) but large enough to explode spectacularly as superbolides, provide useful scientific data, and leave meteorites on the ground. Figure 9 shows a map of 20 years of detected superbolide explosions, recently released by the U.S. government. This steady rain of small asteroids will continue to fall, providing the opportunity for a new business plan for planetary defense once asteroids large enough to require deflection are all discovered. The creation of a comprehensive death plunge observational campaign would provide rapid benefits to both science and planetary defense. It also would supply a constant flow of meteorites from objects that had been observed in space, at a fraction of the cost of an asteroid sample return mission.

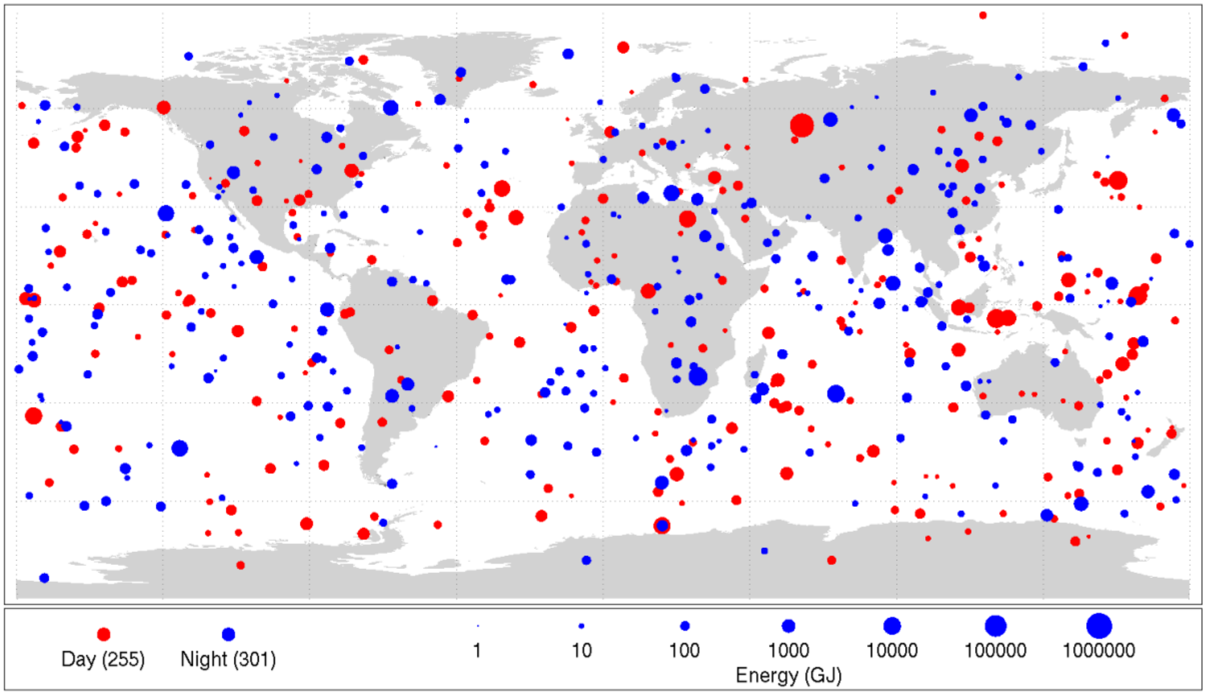

Fig 9. Source: US Dept. of Defense

Fig 10. Source: Don Davis, modified by Mark Boslough

Once all the asteroids big enough to be deflected have been discovered, it will be difficult to continue to justify a planetary defense program using the standard risk assessment and cost/benefit analysis. However, a death plunge campaign would have other economic benefits. Excited tourists might be willing to spend a significant amount of money to see a rare cosmic spectacle (Figure 10) and help collect meteorites on the ground for scientists and museums (Figure 11). Perhaps the allure of adventure and the increasingly high value of meteorites would be incentive enough for deep-pocketed investors to help scientists, humanity, and themselves — all at the same time.

Dealing with asteroids is exciting and glamorous, but how does it compare with other risks? The National Research Council's 2010 "Defending Planet Earth" report listed various causes of deaths compiled by the World Health Organization and other sources.

Fig 11. Source art: Don Davis, modified by Mark Boslough

Cause	**Expected Deaths Per Year**
Shark attacks	3-7
Asteroids	91
Firearms accidents	2,500
Earthquakes	36,000
Climate Change	150,000
Malaria	1,000,000
Traffic accidents	1,200,000
Air pollution	2,000,000
HIV/AIDS	2,100,000
Tobacco	5,000,000

Source: National Research Council, World Health Organization

Asteroids and climate change are the only two threats in the table that can have abrupt and global consequences, and to which everyone on the planet is exposed regardless of their lifestyle or personal behavior, or where they live. In principle, they are both preventable. In both cases mitigation would require international agreements and cooperation. But would such collaboration even be possible if a threatening asteroid were discovered, or would we be bogged down in the same kind of denial, willful ignorance, and obstruction that has prevented action on climate change?

Evidence from Greenland ice cores and other paleoclimate data show that spontaneous and extreme climate changes take place much more frequently than large impacts and on time scales that can exceed human adaptive capacities. Asteroid impacts are rare events, but abrupt climate changes are common by comparison. Only 13,000 years ago, the North American megabeasts including woolly mammoths, saber-toothed cats, and giant sloths had a very bad day — or at least a bad millennium. They disappeared.

It was so bad that some scientists have mistakenly attributed that mass extinction to a giant comet explosion in outer space, directly above the North American continent — a fringe theory that has been repeatedly debunked. Paleoclimate researchers, on the other hand, have found a pattern of abrupt climate change related to sudden alterations in ocean circulation caused by ice sheet collapses and large releases of fresh water. The environmental disruption — coupled with hunting by newly arrived human superpredators with advanced killing technology — is almost certainly the cause of the extinctions.

Now that most of the asteroids above the catastrophe threshold have been discovered to be in safe orbits, the statistical probability of a global catastrophe from an impact this century is about 0.0005 percent. On the other hand, the uncertainty in climate sensitivity suggests that there is up to a 2 percent chance of a global catastrophe from anthropogenic global warming by the end of this century. It is reasonable to suggest that a human-caused climate catastrophe is at least several orders of magnitude more probable than an asteroid catastrophe.

The alarming lesson of the North American megabeast extinction is that it doesn't take a giant impact to create a bad day. Earth is susceptible to catastrophic climate changes that can be triggered by much lower-energy events such as ice sheet collapses, and we humans are the most powerful force of all. We are now in the process of disrupting Earth’s energy balance with a speed and magnitude that only the largest impacts have achieved in the past. We should not be comparing ourselves to the dinosaurs. We are the asteroid. It would be the ultimate irony if we successfully defended our planet from the next cosmic catastrophe, only to commit global suicide. If we don’t do something about our own destructive behavior very soon, we are in for a very bad century.

ORIGINS OF THE COSMOS

Astronauts, Cosmonauts, Nobel Prize winners, eminent researchers and prominent figures from science, culture, the arts and music attended the second Starmus festival of science and music on Tenerife in 2014 to try to answer the biggest questions the human race faces: Where do we come from? and Where are we headed? The special guest lecturer was none other than the legendary Professor Stephen Hawking, who delivered two public talks, and was greeted by the huge audience as if he were a rock star. Indeed Starmus is supported by a unique constellation of actual rock stars, including Brian May , Rick Wakeman, and Peter Gabriel.

The book achieves quite a serious goal insofar as it synthesises our current view of life, the universe and everything as seen by these leading scientists… in words and pictures that are understandable to anyone with an interest in these matters. As such it is an invaluable read for such enthusiasts as well as students of space, astronomy, astrophysics, cosmology, and the evolution of life. For those interested in music, the concerts, classical and rock, are included in pictures and linked online.

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