Impactus Finiens Orbem Terrarum:
An Updated Risk Assessment of World Ending Asteroid Impacts

Max Salman[1]

[1]University of Waterloo; Department of Earth and Environmental Science; e-mail: m4salman@gmail.com

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Abstract

As technology develops, the rate of discovering and observing space tends to relatively increase. Our understanding of how the Universe works, and how the planets interact with one another make us weary of what is to come. Technological advancements have led to observational improvements especially in the realm of extraterrestrial bodies, whether they be planets, or asteroids. The importance of some observations are various, and relative to the amount of an effect the potential damage the related body can have on the population. Relationship of the stars, planets, and asteroidal bodies may be the leading concept of astrology, however it is in a sense an important factor when studying the paths of significant bodies, as these bodies move due to gravitational pull, and may either experience an increase in velocity, or decrease in velocity, either situation is relative to a certain degree.

Sociologically, it is almost fair to state that imperatively, there will have to be some sort of preparation for an end-of-world scenario due to such an impact. The inevitability of such a thing to happen, and the damage that would ensue post-impact, leaves a question open to the reaction of the global population, since it would be no longer a question of whether or not it will affect a certain part of the world, but would induce instantaneous destruction, and post-impact strains on the environment, thus potentially leading to the inevitable end of, at least, human life.

This work will discuss briefly the prior works of notable scientists and researchers, and critically analyze them. A followup will be presented to update the information from these prior works, and a detailed discussion on the new information gathered, with a description of technologies involved.

Keywords: Impact; Risk; Update; Asteroids; Technology

Chapter 1

Introduction

1.1 Introductory Statement

Statistically, it is without a doubt that the probability of being involved in a plane crash is higher then being directly affected by the impact of a large extra-terrestrial body, i.e. an asteroid. However we must keep in mind that it is possible nonetheless, and that the damage that an event causing a shift in our communal daily lives is significantly more worrisome than a automobile collision, or a bridge collapsing. Studies of large extraterrestrial objects have led to the development of understanding the power that is stored in an impact event potentially destroying the world either instantaneously, or via global change leading to our inevitable demise of this world throughout a number of years. Both of these events can be summed up in a single term, meaning straightforwardly: "World Ending Impact". This term is henceforth titled as *Inflictum Finiens Orbis Terrarum,* or IFOT for short. We will incorporate also the ideology of social breakdown within the term, on the basis of a direct relationship with an extraterrestrial impact. A fair question would be, if we were to survive an impact that changes the natural balance of the Earth, causing an absurd change in climate, would we be able to cope, or will we destroy ourselves for means of self-living?

Thus, historic, and modern research has given us grounds to understand the surroundings of the world, and the implied risk that has risen from this so called understanding. The research is also inclusive of prior events that caused significant damage, and worldwide change, for example the Chixculub impact at the Cretacious-Triassic boundary that rendered the dinosaurs extinct. If we find such an event imminent, and realistically possible within the next 10 years, would we be ready? What would be the probability of this asteroid actually impacting us, and if it were sans objection that this hypothetical asteroid were to strike the Earth, where and how would it do so? And would it matter?

1.2 Importance of Assessment

The importance of assessing the risk of an *impactus* is certainly key when discussing international relations, as the asteroid could impact at any location, and then the rights to the impacted object would have to be settled. However, without prejudice, there are tensions between governments, and the diplomacy that would be expected to develop an extraction plan, concerning economic potential of the asteroid, can be of minimal magnitude, if any, thus posing another risk on the general population as tensions may unleash and create war. Thus, is the global population ready for such an event, or even the fear of such an event happening?

As the human race starts understanding more and more about the [influential] universe, and as Hollywood does its part in marketing the end of existence, it is fair to state that while an IFOT is fairly unlikely, it is still possible, and while thinking beyond reasonable doubt that if the Earth were to be impacted by a K/T like asteroid, we would be affected to a very high degree. We will discuss why we take this into consideration when focusing on this issue.

1.3 Advancements

Technological advancements may actually give us room to improve our numbers relating to this quasi-quantified risk. Funding for such a monitoring project is crucial, as it serves as a lookout on a very time consuming basis. The 1994 work by David Morrison and Clark Chapman has opened the floor to discussion of follow up papers by these two mentioned, and others that have started to take concern on this issue as well. We will discuss this work further post-introduction.

NASA's Near Earth Object Program (NEO) has made quite an impression in the mold of the scientific community concerned with these specific issues. The work done has been crucial in the understanding of the way that asteroids passing near the Earth interact within the solar system.

1.4 This Paper

This work has a main goal of giving an updated risk assessment on asteroid impacts, both quantitatively, and qualitatively, by use of data that has been collected throughout the years (roughly 20 years), thus data, tables and diagrams in this paper will be analytically considered until the previously mentioned time unless otherwise stated.

The potential impact of an imminent threat on sociological parameters is something to consider as well, and although important to understand, we will touch on it only briefly, and should not be held as the main purpose of this paper.

1.4.1 Outline of Topics

Our work will be divided into various sections based on the category of discussion, and we will subsequently divide the categories into subcategories to ease and facilitate the division of the topics at hand, and to add a form of coherency through divisiveness. The categorical topics of discussion are as follows: (1) Introduction; (2) Fundamental Understanding; (2) The IFOT and Case Studies; (3) Data Collection Methods; (4) Manipulation of Data; (5) Results; (6) Critical Analysis; (7) Sociological Interpretation; (8) Importance of Findings; (9) Relation to Today Versus Prior Data; (10) Conclusion.

By taking an appropriate amount of time to discuss each of these topics, we will cover a great deal of detail so that readers may get a general yet comprehensive idea of the topics we are about to discuss.

Chapter 2

Chapman & Morrison 1994 Article Review

2.1 Introduction

This section aims to review the seminole paper of Chapman & Morrison of 1994 published in Nature Magazine. Justification of such is its widely acclaimed success, and ingenious concept and innovation regarding this field. The paper introduces many aspects involving the asteroid impact hazard, and expands on secondary hazards pertaining to asteroid strikes on Earth.

2.2 Revision of Discussed Topics

The paper in question ascertains a level of confidence in the threat to human civilization by an *impactus* as small as 1km in diameter. This is key in the perception of the absolute consequences. It is mentioned that impactors less than 50m in diameter will dissipate their energy (quoted at 10MT) in the upper atmosphere. The likelihood of events slightly greater than the aforementioned are on the order of centuries (Chapman & Morrison, 1994). It is mentioned that the asteroid impact hazard has become more mainstream in the media's eyes, mainly due to the technologies involved being controversial.

A review of the impact flux is made to give a brief introduction to the impact hazard. The largest Earth crossing *impactus* was noted to be 1627 Ivar, which is stated to be roughly 8 km in diameter (Chapman & Morrison, 1994). It is also confirmed with confidence that smaller asteroids, other than those that make up the count of 1992, exist. Shoemaker in 1983 presented an impact flux which was revisited in the total impact flux of the current paper in discussion. The assumption is made for v = 20km s^{-1} impactors which are stony.

The following are sub headers of the 1994 paper, and will be discussed in individual sections in this chapter; (1) Nature of the Hazard; (2) Hazard Analysis and Perceptions of the Hazard; (3) Risk Reduction and Mitigation.

2.2.1 Nature of the Hazard

It is confirmed that the Earth's atmosphere is a shield against smaller interceptors which end up burning in the upper atmosphere and displaying as streaks of light in the night sky (i.e. meteors). Meteorite impacts are very unlikely, since they are very small and there have been no accounted deaths related to meteorite impacts (Chapman & Morrison, 1994). Annual occurrences of Hiroshima-like meteoric events do not perturb life on Earth, as the energy propagation from bolide explosion does not reach the surface of the Earth. This energy in form of shockwaves. Meteoroids larger than 50 meters in diameter are noted to be able to penetrate through the upper levels of the atmosphere, and potentially cause life loss. This is dependent on the level of binding energy inherently within the body. 10MT impactors at altitudes of 25km above the ground surface could have repercussions on the a population within its destructions zone. These events occur on the order of centuries to millennia. Impactors causing such damage would be comparable to detonation of nuclear weaponry, however without all the associated radioactive components. Local destructors are rated at 250 meters in diameter, either being stony, or metallic in composition. The estimated energy released is 1GT. The produced crater would be 5km in diameter (Chapman & Morrison, 1994). These events occur every 10,000 years.

The rarest form of impacts known are the ones that are globally catastrophic, inclusive in this domain is the K-T Boundary Event. The supposed 10km diameter object excavated a 180km diameter crater (estimated) (Chapman & Morrison, 1994). Consequences post impact involved wildfires, and changes in oceanic and atmospheric chemistry.

Chapman and Morrison define a "Threshold for a global impact catastrophe" as a decline (death) of 25% of the global population. An example of a by product of such an event is the stratospheric dust injection of roughly 100 times the amount that the volcano Pinatubo ejected, which is noted to be roughly 10^{16}

grams. Note that this threshold is associated with an uncertainty potentially on the order of, and possibly exceeding, an order of magnitude, whether it be below, or above the proposed number.

2.2.2 Hazard Analysis

A reference to the Chapman and Morrison (1994) article, Table-2, gives a very clearcut conceptual interpretation of fatality rates and scaled as a function of various parameters. We suggest reviewing this table. Without mention of the by-products of asteroid impacts, however assuming they exist, a review of Figure-2 will be made to underline the relevant case studies in our work.

The average fatality rate in event associated with a Tunguska like event is roughly 10^4 with an annual chance of a little less than 10^{-3}. On the other hand, the K-T Boundary Event is clearly beyond the global catastrophe threshold, and its associated uncertainties. Thus the world population would perish. This chance per year of a similar event is ~10^{-8}.

Comparing the asteroid impact hazard to other more likely, and devastating events, such as wars and more frequent natural disasters, alludes to create a scale on the dominate causes of death. Thus two categories exist when qualitatively judging risk, first, frequent events generally have lesser consequences, versus infrequent events, which bear larger consequences.

2.2.3 Risk Reduction and Mitigation

Mitigation techniques have been examined and exist, though they are controversial as previously touched on. Chapman and Morrison describe the Spaceguard Survey which, in the 1994 paper, was a proposed program to catalogue virtually every object that crosses the Earth's orbit. Their timeline was estimated at 20 years. A remark on warning time is made, where asteroid warning times could be as much as decades, where as long period comets may only be detectable months prior to possible interception. The main purpose of mitigation technology is to act upon impactors beyond the global catastrophe threshold. Nuclear weaponry impacting the surface of a large enough asteroid may be not ideal since the fragmentation could lead to a scatter impact of the main asteroid, causing more damage, which is against the purpose. A proposition to have a near field explosion enough to deflect the object just enough to rearrange its orbit so that it does not pose a threat.

2.3 Concluding Remarks

Chapman & Morrison produced an outstanding piece of work, acting as a basis for our work, and giving the general population and the scientific community an update on the current situation and circumstances involved in our response to the threat. Since 1994, the perception of risk, from various researchers and the public, has changed. We will explore these changes and discuss them accordingly.

Chapter 3

Fundamental Understanding

For the purpose of our paper, we will need to cover the basics to thence lead us to concepts that will incorporate the following points, the compendium of these points is referred to in our case as the Fundamental Understanding. Our subcategories include: (2.1) Definition of Risk; (2.2) Risk Assessment; (2.3) Definition of Asteroid Impacts. A concluding statement will summate our categorical discussion to indicate the usefulness of the terms which we now present.

3.1 Definition of Risk

The New Oxford American Dictionary defines risk as simply being:

"a situation involving exposure to danger."

Evidently, this statement that defines risk is very unspecific, and underlines only the causal reason of the actual nature of this abstract feature of our reality. We will take the definition above and compliment it with applicable ideas so that we may understand the way that we interact with risk, and how our rational minds either lead us to take risks, or not. This philosophical matter gives us grounds to reject, accept or conditionally accept the risk that is presented to us whether on a day to day basis, or on larger magnitude potentialities.

Methods to relate *risk* to human activity can be analyzed by trying to develop the pseudo-correct algorithm to assess risk. Since we generally know that the probability of being hit by an IFOT is very low, we restrict ourselves to a simple algorithm to assess the risk of asteroid impact.

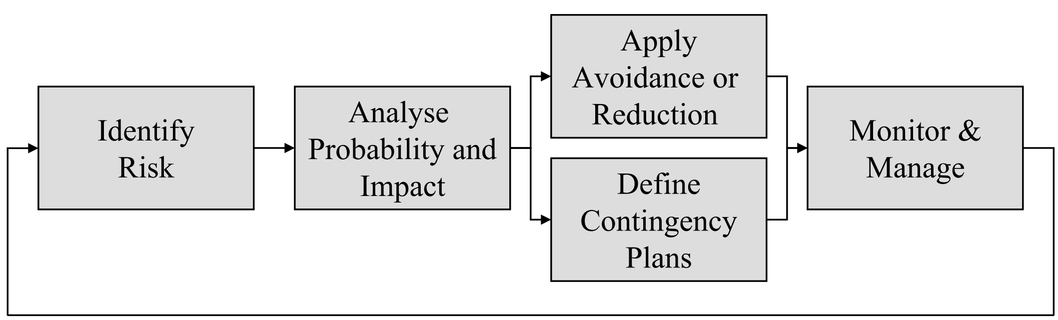

Figure 1.0: Simple conceptual model displaying an algorithm of IFOT Risk Assessment. (Source: Wallace, S.; 1997-2007)

The ambiguity of the work we are doing gives us a level of uncertainty that makes us believe a complex model cannot be applicable to our situation. Henceforth, we accept the above model for the sake of this paper, and for the sake of simplicity through the potential ambiguity. Research that has been completed has reached the second stage of the above model, for there is no concrete method yet set forth as a primary avoidance strategy, or contingency against an IFOT. Contemporary methods have been presented, i.e. Deflection or Destruction (Shustov, 2010). Note that we will explain these methods later on in our paper. These methods have been accepted as possible mitigation methods, but have not been placed into any *in situ* conditions, thus the uncertainty is partially from that one reason. From the prior statement, we can clearly see why we have not reached the 3rd stage of risk assessment algorithm.

How can we then properly define risk as a function of threat versus mitigation? Until now, we can only hypothesize, but since extensive, and almost mainstream, research has been started by Clark Chapman, and David Morrison, we start seeing now more and more clearly the real threat of being terminated as a civilization, or as a species. This is not to say that we are more likely to get physically impacted, but possibly more likely to get destroyed by our unpreparedness.

3.2 Risk Assessment

Risk assessment related to *asteroid impacts*, whether they be an IFOT or not, must be studied in a completely different manner than any other geohazard in which we know of. Since asteroids have an equipotential surface to impact (Earth), there is the possibility of impact anywhere, at any time, in any way, at any rate. Parameters involving asteroidal geohazard are complex, and numerous compared to other natural processes on the Earth.

The probabilistic nature of dying from an asteroid impact (IFOT or not) is in a sense unconditional, as there is no need for any other natural physical process or parameter to exist as a prior condition. The prior statement however is made with a defined fence around the realm of nature. Contemplating a little longer about this issue, we stop and ask ourselves if the real threat is the impactus, or our own being as humans, and the way we may react relative to an IFOT, or something sub-equivalent. If we were take into account human behavior, then our results may have to account for the disastrous nature of the subsequent war after IFOT, assuming this war occurs. We will leave this topic as it is more sociological, and focus more on the assessment of risk involved with asteroid impacts.

Charts have been plotted to show the magnitude relative to the frequency of asteroid impacts. For our analysis, we will focus on creating a timeline of research done to derive an estimate of the potential impact hazard. We will examine two case studies, and correlate them through time from 1994 (Chapman C, and Morrison D.) to the present. The two cases we consider are; (1) Tunguska (1908), and (2) K/T Chixulub (~65Ma). Use of these two events are relevant as they both have the capacity to severely harm human society.

Our updated risk assessment will focus on the relative translational movement on the Magnitude/Frequency Chart {INSERT FIGURE NUMBER HERE!!!}. From the translational movement of the two points, we could create a rough line of best fit to come up with recurrence intervals for the various other orders of magnitudes concerning asteroid impacts. The new line of best fit will potentially show us the functional recurrence interval of the two case studies. This result is plural, meaning that there is certainly different logical understanding of our results, which range from social implications, to physical implications. This matters as survival on this planet is without doubt relative to an event similar to the one we are discussing [IFOT]. Stability of our societal system is important and we concern ourselves very much with this finite risk, however we have not much contemporary data to work with, and hence, we use the two above mentioned case studies to relate possible future IFOT events.

Another point of concern is our level of ability to mitigate against imminent asteroidal disaster. Modern technology has allowed us to release kilotons of energy near or at the surface of the Earth and back-analyze the resulting effects; this technology is effectively the nuclear bomb. The energy released by this technology may be able to account for the in-space destruction of an asteroid (Morrison, 2006). Although this may be the case, there is a threshold to refute the prior statement, where technology is still unable to destroy an asteroid with a diameter of >500 meters (Shutov, 2010).

The hazard of an asteroid impact is amplified by our unpreparedness, the hazard plus its amplification is what we refer to here as *risk*. This is magnitudes more difficult to calculate since we are not a homogeneous society [global], and reactions to an imminent IFOT will vary by country, or even region. The heterogeneity of this issue is worrisome in a sense, as countries who are unwilling to take initiative on the subject of an asteroid will have a different local risk factor than everywhere else; this is obvious. International effort is evident as groups now exist monitoring and researching. Harmonized efforts to accept a global standard mitigation strategy (GSMS) are in development. For the aforementioned reason, we claim that the lack of GSMS can have an effect on the risk of global disaster.

A strong misconception about the risk associated with asteroid impacts comes from the general notion of the lack of actual events occurring. Through an array of conversations involving this topic, people generally do not believe in asteroids ending our existence at least in the near future, understandably (Morrison, 2006), and somewhat agreeable at least from our point of view. The future generations however, without being too subjective, will have an easier time with mitigation strategies if we start now. This will give future generations the head start on defending themselves from a potential IFOT.

3.3 Definition of Asteroid Impacts

We move on to defining what an asteroid is, and how impacts may directly affect us, physically relative to the impact.

3.3.1 Asteroids

There is a very intimate relation between an asteroid's impact on the Earth's surface, and the amount of destruction that pursues. Before a clear and precise explanation can be made on the subject of asteroid impacts, we will define what an asteroid is. An asteroid is a rock matter in space, significant in size, analogically a minor planet, or planetoid, or more agreed upon, a planetesimal. They are generally carbon rich, silicate rich or metal rich. They vary in density based on their method of formation, and thus resulting in different magnitudes of damage on the surface of the Earth upon impact. This brief resume of asteroids opens our minds a little to encounter the following information to be presented subsequently in this paper. This paper will focus only on the issue revolving asteroid impacts, and their associated hazard.

3.3.2 Asteroid Impacts

For this section, we will not go into depth about the *Impactus Finiens Orbem Terrarum*. There will be a dedicated category devoted to examine this specifically. Small scale asteroid impacts (*Impactus Minor*(*es*)) (IM(s)) have the potential of causing a fair amount of damage depending on where the *impactus* stikes. For example, an asteroid striking the desert versus the downtown core of Toronto. Population density plays role in impact damage its resulting casualties. Asteroids must of course be of a significant size to penetrate through the Earth's atmosphere and impact the surface, where if the asteroid were too small, it would become a pseudo-meteor, burning up completely due to frictional heat forces caused by the air (fireball). Roughly a million tons of debris fall on the Earth everyday, caused by atmosphere burn up (Morrison, 2006). There is space material affecting the Earth, not significantly in any way, however we know that there is still space activity contributing to this global deposition of meteor dust. Morrison (2006) presents a frightening number when describing a "smallest scale impacting asteroid" scenario, comparing its energy release to an "[...] explosive energy hundreds of times greater than the Hiroshima atom bomb.".

We can imagine a hypothetical situation of an *Impactus Minor* taking place over a dense rural region, where absolutely no means of mitigation has taken place at all. The scenario is of a 2km impactor, which we would consider in this paper as an *Impactus Finiens Orbem Terrarum*. The impact would produce "10^{16}kg of ejecta" (Morrison, 2006). Morrison and his team do a fantastic job to compare and analogue these events to other events which we might understand more, i.e. in relations to volcanoes and earthquakes.

Asteroids are not restricted to only impacting the Earth in a normal (90^o) manner, they can also enter the Earth's atmosphere and impact the surface from an angle causing the *impactus* to scrape the Earth, possibly causing more lateral damage on the surface. In this case, wave propagation in the sub-surface would be lower than if the impact were normal, as the energy would be frictional energy against the shear on the face of the Earth, versus the relatively full energy input from a normal impact (*Impactus Normalis*). We could see the relative percentile energy release plotted in [Figure 2(a,b)], where in the upper figure [Figure 2(a)], the impact angle of the *impactus* (x - axis) is plotted against the pressure at impact angle θ divided by the pressure at impact angle 90°. The lower diagram is plotted similarly as the impact angle of the *impactus* (x - axis) is against the (temperature at impact angle θ) divided by the (temperature at impact angle 90°).

Since we are approaching this issue statistically, we must take into account the current impact structures that are present on the Earth's surface, and then analyze them probabilistically to see which angle of impact (θ) is most probable of occurring. From that, we may be able to relate our findings with [Figure 2], and

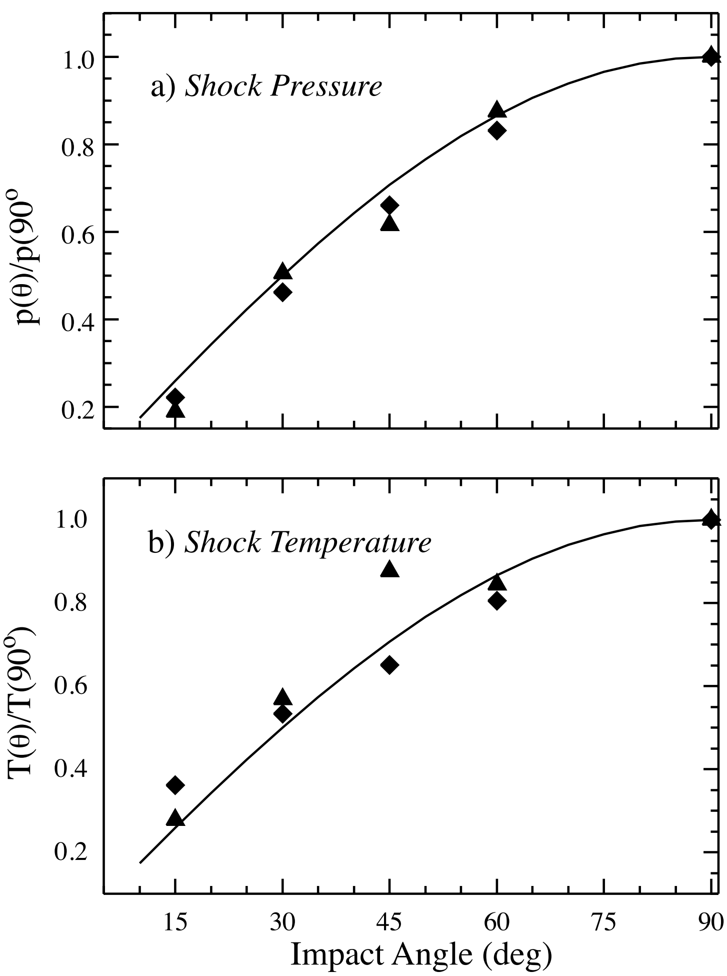

Figure (2 (a) upper; (b) lower): Plots showing the relation between the impact angle, and relative pressure upon impact (a); and relative temperature upon impact. (Source: Pierazzo, Melosh; 2000) understand more fully the probabilistic hazard of the respective energy release.

Since our main focus is dealing with the event of an *Impactus Finiens Orbem Terrarum*, we assume that the orientation of impact (i.e. impact angle) is irrelevant, as the amount of damage will be so great, that the level of concern over the orientation is negligible. That being said however, the impact angle of an asteroid with the criterion making it deserve a level of major concern, may buffer the potential energy release, because as we have seen from [Figure 2, (a) and (b) inclusive], the angle at which the asteroid hits the Earth will determine its respective energy output. Thus a more horizontally oriented asteroid impact will possibly cause lesser damage.

For the sake and purpose of this paper, there will be no consideration for the impact angle when exploring the Tunguska Event of 1908, and the Chixulub Event (65 Ma).

Conditionally, we may recall the notion of oblique impacts, and if so, these iterations will serve as a means of clarification.

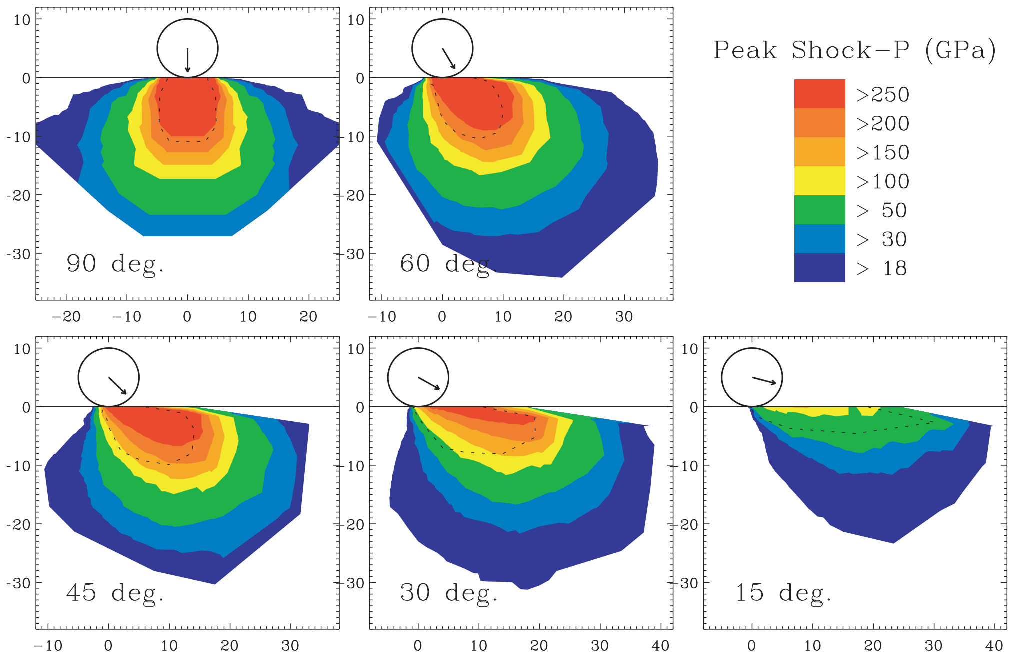

Figure 3: Graphical representation of 5 different impact angles and their associated scale of released shock pressure and extent of shock propagation. The *impactus* is considered in this case to be 10km in diameter. (Source: Pierazzo E., Melosh H. J.; 2000)

Asteroids leave a scar on the Earth's surface at impact, known as craters. Crater features are tools that we use to understanding asteroid collisions with the Earth, potentially other planets. Interactions with the Moon's surface helps in identifying a low to no weathering situation where craters are longer lasting. n Earth, structures formed by asteroids are preserved throughout millions of years, as we see for instance in the case of Chicxulub, however not obvious at the surface, it is evident from geophysical data [Figure 4]. Richard Grieve has done commendable work on the subject of impact craters, and we will refer to him accordingly we discuss craters. Our assessment of asteroid craters will serve as a means of understanding the real threat of the next IFOT, and its indirect impact on the environment [local]. Since we have concluded that the impact angle plays a role in the released energy from the *impactus*, it is fair to assume that the crater formations will be relatively resultant, relative to the impact.

Since impact angle is a general word signifying an impact at angle [physics], we introduce the following term: ***Angulus Impactus*** (AI[θ]), it is the specific term that we will use henceforth to refer to an asteroid impact with Earth.

We display this interest since as shown in [Figure 3], an ***Angulus Impactus*** of 30° (AI[30]) may

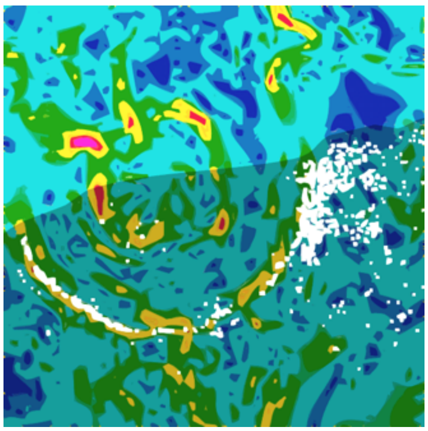

Figure 4: A geophysical readout of subsurface topography, showing a complex concentric ring pattern. This is believed to be the Chixulub impact crater remnants. Location: Yucatan Peninsula, Mexico. (Source: http://rst.gsfc.nasa.gov/Sect18/Sect18_4.html)

cause a pressure differential further than compared to a 90° strike. Relative to a densely populated city, this difference is significant as there is more civility to be disrupted. Note, an assumption that a higher population density will be more commercially aware and economically valuable, which in turn may have an impact on the global economy.

A reference formula to understand the probability of an impact at angle [θ] is represented by Formula (1) below (Pierazzo, E.; Melosh, H. J., 2000):

$$dP = 2\ \sin\theta\cos\theta d\theta \tag{1}$$

From this formula, the target's gravitational field has no influence on the impact location. It is assumed that the target is subject to an isotropic distribution of impactors. The above does not account for the size of the target, which in this case will be relative to the radius as presented with this formula recognizing the radius of a non-gravitational body.

$$P = \pi(R^2{}_B)\ F \tag{2}$$

Where R_B is the radius of the planetary body, and F being the impactor flux. From further derivation, Pierazzo, E. & Melosh, H. J. (2000) have noted the gravitational factor would result in the rendering of Formula (1). From that, the highest probability of impact is associated with an *Angulus Impactus* AI[45]. Once again, from Formula (1), the probability of impact at AI[90] and AI[0] is zero, we consider it negligible.

If we hold this to be concrete and true, all impacts that have ever been recorded on Earth (and all that have not been, inclusive) must have impacted at an angle of $>0^o$, and $<90^o$.

The importance of relating this to impact events is appreciable, since applications to formal probability calculations can be made as a function of the angle at which an *Impactus* would strike the Earth.

In 2006, Richard Grieve brought forth a magnificent compilation of several research worthy impact structures in Canada. We will focus more on the characteristics of impact structures as opposed to the specific case studies. To present, a number of impact structures have been discovered, roughly 170, where 40% have been dated using isotopic methods (Grieve, 2006). This has been a significant resource for researchers to assess the recurrence interval of impacts, and how their age is represented physically as impact structures on the Earth. Weathering and other processes give rise to interesting results of impact structures, and possible interpretations, as a function of time. In some cases, thi process may directly, or even indirectly, have provided a beneficial response, as the burial of such structures preserve the site characteristics (i.e. ring structures, mineral associations, ejecta parameters).

Understanding the changes in the Earth's surface from asteroid impact interactions and their extent of damage is beneficial. This is important when dealing with populated areas as the death toll would be proportional to the impactor size and cratering parameters. Craters are interesting structures, since they are widespread, and locales are equipotential on the Earth's [continental] surface.

First considering the case of a simple crater structure [Figure 5] (normally 1 ring structure circum the *impactus* centre), the first condition is its size on Earth. The diameter of simple structures are roughly <4km, larger diameters result in complex structures (multi-ring structure).

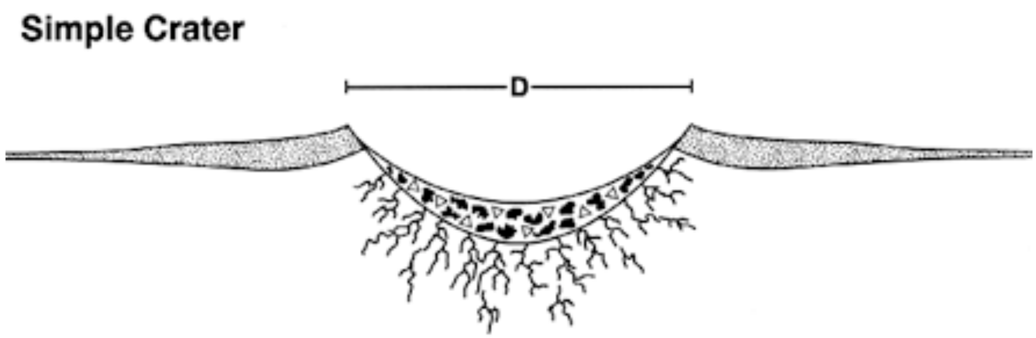

Figure 5: Simple bowl shaped crater formation from a structure <4km in diameter. Notice the lack of central uplift, and a single ring at the circumference of the crater. (Source: NASA)

For the case of more complex structures, as the energy distribution varies, the structural ring formations will also vary in distribution (i.e. distance between rings). These structural tendencies are favorable to crater diameters of roughly >4km. A remarkable feature in complex structures are the appearance of a central uplift, this is causal of the elastic rebound of the ground, after the loading stress has been relieved (French, 1998). We could compare this phenomena to isostatic rebound, where a gradual uplifting of the surface takes place after the unloading of overburden. A common example of this would be the rebound of a surface on which a significant level of glaciation has been removed. Post impact features other than uplifting or multi-ring formation exist. In complex structures, there is a degree of normal faulting induced by the steep slopes on the walls of the primary [first] ring structure of the impact crater. This may be a significant issue provided that possible restoration [development] of the land may be at risk of this faulting to occur. Note that the size of the impactor would have to be large enough to excavate a crater mighty enough to be worth developing on.

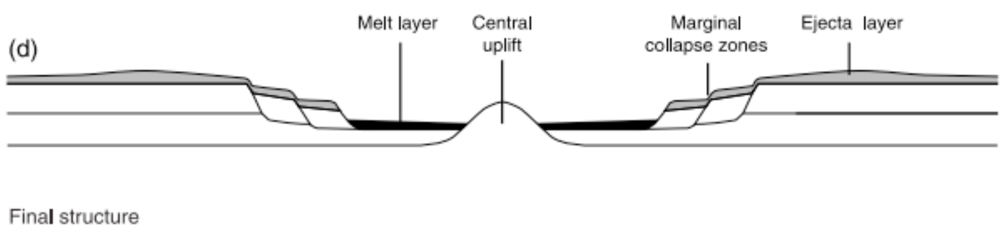

Figure 6: Simple diagrammatic model of a complex impact structure. Notice the differences between this figure and [Figure 5], where in this case, there is central uplifting, and collapse zones, notably normal faults. (French, B. 1998)

Ejecta also exists as a threat to the of the planet. Ejecta is the particulate matter that is excavated. The particles range in sizes depending on the material properties of the *impactus* and the target. Transportation of a plume of ejecta, particle size relative to suspended volcanic ash, would be a reason for concern. Subsequently, ejecta of particle size that leads it to be a projectile without any properties allowing suspension in the air could pose another danger. These particles could impose a serious threat, if large enough, to populations that are within its ejecta projectile impact zone . Ejecta of relevant sizes (small and in atmospheric suspension) are governed by meteorological conditions, we could obviously back study the effect of the weather on volcanic ejecta. We will not go into depth regarding the specific distribution properties of ejecta in this paper. Understanding of what may be a secondary threat, as a product of an asteroid impact is fundamental nonetheless.

Since we are more concerned with the structures involving the damage of the surface, we will not discuss the melt and other detailed by products of asteroid impacts.

Chapter 4

The IFOT and Relevant Case Studies

Impactus Finiens Orbem Terrarum, which literally translates from Latin: Impact Ending the Orb of the Earth, is a very strong name to give to such an event, but justice is made when relating it to the true potential of destruction that ensues from such an asteroid impact. This term encompasses various scenarios which we define.

The IFOT is the event in which an asteroid impact causes a major defilement of human society, whether it be from direct energy release, or societal degradation leading to the demise of human relational integrity and sustainability. A common misconception is that an IFOT must be an event similar to what caused the extinction of the dinosaurs (Chicxulub 65Ma). Our definition of the IFOT is supported on three parameters: 1) Size of *impactus*; 2) Location of impact; 3) Social response. These are the three general governing parameters that must be considered before designating an asteroid nearing the Earth to be an IFOT.

These events are very unlikely, and the interval of reoccurrence is very large [Figure 7].

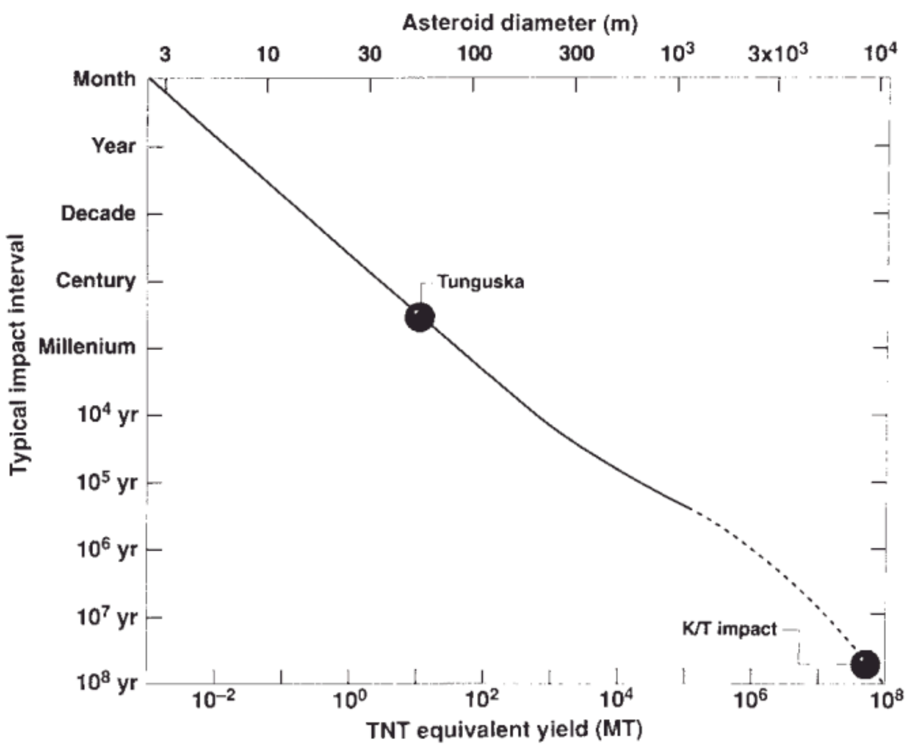

Figure 7: Magnitude/Frequency chart from Chapman C., and Morrison D. (1994). Depiction of two prior events and their relative impact intervals. From this graph, Tunguska (1908) occurs roughly every 1000 years, whereas the significantly larger K-T impact occurs roughly once every 10^8 years. Asteroid diameter (upper X-Axis) is relational to the TNT equivalent yield (lower X-Axis). (Source: Chapman C., Morrison D. 1994)

With relation to our definition of an IFOT, let us now compare the above statements to the following diagram [Figure 8].

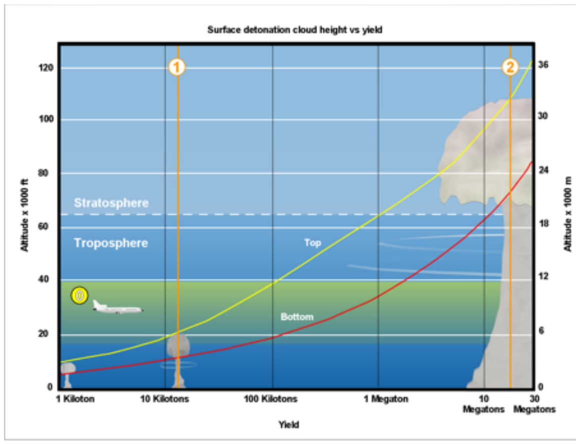

Figure 8: A simple diagrammatic model of detonation clouds for different TNT yields. For Tunguska, with a yield of 10MT, the detonation cloud may reach roughly 100,000 feet in altitude. (Source: http://upload.wikimedia.org/wikipedia/common/6/66/Nukecloud.png)

The Tunguska event of 1908 is interpreted to have released energy on the scale of 10MT. Provided that an impact with such energy were to hit at a specific time and place where global society would be perturbed, we may have grounds to call this an IFOT event.

The *Impactus Finiens Orbem Terrarum*, for our sake, will act parallel to the Magnitude/Frequency charts. Although we take into account the impact target on the face of the planet, we will consider the impact to have a globally altering effect no matter its impact site.

4.1 The Tunguska Impact

Considering the array of asteroid impacts, the Tunguska event of 1908 is mainstream, and is regarded by scientists to be a difficult case to fully understand. Controversial matter has been disputed, however our discussion will be focused more on noting on the literary findings from different works. We do so accordingly and without bias. This is also applicable to our discussion of the K-T Boundary Event (65Ma). Vast acceptance of the Tunguska event is present concerning to its characteristics upon entering the atmosphere. Simply put, the asteroid entered the atmosphere and release its energy upon aerobraking, causing it to explode at altitude, rather than hitting a single target on the ground (Chyba, C. et. al., 1993). We will take advantage here to demonstrate a formula that is used to construct a deceleration model (Chyba, C. et. al., 1993).

$$m\frac{dv}{dt}=-\frac{1}{2}C_D\rho_a A v^2+\frac{g}{m}\sin\theta \quad (3)$$

The variables here are described as (r) being the radius of the bolide, (ρ_a) is the density of the atmosphere, (g) is the gravitational acceleration (i.e. Earth: $9.81ms^{-2}$) A is the cross sectional area of the bolide, t is time, and C_D is the drag coefficient. This is applicable to all incoming impactors within any atmospheric environment where variables are available to satisfy Equation (3). Since energy is input into the atmosphere at a very significant rate from a large enough body to create concern, the Tunguska event has been diagrammatically represented in [Figure 8], where we can see clearly where the energy would escape to cause the mass destruction that was reported at the main site [Figure 9] (Svetsov, 1996). The shockwave that toppled the trees in [Figure 9] was caused by this energy release. Full ablation of the Tunguska impactor occurred at 5 km over the ground

(Svetsov, 1996). There have been few speculations revolving around the composition of the asteroid that induced the massive Tunguska event. We will not discuss in detail the different hypotheses, yet it is nonetheless important to know what are the various thoughts on the characteristics of this impactor.

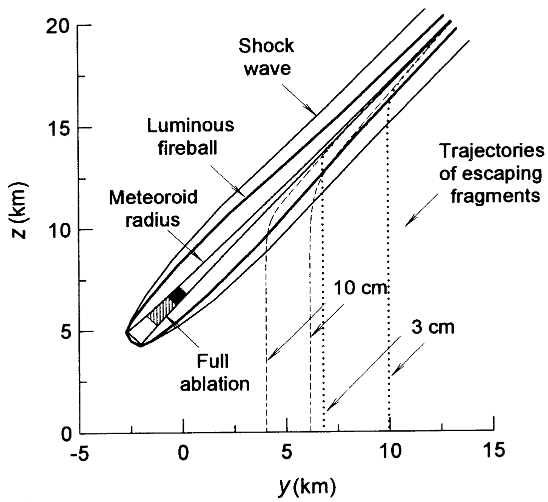

Figure 8: The trajectory and release characteristics of the Tunguska impactor. Depicted here are the various physical components of the asteroid as it traversed through the Earth's atmosphere. Notice the scale of both axes. Vertical axis is the height above ground in kilometers, and the horizontal axis is the longitudinal distance of travel of the impactor relative to its point of full ablation (~0 km in this case).(Source: Svetsov V., 1996)

Figure 9: Photo of the toppled trees in the Siberian region where the impactor released its peak energy. The scale of this photo represents a large area (and beyond the domain of the photograph) of the destruction potential of the Tunguska event. The common agreement amongst scientists is that it was the ablation of the asteroid that caused the trees to topple as such. (Source: http://lightsinthedark.files.wordpress.com/2009/06/tunguska_event.jpg)

The first hypothesis of the Tunguska impactor is that it was a fragment of another stony asteroid. This was manifested by Sekanina (1983), however was objected extensively by Levin and Bronshten (1986). A second hypothesis was released, prior to the "Fragment of Asteroid" assumption. This was made by Petrov and Stulov (1975), where the hypothesis assumed the impactor of the Tunguska event was a porous snowball. This was described to have been objected on numerous bases, and was found to be erroneous (Bronshten, V.A., 2000). Thirdly, the idea of the Tunguska impactor being related (directly or indirectly) to a so called "Plasmoid" was brought forth by Dmitriev, and Zhuravlev (1984). This was attacked as claimed in the work of Bronshten (2000), where the hypothesis has not been confirmed for 15 years, hence it is not a valid hypothesis.

We find that no matter the theory that is associated with the impactor involved in the widespread destruction of the Tunguska event, we are interested in the destructive properties, the potential of a reoccurrence of such an event, and its toll on human civilization.

The above presentation of hypotheses was to deliberately clarify the potentialities of the material of the *impactus*, and serves as a method of enrichment of knowledge, yet does not serve the purpose of changing our results. These hypotheses are not sensitive parameters in our analysis.

Tunguska is located in Krasnoyarsk Krai, in central Siberia, Russia.

4.2 The K-T Boundary Event

The K-T Boundary event is what most scientists, and knowing public, understand to be the event that caused the extinction of the dinosaurs 65 million years ago. The K-T Event was of a magnitude to be noted to be roughly ~10^8MT [Figure 7]. The release of energy was significant on the Earth's system, evidence of post impact "secondary" destruction continued through time to cause frightful consequences, one of which is the demise of a large portion of living matter on Earth. The impact site at the Yucatan Peninsula has been mapped and data has been collected trying to prove (or dismiss) the causal factor of the absolving of certain species in that period. The *impactus* was large enough to obliterate its direct impact target. It was roughly 10km in diameter (Various Sources). The buried crater that was formed by this impact has a diameter of 170km. It is the third largest impact structure that has been discovered to date on Earth. The two larger impact structures are Vredefort (300km), and Sudbury (250km). We disregard these for they are over 1Ga in age, and their association to life on the Earth is ambiguous. The resolution of the data is not as known due to environmental effects. The impact structure is complex with a clear central uplift (Grieve R. 1998).

As a subcategory, we will discuss the possible byproducts of the K-T Impact.

4.2.1 Possible Byproducts of the K-T Impact

Since the *impactus* was estimated to be so large at the time of impact, it is fair to assume that other catastrophic events may have been triggered. Conceptually, we will discuss the numerous issues that arose from this event. These issues are important since they fall under the umbrella of IFOT parameters.

The first discussion around the byproducts of the K-T Impact is directly related to acid rain, and the alteration of the atmospheric chemistry from shock heating, and chemical re-arousal (Prinn, Fegley; 1987). The assumption concerns the ozone that is ionized by the heat produced (thus destroying bonds of the O_3), then being reacted with Nitrogen in the air, causing NO_2. This, and many other agents can be produced, some detrimental to vegetation, and animal life on the Earth. As we know, water is a valuable resource, and being ruined by such an event will bare consequences, possibly irreversible.

Another hypothesized byproduct of the K-T boundary is the risk of wildfires. Wildfires have been associated with excessive atmospheric heating due to the *impactus* (Schultz, Gault;0 1982). The heating would cause widespread heating and drying. *Impactus ejecta* are of concern since they are hot at time of excavation and are able to travel large distances, transporting the heat onto another medium that can potentially ignite. Melosh (1990) describes the heating characteristic of the Earth's atmosphere as the *impactus* made contact with Earth. Temperature have been estimated to be up to 150 degrees Celsius in some regions within roughly 10 minutes of impact. This quick input of heat would cause widespread wildfires to take place.

These fires would then lead to the introduction of aerosols into the atmosphere. Not only fires, but impact ejecta particles small enough to stay in suspension would create the same effect. Similar to the largest volcanic eruptions that have occurred in Earth's history, large impacts (i.e. K-T Impact) act very much alike, where the ejection of suspendible material in the atmosphere would trigger global cooling (Covey, 1994). This particulate matter allows the Earth to shield itself partially from incoming solar radiation, hence cooling the surface of the Earth.

Since this impact event was near water, a tsunami was triggered, displacing a staggering amount of water (Bourgeois, 1988). Researchers have reported that waves as high as 300m reached the shores of the Caribbean, and other nearby shores. Today, this would be a critical situation, the tsunami wave on its own would be sufficient enough to wipe out a major part of the human race. Note that the prior statement is applicable to related impact targets (i.e. involving large bodies of water).

There are several other byproducts that, as we read on, would seem to be secondary byproducts from what we discussed.

4.3 Discussion of Case Studies

Our means of collecting this data is through literature review, we found that it is important to look at these two events (Tunguska 1908, K-T Impact 65Ma) so that we could transmit some information of destruction noted through historical cases. These two cases definitely show real disastrous potential, and as we become more dependent on our social stability as a global establishment, we continue to research the implications, and the risk associated, with such events as the Tunguska event, and the K-T Impact at Chicxulub.

Chapter 5

Data Collection Methods

The collection of data relevant to this work is important to discern. We grant acknowledgments to researchers who have played a huge role in the field of risk assessments of asteroid impacts, and studies involving magnitude and frequency relationships. Our methods of gathering data are straightforward, and formulation involved with our research will be explained in section *(4) Manipulation of Data*. We first read critically the Clark Chapman, and David Morrison article from Nature Magazine (1994), and used this as a foundation for our revision of the asteroid impact hazard.

This work will review the works of various notable researchers that have made a statement on the Magnitude and Frequency Relationship (MFR) of asteroids impacting Earth. Since we are going to focus on two major events (Tunguska 1908 & K-T Impact 65ma), we will not pay major attention to the other magnitudes of asteroid impacts, and their associated frequencies. Although we disregard impacts other Tunguska and K-T, we must nonetheless recognize that a change in the two cases we are reviewing will change the slope of the trend line on the Magnitude/Frequency Chart. This means that these changes are relative.

From the information that we collect through readings, a compilation will be made to conclude chronologically the variation in the perceived MFR of our impacts of interest. The compilation will be ordered chronologically, then projected to yield a graphical response to the inputs. These inputs being the MFR of the Tunguska and K-T Boundary events. By using these two points, there will be a superposition over the 1994 slope generated by Clark Chapman and David Morrison (1994) to see how the frequency and magnitude have changed throughout a little less than two decades.

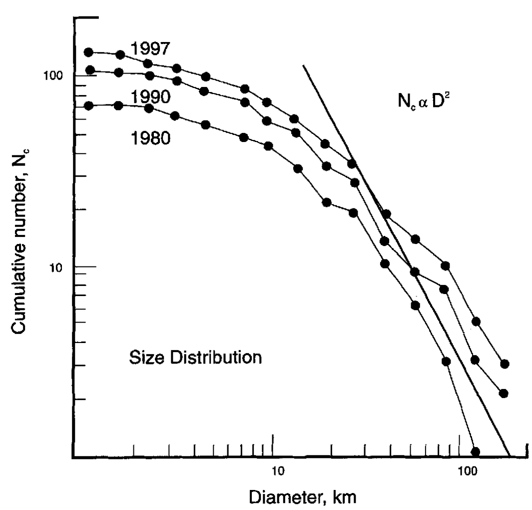

Figure 10: Chart representing the cumulative number of discovered asteroids, contoured by lines with their associated year. (Source: Grieve, R., 1998)

By this methodology, we find that it is very straightforward, and will give us the desired results. We are not expecting a specific outcome, due to the highly aleatory nature of the phenomena, and the uncertainty revolving around it. The results may vary from a decrease of recurrence interval, to an increase of recurrence interval. The fundamental difference between the two is huge, since it would mean that if technology were to trend (i.e. progress) as it is now throughout the future, we may find that these recurrence intervals may follow that trend. This suggests that for instance, an increase in frequency of a certain magnitude, catastrophic for that matter, the perceived risk of asteroid impacts will possibly motivate a higher need of awareness of IFOT's or other objects that may harm our society.

Delineation of the relative change in MFR of asteroid impacts will render some information for us, however we will need to relate it to society. Thence, we will review, and discuss the various effects that an IFOT will have on population stability on various scales, this will be done by referring to prior publishings, and our own reasoning. The importance of doing as such, for the sake of justification, is to render a general understanding to the related population. This will show great relation to the problem, and help us transmit our results more fluently, and with consistency to a general audience.

We will now move on to demonstrate the manipulation of our data.

Chapter 6

Methodology

The method in which we choose to manipulate our information consists of simple diagrammatic interpretations as a function of time. This may sound trivial, however it is tedious to delineate the results. We will refer to publications from 1994 (Chapman & Morrison), and their latter equivalents to create a trend line our output graph.

This method will render results that we are aiming to receive. Once again, the results that we are expecting are 1) Higher probability of impact; 2) Lower probability of impact; and 3) No change at all. These three results will be studied in relation to the article published in Nature Magazine by Chapman and Morrison (1994). We will look at the advancements in recurrence interval (frequency) estimations, and how they have changed since then. The change in perceived magnitude as well will be taken into account.

Papers that we have referred to to compile the information needed will be in the reference section of this work. Citations will nonetheless be made accordingly within this section.

Results may be subject to a level of bias, since the interpretation may be made from diagrammatic readouts, hence generalization may occur.

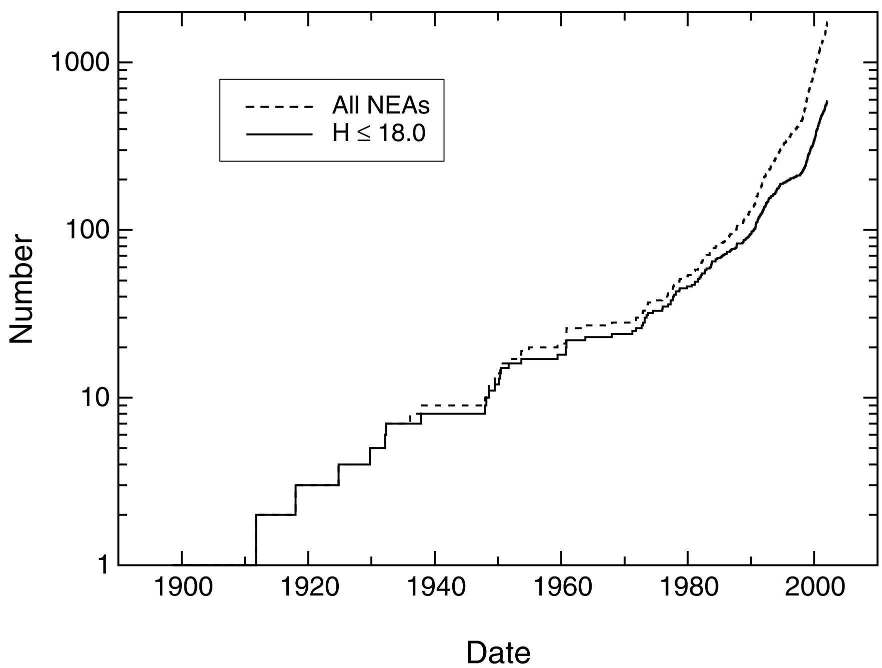

Figure 10: Logarithic scale diagram of the number of asteroids discovered. (Source: Morrison, 2002)

The reason why this study matters, is that throughout the last 20 years, the issue of the asteroid hazard has become increasingly mainstream in the scientific community. The Spaceguard program, and other research initiatives have increased their inventory of asteroids discovered [Figure 10] (Morrison et. al., 2002). For this reason, estimates of at least a subtle change in the MFR from 1994 are worthy of study, and are relevant nonetheless.

The readouts of the various diagrams that will be examined may show variations relative to the frequency of asteroid impact, such that the newly generated curve that will be produced may be above, or below the original 1994 interpretation of the MFR of asteroid impacts. Perception of the risk may change due to these effects, however it is a matter of the newly developing understanding of the risk associated with asteroid impacts that is the main concern.

Cumulatively, the graph may show anomalies and outliers, this is possible based on the level of accuracy, and time scaling that has been established for the study. For instance, the study deals with a time interval of approximately 17 years. Hence the study is at the mercy of the interpretation, and plotting technique, as trying to assure the best results, with the least ambiguity.

Standards involving the conception of such a graph are not directly outlined, and thus presentation of the graph will require explanation. This allows a clear understanding of the transmitted information regarding the change in the MFR of asteroid impacts.

6.1 Reasoning Behind Methodology

Based on the prior discussion concerning asteroids, and their magnitudes and frequencies (Section 2.x), the reason associated with the chosen methodology is basic. Since the discovery of the concept of precedence, risk has become a very valuable asset to understand. Recall that risk is the product of the probability of occurrence, and its associated consequences. In addition, the compendium of consequences directly, or indirectly associated with the Earth, is also inclusive within the realm of the "associated consequences" as presented just now. Fascinating associations have been made directly regarding earthquakes in various parts of the world, where fortunately, engineers have been able to design against such natural phenomena. The comprehension of the recurrence interval of these events, i.e. earthquakes, have allowed for fairly righteous decisions on high cost investments in the best interest of the society that is exposed to high risk.

Better clarification on the general trend concerning the future of the risk associated with asteroid impacts on Earth will lead to a better understanding, and proper estimation, of our level of concern. Thus, the question: "What is our level of tolerance?" may have to be introduced, yet we are not acquaint with such an event, meaning that there is no certain answer to that question. Based on physical models, there is still a level of understanding of the effects of *impactus* events. The issue is a matter concerning the global population, and its general reaction as a collective body.

Socially, the reference to which a comparison can be made would be the Hiroshima bomb that wiped out a significant portion of the population of Japan. This will be discussed further in later sections.

Prior investigations of asteroids within our Solar System has been done for numerous years, and is still undergoing with developing technologies (Svetsov, 2010). As larger telescopes are being proposed, on the scale of larger than 10 meters, allowing scientists and all those who are involved with a better view of space to see more, thus understanding more, subsequent to technological advancement. Information gathered from the Moon has played a huge role in understanding the cratering tendencies, and Earth interception rates. Mars has also been evaluated extensively to try to understand the potential interception rate of Earth. This has been established and brought forth to the science community through an array of publications.

If applicable, a commentary within the Results section will be to describe its effect, potentially, on the perceived MFR of asteroid impacts.

Chapter 7

Results

The application of the previously mentioned methodology has output a result showing a significant level of variation. Graphical representation of the data input manifests a number of tendencies which are relevant to the study done here. Firstly, it must be noted that the lack of precision and accuracy is not the main matter of concern, it is the actual depiction that is relevant. Approximations have been made, and these will be listed in the latter discussion.

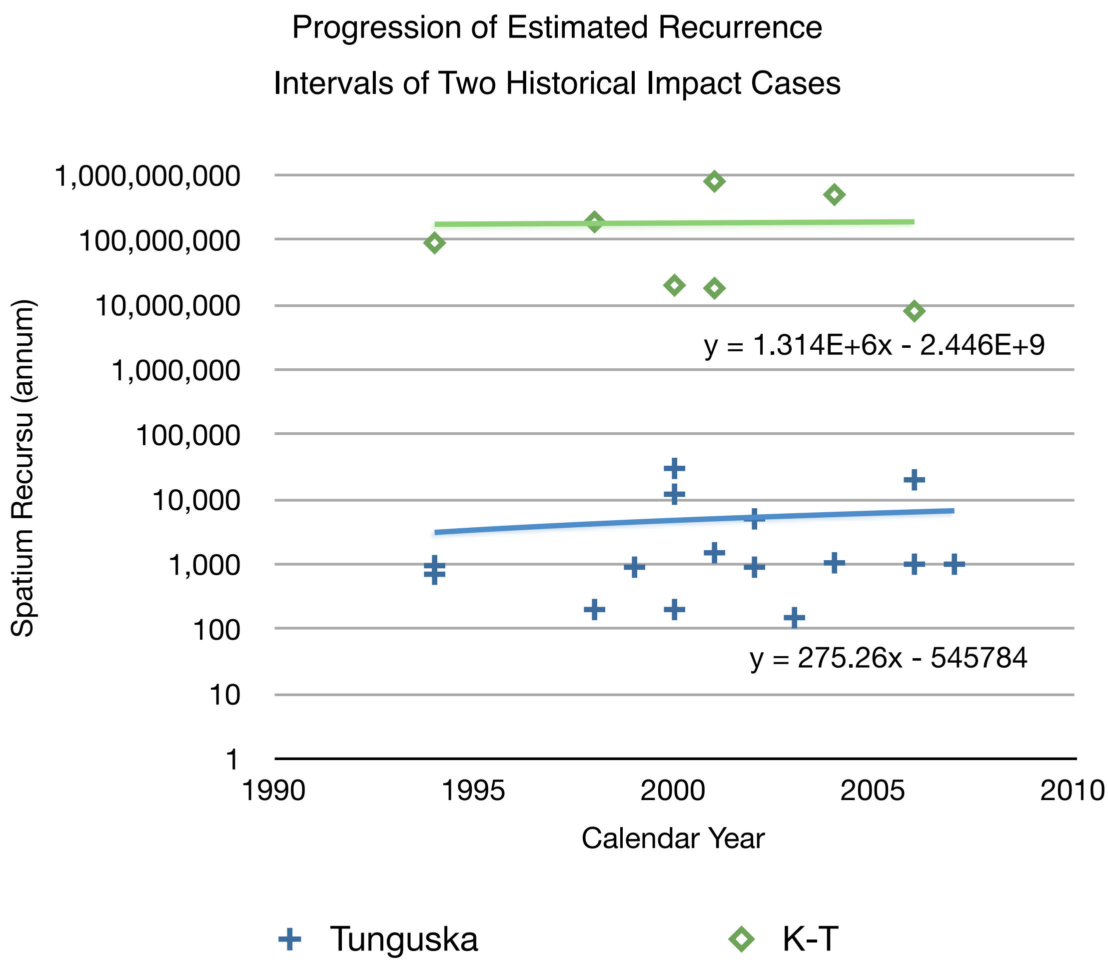

Figure 11: Generated log-lin chart from associating reviewed asteroid impact recurrence intervals to calendar year of publishing/research. The diamond symbols are associated with the K-T impact event, and the cross symbols represent the Tunguska event.

7.1 The Tunguska Case Study

Both case scenarios previously described have been applied to the study. The first case that is examined is the Tunguska event of 1908 over the Siberian region of Russia. Each data point will be represented in text as S.R. {Interval}[Year].

The significant variability in the data from 1994 to 2007 is pertinent to the field of research, both on an astronomical sense, and on Earth Impact Risk Assessment. Comprehensive analyses over the years have output different probabilities and recurrence intervals of this event. The base paper that has been referred to (Chapman and Morrison, 1994) has been estimated to have output approximately S.R. {700}[1994]. Subsequent research at the end of the 20th century has then released a number of roughly S.R. {200}[1998] and S.R. {190}[1999]. The beginning of the 21st century then has output astonishingly higher recurrence intervals, a whole magnitude higher than the initially discussed intervals of the prior millennia. In 2000, Rabinowitz et al published a value of S.R. {30,000}[2000] via the NEAT program. The same year however, another recurrence interval was accounted at S.R. {12,000}[2000]. Comparatively, the scale between these two numbers is not very significant, nonetheless, the fact that the difference between the minimum return interval, and these values range two orders of magnitude, which is significant. Further research has released very similar numbers to the 1994 index. By referring to the produced chart, a focus of the points is obvious until 2007. In 2007, the interval was noted to be S.R. {1000}[2007]. A linear approximation was derived from this generated graph, its function being:

$$Y = -21.555X + 47586$$

This approximation contains an element of bias discussed further in the following section. This equation represents an assumed steady-state technological advancement versus advance in time proportionality which would result in a value relative to time of the recurrence interval of the Tunguska event. This is nowhere near reality since the concept of exploration would lead to further findings and subsequent anomalies which may be irrepresentable in this manner.

7.2 The K-T Boundary Case Study

The K-T Boundary Event is not as easily determinable as the Tunguska event in any sense. Ambiguity in the results is very evident, and in no way is the solution to this issue trivial. There are only 5 data points in which reference is made to, due to the prior mentioned reason. Ranging from 1994 to 2004. Two of the data points are plotted at 2001. The reference index is S.R. {100,000,000}[1994]. The maximum and minimum values were both published in 2001. The minimum being S.R. {18,000,000}[2001] and the maximum S.R. {800,000,000}[2001] (Werner et al 2001, Stewart 2001; respectively). The value manifested in 2004 is S.R. {500,000,000}[2004]. The extreme variety of these results depict the evident uncertainty through time, and no centering in of the recurrence interval, whereas the Tunguska curve shows evidence of such. The data can be interpreted via the power law:

$$Y = 4.338E{+}7X - 8.642E{+}10$$

The plotted data is not specific to the actual date, but to the year in which the work was published, or noted to have been retrieved. Thus, the data interval is one year.

7.3 Overview of Both Cases

From the plot, there is an apparent anomaly in 2006, related to the 2006 work of Bland and Artemieva. This it due to the representation of both surface and atmospheric data and modeling. This is clearly represented in their figure 17. After the completion of the graph, interpretation of either scenario were notably unrelated to one another. The interaction of the smaller bodies with Earth is very contrastful with larger bodies. Atmospheric and surface data vary on orders of magnitude, and this is very noticeable when referring back to the Tunguska results. The K-T Boundary results were analyzed based on reverse-bifurcated reproductions, notably in the Bland & Artemieva 2006 paper. The Tunguska trend line is sloped positively, as the *spatium recursu* of the similar events become greater. Thusly, the atmospheric data, and surface data and modeling, are bifurcated. The maximum and minimum variations in the data could be respectively associated with these study methods. This does not void the concept of uncertainty applied to the prior estimates.

Chapter 8

Discussion

The results processed according to the methodology presented in Chapter 5 represent a variety of interpretations. Although perception of the asteroid impact risk is variable, there must be a solid conclusion. Time is unmentionable regarding this. Until there is quasi-perfect knowledge of the system as a whole, this variability may exist for much longer than might be thought. Assumptions and estimates are made based on knowledge and data available, this is evident, and must be understood to comprehend the true variability of this study's results. Anomalies exist in our results, nonetheless they are very important in appreciating the true nature of the results, and the inevitabilities of modern fallacies, i.e. technological limitations, human error, etc..

A higher level of variation exists specifically for the output results for the Tunguska event. Since this event is highly studied, and is doubtlessly a potentially catastrophic event, it is justified to spend an ideal amount of time discussing this further, and deeper. From the graphical output of the results, a trend line was issued to illustrate a general trend of recurrence interval estimates since 1994. This trend line has a linear slope of approximately -21, for a span of 17 annum. There are 12 inputs for the respective plot.

The Tunguska impact recurrence interval is of significant importance since it documented, and witnessed by relatively modern society. This event occurred at a latitude considered to be fairly northward, which by referring to [Equation 1 & 2], is fairly improbable. This is assuming that the impactor origin is a horizontally, planar like orbit, relatively orthogonal to the Earth's axis of rotation. Therefore the probability of a similar impact to the Tunguska Impactor would be higher for the Equatorial region, and lesser for polar regions. The logic holds, based on the following assumption, that the published impact intervals are for the specific region only, such that the published probability of the Tunguska Impactor is applicable to that specific latitude. Based on the results, and the prior assumption, this would be significantly important for the equatorial regions, where especially the minimum probabilities from the chart would mean that these regions are significantly more prone to impacts of the sort. Evidently, impacts of that scale are not very frequent, thus making an impact on the perception of the specific risk versus the absolute risk. Specific risk is risk associated to a particular latitude, whereas absolute risk is the risk of impact anywhere on the planet. The absolute risk would therefore in this regard be the maximum risk of impact, since it is the most likely to occur. For this statement to have an effect, there must be a general consensus on the true probability.

Perception of the absolute risk is inherently different than the perception of the specific risk, in the sense that a specific risk is only within the domain of the specified latitude, hence, the polar regions would be less concerned versus the equatorial regions. Although the perception of specific risk is important, the absolute risk is more applicable to the Earth, and is relevant to the entirety of the globe. This is directly related to all the byproducts of an asteroid impact. Given an asteroid causes mass damage to the direct impact site, and provided the asteroid is large enough, it can cause planetary alterations, such as a decrease, or speedup in the rate of planetary rotation, etc.. Characteristics in lunar properties may change due to the inequilibrated interaction with the Earth, in the sense that its orbit may suffer a physical change to reach an equilibrated state. These changes can have long term consequences for the stability of life on Earth.

The variations in the resulting plot is also indicative that different technologies and interpretations alter the perception of asteroid impact risk. Observing the generated plot, the are more points above a 1000 year S.R., which shows that subsequent research as of 1994 showed less likelihood of an impact such as Tunguska to occur. Nonetheless, there are points below the 1000 year S.R. and they are not to be neglected. These points are however not as prominent as the >1000 S.R. points. Another observation is that these points lie roughly in the centre of the study interval, 2000 to 2003. Based solely on this fact, the assumption is that the absolute probability of an asteroid impact is going down. Note that as absolute probability lowers, the specific probability also lowers proportionally to the latitude.

Subsequent observations show an apparent focusing of the points as time progressed. Advancing technology may be the cause of this focus. The focus is the S.R. 1000 region. Note that focusing is possible in any direction. The assumption is that the reference was made back to earlier work manifesting 1000 year recurrence interval for the Tunguska event. Still and all, the reference was deemed to be just, and accepted, hence it is, nevertheless, of value to the consideration of risk perception.

The K-T Boundary event is represented on the graph with few points. This is indicative of a high level of uncertainty and unsupported justifications. A scatter exists in the data points represented in the resulting plot, though differences exist between this and the prior examined case. The S.R. of the K-T Boundary event is accepted generally at 65 million years, though the results show the S.R. of the event to be changing. 5 points representing this event show an increasing S.R., where the 2004 interpretation yielded an S.R. of 500 Ma. This is a significant difference relative to the accepted 65 Ma estimate. A power law demonstrated the resulting curve:

$$Y = 4.338*10^{7}X - 8.642*10^{10}$$

This event is important in the sense that it is large enough to cause mass extinction. Unlike the Tunguska Event, this is significantly more disastrous, and follows the inverse relationship concerning magnitude and frequency. The Tunguska Event is more frequent, and nonetheless catastrophic. Asteroids that are similar to Tunguska exist, and have been paying us visits (i.e. 1989FC, 2008 TC3, etc.). Although consequences of K-T Boundary like events are much higher, it is not as frequent, and the relative benefit of examining it is little in comparison to the benefit of studying Tunguska like events. Society will be faced with a challenge smaller than the K-T Boundary event, but potentially as disastrous as Tunguska within the lifespan of civilization.

In the last 17 years, it is manifest that there is ambiguity in the studies over time. However, there is no concrete way to acknowledge one right estimate. The work that has been done is commendable and contributes to the scientific community greatly.

In 2006, Bland and Artemieva have proposed the assumption that the broad majority of impactors are Asteroids, containing the same composition steadily (Bland P. A., Artemieva N. A., 2006). This implies that the study revolving around asteroid research should be more focused on asteroids. Knowledge of cometary and other far-field impactors is however important, though impact is not as probable.

Chapter 9

Relation to Today and Societal Impacts

9.1 The General Perception

The global population is not distributed evenly, instead it is very localized, focused, and sparse. This presents a challenge in understanding specific risks of an IFOT event. Global population has also been increasing at a noticeable rate, and in certain regions. Growth has no effect on the probability of asteroid collision, due to its sheer independence of the matter. The population distribution on Earth, is important. It is general knowledge that asteroids exist, and that they do impact the Earth on occasion. Large scale impacts are very improbable though they are possible (Morrison, et. al., 2002). Relating to the magnitude frequency relationship of asteroids, this would imply that smaller scale asteroids are more probable. A smaller scale asteroid is >1km in diameter.

The population on the Earth is exposed to danger differently based on geological settings. Fault lines may be activated causing massive earthquakes along respective regions. Though other regions of the world may not have such potentially catastrophic geological components. Asteroids are better understood, and the general public is offered an array of services to refer to asteroid information, for instance the NASA NEO website contains information on all Near Earth Objects that encounter Earth on a relatively close scale. The public now understand more on the topic, and are becoming more informed. Projects and foundations such as the B612 foundation strive to excel the objective of intercepting asteroids headed for Earth. Programs have been developed to coin a better understanding of the asteroid hazard. Spaceguard being a prominent name in the field of asteroid hazard assessment is a leader since the late 20th century. It is comprised of many partnerships and team members, working together to press forward on the understanding of the asteroid impact hazard. For the general public, this information is not made mainstream, and is not widely available. It is available on certain websites dealing specifically with this issue.

Asteroid impacts affect everyone given impact over a prime location, for example dense business districts. A densely populated, high traffic, commercial city would be absolved from the surface of the Earth if an impact similar, or larger, than Tunguska would occur. This presents repercussions to daily life. If not dealt with accordingly, a substantial amount of money will be lost, and people will suffer. This hypothetical reality is unlikely but has a finite probability as seen previously. The consequences of an economic meltdown are known, and are apparent from the reaction of the general public to tough economic times. Foreshadowing of the effects of an economic crash can be made based on prior events, such as the downturn of the early 21st century, and the economic crash of the early 20th century. An asteroid impact destroying the city of New York would have extreme consequences, and immediate measures would involve mass job losses, currency crashes, and general economic hardship.

A modern case scenario is the possible Apophis strike of 2029 or 2036, where a slight alteration could drastically change the outcome of the astroid's impact capacity. Apophis has the potential to severely damage a large region upon impact. It is noted to be approximately 210 meters to 330 meters in diameter. (NASA/JPL/NEO, 2008) The probability of a strike occurring is on the order of negligible amounts today. In 2004 however, the asteroid had a probability of 2.5% of striking the Earth. Scientists and astronomers estimate a return of the asteroid in 2036 provided it transits through what is known as a keyhole. This keyhole is very small, though still a matter of discussion in the community.

9.2 Variability in Asteroid Hazard Perception

Societal interpretation and perception of the asteroid risk is variable on a personal level. The significance of an asteroid impact may be of great importance to some, and completely negligible to others. The result of an asteroid impact, such as by product effects, are not well understood, and can skew the interpretation of the hazard. Similar to nuclear weaponry, asteroids can emit energy in alarming amounts. Amounts could be high enough to ignite clothing, blind upon sight, deafen. These occur at proportional distances relative to impactor size.

9.3 YU55

An NEA approach (YU55) is due for November 2011. The asteroid will reach a a minimum distance to Earth of 0.85 Lunar Units, or roughly 326,000 kilometers. It has a diameter of approximately 400 meters (NASA/JPL). The probability of impact is very low and is deemed unlikely to strike the Earth. A strike of this magnitude will have devastating effects on populations, given the location of impact is a relatively densely populated region.

9.4 Progress and Change

The monitoring systems have developed to accommodate evolving technologies and concerns. Scientists use this information to better understand, and to comprehend the mechanics of such bodies. The general population has not acted upon this increased knowledge, though the scientific community is thriving on the progress of the understanding of the asteroid impact hazard.

Since it is clear that the asteroid impact probability is variable relative to latitude, the death toll proportionality thus becomes an issue of population density per latitude. This is not taken into account when developing magnitude frequency charts, since life is not in consideration. The change in probability of impact is of concern if it is related to a definite impact. Probability variation due to latitude is useful in predicting impact location based on statistical methods. With regards to near misses, the concern is focused primarily on the probability of impact, and not the probabilistic approximation of the impact location.

9.5 Concluding Remarks

Reaction of society due to an impactor larger than 1 kilometer could be diverse based on the location. Fires and Earthquakes can be generated by asteroids as little as a few megatons worth of energy (Morrison, 2006). Hollywood's depiction of armageddon is not all false, though scientifically is not very well backed up and represented. The public perception of the mass havoc of asteroids is not far off in terms of energy released and death and destruction associated. Educating further to ensure understanding, and to inspire projects, can have a positive effect. The consequences of the results that were produced in this study is that there is still no clear conclusion on the asteroid impact hazard, and IFOT hazard. It is widely agreed upon that there is no imminent threat to humanity by an asteroid impact, though as Morrison explains from the 1998 work of Alvarez, that smaller, more frequent events still have potential to penetrate through the atmosphere, and cause mass damage (Morrison, 2006). This is becoming clearer, and as information is transmitted at stunning speeds, the general public is becoming more educated of the consequences of an asteroid impact, although the hazard is still a matter of discussion, and criticism.

Chapter 10

Conclusion & Acknowledgements

The asteroid impact hazard and IFOT hazard are two separate entities in essence, the lesser more frequent, whereas a mass extinctor not so much. This abides by the law of inverse relationship of magnitude versus frequency. Science is evolving (Shustov, 2010). Evolution in the understanding of asteroid interactions with the Earth has driven science to excel in providing near accurate information on Earth approaching asteroids. The late 20th century case involving a near miss of 1989FC, where detection of the potential impactor was late. The impactor was significant in size to cause alarm (Gilchrist, 2008). A worthwhile undertaking is occurring in this ever broadening science, as its potential outcome is pivotal on the perception of life on this planet. Without proper warning, or conventional technologies, it is dangerous to disregard the threat of an asteroid impact. This risk is real, and the probability of a collision with Earth is finite.

The results showed a vast amount of fluctuation in the yearly probability of asteroid impact, and does not agree with one specific result. Its broadness is a matter of concern, and is to be studied deeply, and with much attention. This is a new science, technology is ever evolving, and science has helped the community evolve thus far. Programs exist to bring awareness and to study the potential disasters of the various impact events that may be imminent. As the technology advances, and new technologies allow better cataloguing, and better interpretation, the human society will be faced with superior knowledge on the threat that is until now, still, misunderstood.

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Chapter 11

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