Risks Posed by Comets and Asteroids and Their Wider Impact

The Long View

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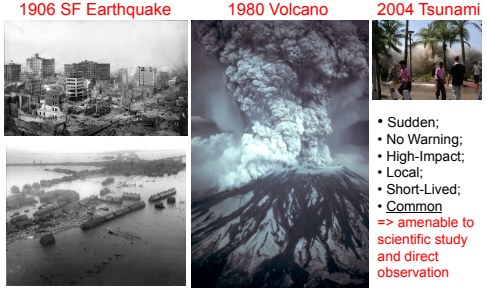
Natural Catastrophes

1906 SF Earthquake | 1980 Volcano | 2004 Tsunami



- Sudden;
- No Warning;
- High-Impact;
- Local;
- Short-Lived;
- Common

=> amenable to scientific study and direct observation

1953 Flood

Images from Wikipedia Commons and sources therein

"Unnatural" Natural Catastrophes

Neither sudden nor short-lived

- often a slowly acting process, plenty of warning

Can have a global reach

- e.g. climate change; we are all affected

Often no recent experience of their seriously adverse effects

- => an inevitably more "subjective" reaction to the risk, ranging from denial to fatalism; and
- need to rely on science, but greater scientific uncertainty owing to inevitable extrapolation from current best theories

History perhaps our best guide

What is "Risk"?

1. Risk: "hazard, damage, chance of loss or injury; degree of probability of loss…"
   - Chambers 20th Century Dictionary
2. Risk: "the possibility that something unpleasant will happen…"
   - Compact Oxford English Dictionary
3. Risk: "Uncertainty in outcome, whether positive opportunity or negative threat, of actions or events…"
   - HM Treasury "The Orange Book" (2004)

Specifying Risk

In common parlance, Risk is "the chance that something adverse will happen…"

- this is too loose; we need to specify the circumstance and the probability of it happening;
  - => risk can never be reduced to a single quantity; it always contains two separate components

For example, Risk is "the probability that a specified undesirable event will occur in a specified period or as the result of a specified situation…"

- HSE "The Tolerability of Risk…" (1992)

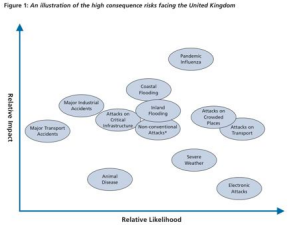
The Risk Matrix

	IMPACT	1 Low	2 Low-Medium	3 Medium	4 Medium-High	5 High
SCORE / FREQUENCY						
5	High	5	10	15	20	25
4	Medium-High	4	8	12	16	20
3	Medium	3	6	9	12	15
2	Low-Medium	2	4	6	8	10
1	Low	1	2	3	4	5

Here, for example:

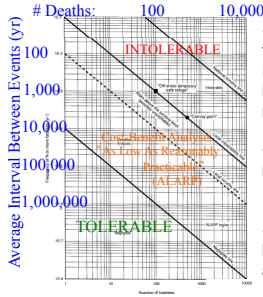
1) "High Impact" means "Resulting in failure of key Observatory and/or Department objective(s), or financial loss exceeding several £M, … or significant public embarrassment to the Department and/or National media coverage, or attention from the Assembly and Public Accounts Committee…or Death";
2) "Low-Medium Frequency" means "Might conceivably occur at some time".
3) The Risk is the product of Frequency and Impact, in this case RED

Graphical Representation: The Risk of Rare, High-Consequence Events



Frequency-Impact diagram for various high-consequence risks facing the UK (Figure from UK Cabinet Office National Risk Register, 2008)

"F-N" Criteria for Societal Risk



- Risks deemed intolerable if the annual frequency (F) for N deaths lies above the intolerability line => action must be taken to reduce risk
- Below this, seek to reduce risk to an acceptable level, "ALARP"
- Risks deemed tolerable if below the negligible line => accept the risk.

After Nigel Holloway (1997 Spaceguard Meeting, RGO, Cambridge). Figure adapted from HSE Fig. D1 "Tolerability of Risk" (1992)

Death of the Dinosaurs

- A "random" impact of an asteroid or comet 65 Myr ago changes the course of evolution of life on Earth;
- Without this asteroid impact, we would not be here today

Painting by Don Davis, showing asteroid impact that killed the dinosaurs. Source NASA and Wikipedia Commons

Bombarded Earth

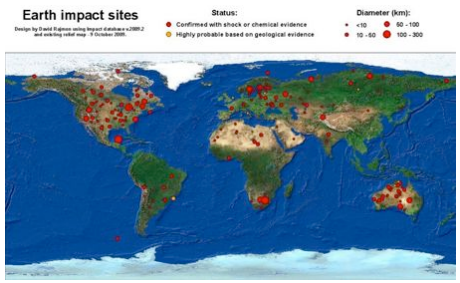


Image from David Rajmon (2009); Impact database 2009.2.
On-line: http://impacts.rajmon.cz

What Are They?

Near-Earth Objects (NEOs)

- any astronomically "small" body capable of passing close to Earth

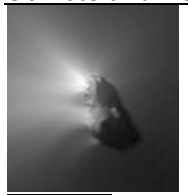
They include:

- comets
- asteroids
- fragments of comets or asteroids
- asteroid-like, "dead" or inert, devolatilized comets

Sizes range from houses to mountains

- i.e. tens of metres up to tens of kilometres or more

Comets and Asteroids



Comets:
1P/Halley, 81P/Wild, 19P/Borrelly, 9P/Tempel

Asteroids:
Eros (L); Ida and satellite Dactyl (R)

Spacecraft images courtesy NASA and ESA

Growth in Knowledge of NEOs

1801: first asteroid discovered asteroid (Ceres)
1898: first discovered Earth-approacher (Eros)
1932: first discovered Earth-crosser (Apollo)
1970: about 30 NEOs known
1990: about 135 known
1999: about 900 known
2010 (Jan): about 6650 known
- cf. all known asteroids ≈500,000

- Estimated population of NEOs larger than 1 km in diameter is approximately 1000; this leads to
- Mean collision frequency ≈1 per 200,000 years

Movie courtesy Martin Murphy and Scott Manley (Armagh Observatory)

Effects of Impacts

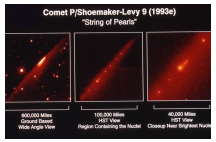
Diameters 50 to 100m
- energies 10 to 100 Mt*; craters up to 1km across

- Diameters 100m to 0.5km
- energies 100 to 10,000 Mt; craters up to 5km
  - Impacts on land destroy a large city or a small state
  - Oceanic impacts produce massive tsunami
- Diameters 0.5 to 2km
- energies 10,000 to 500,000 Mt; craters to 20km
- tsunamis reach ocean scales
  - Land impacts destroy a country or affect global climate
- Diameters 2 to 10km
- craters 20 to 100km; global mass extinctions

*1 Mt ~ 4×10^{15} J

Impacts Occur: Comet SL9 on Jupiter

Comet D/1993 F2 (Shoemaker-Levy 9)
- discovered 25 March 1993, having previously passed within Roche limit of Jupiter on 8 July 1992
  - broke into > 20 fragments
- the fragments (the observed S-L9 comet) impacted on Jupiter from 16–22 July 1994
  - produced impacts and impact scars visible from Earth

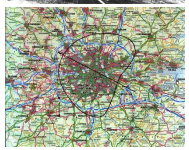


Highlights uncertainty
- if such impacts were to occur "randomly", say on average one event every 2,000 years or so, what is the chance of seeing 20 impacts over the course of a single week
- the key was (1) the orbit; and (2) the break-up event

HST images courtesy NASA and ESA

Impacts Occur: 20th Century Impacts

Tunguska: 1908 June 30



Sikhote-Alin: 1947 February 12

Tunguska tree-fall (Kulik); "Tunguska over London" (J. Tate); Sikhote-Alin meteorite (Russian Academy of Sciences)

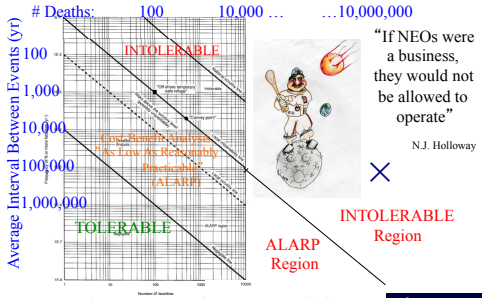
Actuarial Cost of NEOs

The annual "insurance premium" should at least cover the expected losses per year…
- i.e. collision rate times the "cost" of one collision for globally devastating impacts (d ≥ 1 km) …
  - impact frequency ≈1 per 200,000 years
  - fatalities ≈25% of whole population (~15 million)
  - actuarial cost of a single life c.£1.5M

=> for UK alone, "cost" of NEOs ≈ £100M per year

Raises important questions: e.g.
- this is a world risk, so total world cost is even higher
- this is a world risk, so it's not our job!
- as impacts occur so infrequently, we can safely ignore them, trusting to fate; but can we afford to ignore them?

NEOs on the "F-N" Diagram



"If NEOs were a business, they would not be allowed to operate"
N.J. Holloway

After Nigel Holloway (1997 Spaceguard Meeting, RGO, Cambridge). Figure adapted from HSE Fig. D1 "Tolerability of Risk" (1992)

The NEO Impact Hazard is Unique

The risk is potentially unbounded

- not just civilization; survival of species at stake

Impacts are predictable

- years or decades in advance, given sufficient knowledge of the NEO ensemble

Impacts are avoidable

- given enough warning

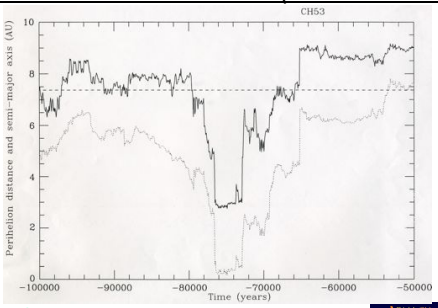
=> most of the risk can be mitigated

- e.g. remove population from "ground zero"; store food supplies etc.
- e.g. deflect the NEO in space, so it never hits
  - but who controls the deflection technologies?

Recent Advances in Cometary Science

1. Size distribution includes large bodies
   - "Giant" comets (diameters > 100 km) exist in both the long-period and short-period comet flux
2. Comet orbital evolution is highly chaotic
   - i.e. highly unpredictable in the long term
3. Comets are very fragile, easily broken up in space (e.g. Sungrazers; Shoemaker-Levy 9)
   - i.e. relatively short physical lifetimes (few kyr)
4. Comet evolution and decay leads to streams, or trails, of debris in the solar system
   - hence, non-random impacts on Earth (e.g. meteor showers, SL9 on Jupiter etc.)

Chiron Orbital Evolution (Clone CH53)



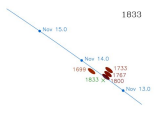
Effects of Impacts

Impacts can produce effects ranging from mass-extinctions of life (e.g. KT boundary c.65Myr BP) to merely local damage (e.g. Sikhote-Alin 1947); and mythology and superstition (Tunguska 1908)

Solar System — Earth Relationships

Focus on Comets

- their orbits, physical characteristics and numbers all vary on time-scales of human concern
- they also contribute to NEOs: a relatively recently discovered population of Earth-interacting bodies
- they produce meteoroid streams that intersect Earth's orbit



Implications: Medium-Term

On the ~1 Myr time-scale associated with human evolution, expect:

- up to ~5 Earth-impacting kilometre-sized NEOs
- up to ~10 Jupiter-family "Giant" comets (with d > 100 km)
- up to ~20 Halley-type SPC giant comets
- up to ~2,500 Jupiter-crossing LP giant comets
- up to ~10,000 Earth-impacting Tunguska-size objects

Suggestive evidence for some of these includes:

- unusual comets and debris streams
  - e.g. 2P/Encke
  - e.g. Kreutz family
  - e.g. the dense Taurid meteoroid stream
- the obsession of ancient societies with celestial events?

Implications: Short-Term - I

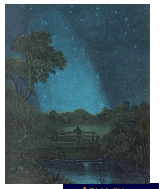
Ancient societies obsessed by the sky:

- e.g. early astronomical interest in "the sky"
  - e.g. megalithic monuments and prehistoric "rock art"
- Neugebauer: " …ancient "astrology" can be much better compared with weather prediction from phenomena observed in sky than with astrology in the modern sense of the word."
  - suggests knowledge of a direct link between the sky and the Earth
- => consistent with more "activity" in the sky in the past
- suggests some solar system phenomena may change on much shorter time-scales than we normally consider possible

Implications: Short-Term - II

Ancient Greek "mysteries"…Problem of the Milky Way … Zodiacal Light?

- Anaximander: describes stars as like the lighted jets of gas spurting out of a punctured hoop of fire
- Aristotle: believes the Milky Way to lie in the sublunary zone, a hot accumulation of the disintegration products of many comets
- Anaximander, Parmenides, Leucipus: the stars lie below the Sun and the Moon;
- Metrodorus and Oenopides of Chios: the Milky Way is the former path of the Sun
- Anaximander and Democritus: Milky Way lies in the shadow of the Earth



Conclusion – I: A Unique Risk

Extraterrestrial processes present unique conjunction of difficulties for conventional risk analysis

- no recent "claims" experience (except perhaps historical record)
- potentially unbounded consequences, though low probability of occurrence
- global reach, so who has responsibility to act?
  - and who controls mitigation strategies?
- The "Actuarial" approach provides a rational way to rank risks
  - but current understanding may be less certain than we believe

The impact hazard is unique: (1) high risk; (2) a precisely predictable time of occurrence; and (3) potentially avoidable

- has implications for survival of civilization and human race
- perhaps also for the future evolution of life on Earth

Conclusion – II: The Long View

As a result of curiosity-driven research we live at a "special time" in the history of life on Earth

- we recognize Earth's place in the Universe; that Earth is a bombarded planet; and an "open" system, in touch with its near-space environment
- we also know that impacts hold the key to the long-term development of civilization, even the evolution of life on Earth

For the first time in the history of life on Earth (≈3.8 billion years) the facts are broadly known

- and a species (namely us!) has the knowledge to mitigate the impact hazard
- will we rise to the challenge or face extinction?

Acknowledgements

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