EARTH 270 – DISASTERS AND NATURAL HAZARDS (v. 2018)

Kensennuma City, Miyagi Prefecture , Japan, March 2011

PROFESSOR S.G. EVANS, PhD, PEng (Room 303, Earth Science and Chemistry (ESC) Building)

UNIVERSITY OF WATERLOO


THE IMPACT HAZARD

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2006) **364**, 2041–2054
doi:10.1098/rsta.2006.1812
Published online 26 June 2006

Asteroid and comet impacts: the ultimate environmental catastrophe

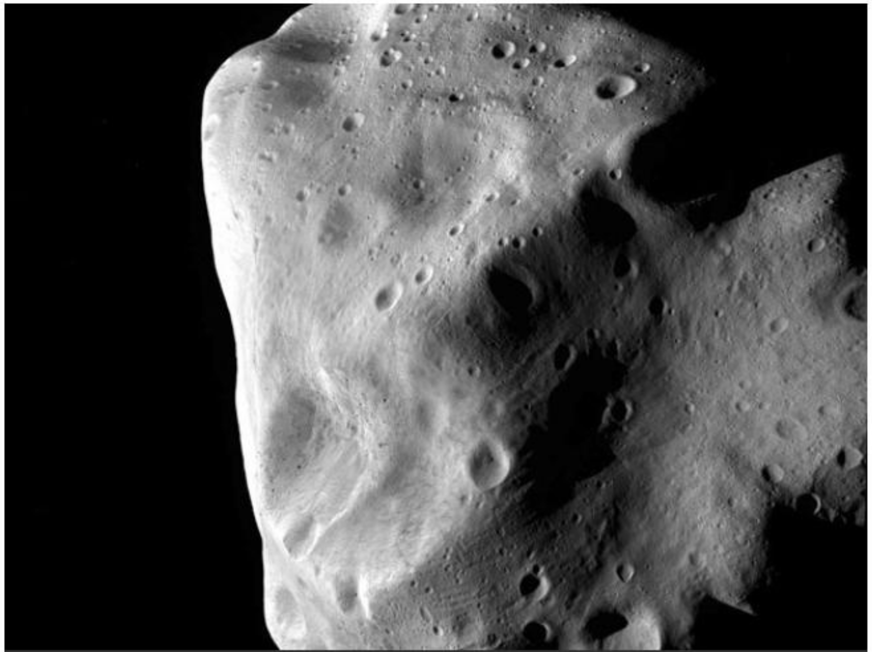
BY DAVID MORRISON*

Working Group on Near Earth Objects, International Astronomical Union
14660 Fieldstone, Saratoga CA 95070, USA

Cosmic impacts represent the most extreme class of natural hazards, combining a very low probability of occurrence with a capability of killing hundreds of millions and destabilizing global civilization. Fortunately, these disasters are amenable to precise prediction and even (in principle) can be avoided entirely by appropriate application of space technology. However, impacts take place so rarely that they have only recently been recognized as a significant natural hazard. Concerted international action to deal with impacts depends on increased public awareness.

Thousands of asteroids capable of catastrophic damage to Earth ‘orbiting nearby’: NASA

NP REUTERS | December 7, 2011 10:52 AM ET
More from Reuters



A handout picture taken by the European Space Agency's (ESA) Rosetta probe on July 2010 and released on November 11, 2011 by the European Southern Observatory (ESO) shows the asteroid Lutetia AFP/Getty Images

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NASA Spaceguard finds thousands of nearby asteroids big enough to harm Earth

Earth defenceless from asteroid collision, says Nasa chief Charles Bolden

NASA chief Charles Bolden has revealed earth is defenceless against any potential asteroid collisions, and the only thing we could do is pray.

By DION DASSANAYAKE
PUBLISHED: 20:25, Thu, Mar 21, 2013

SHARE f TWEET 2 3

Nasa chief Charles Bolden said earth is powerless to protect itself from an unknown asteroid attack

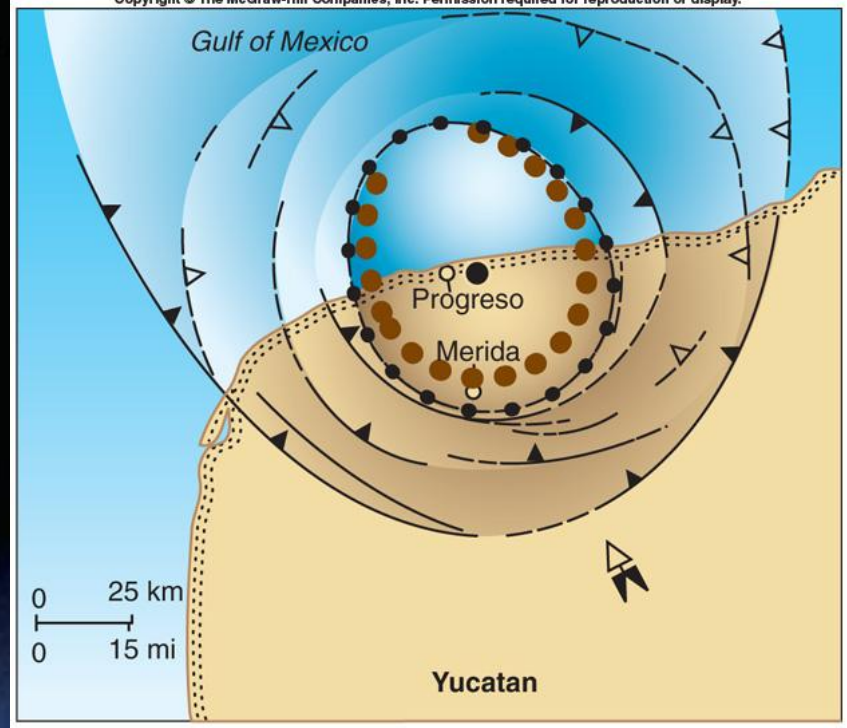
The former astronaut said if an asteroid was detected that would hit earth in a matter of weeks there would be nothing we could do to stop it.

Earth Moon Planet (2008) 102:417–424
DOI 10.1007/s11038-007-9219-6

Meteoroids, Meteors, and the Near-Earth Object Impact Hazard

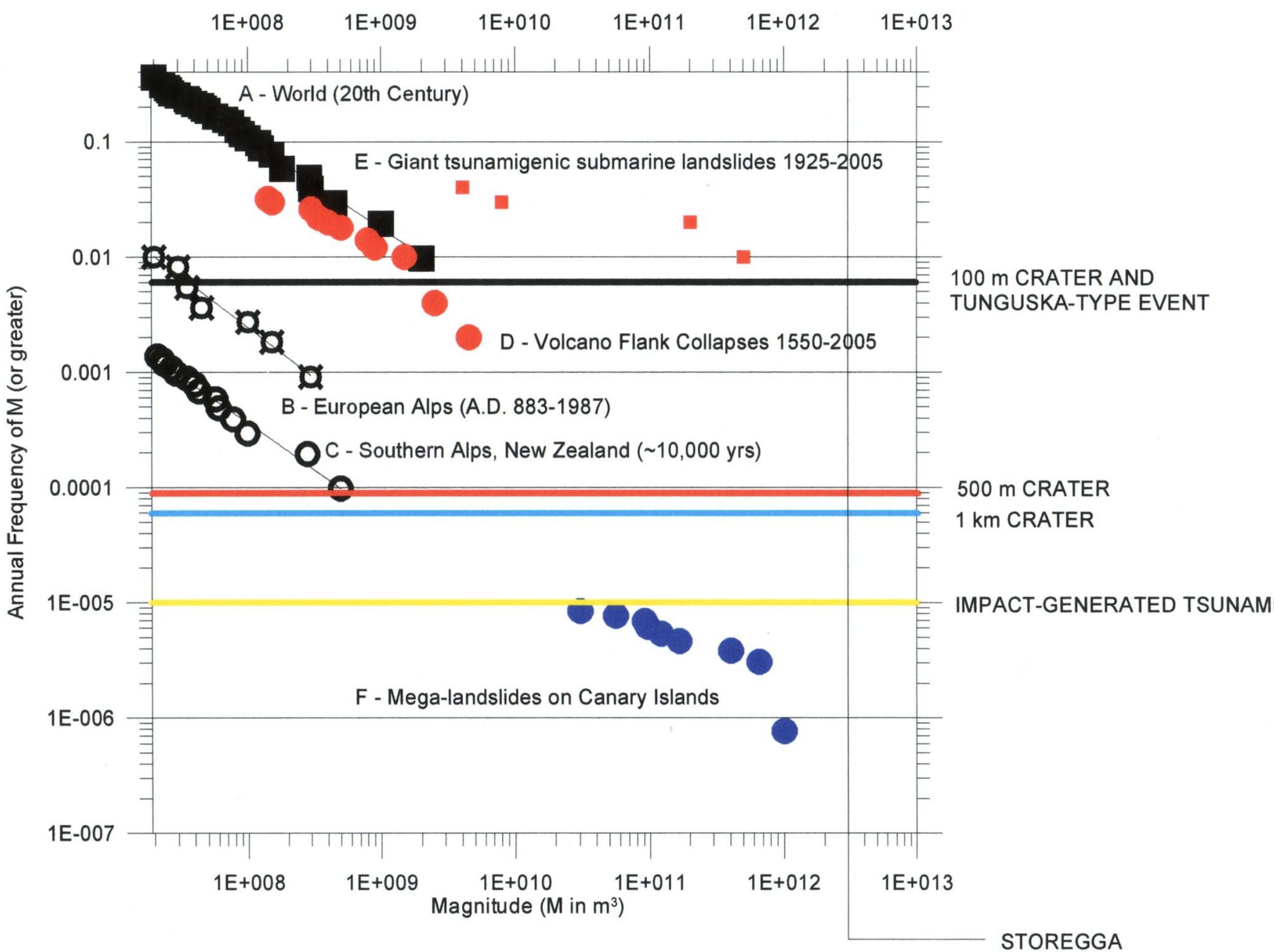
Clark R. Chapman

NASA

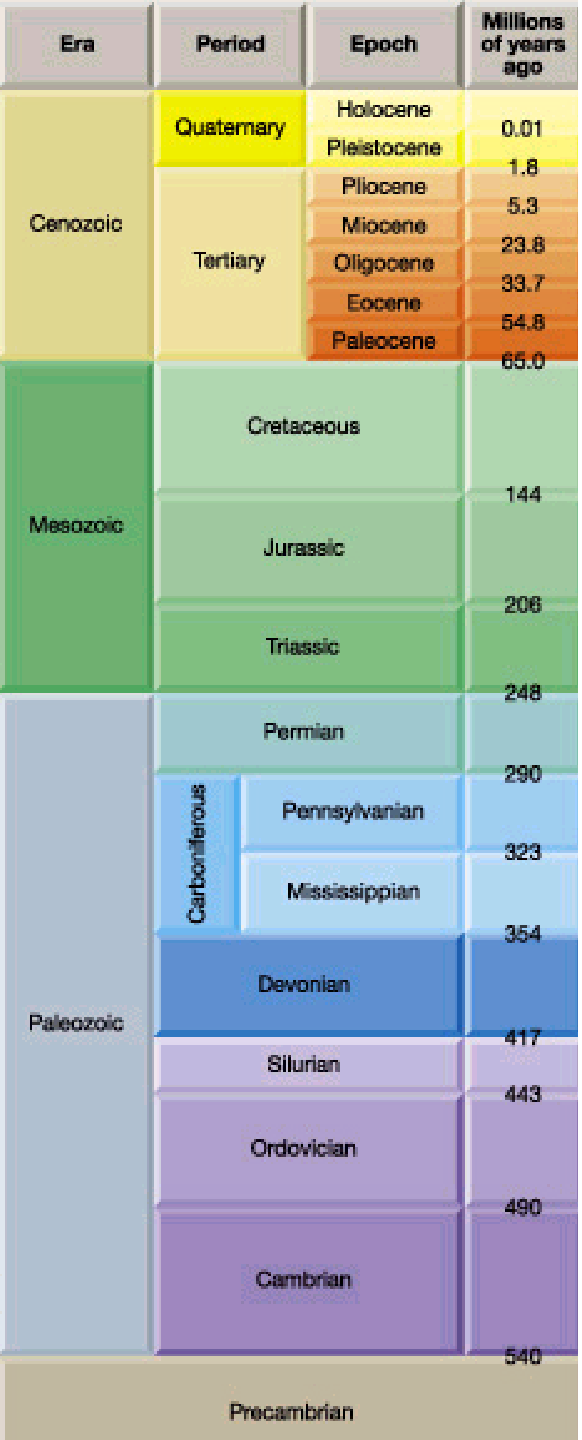


(a)

ASTEROIDS AND EARTH IMPACTS

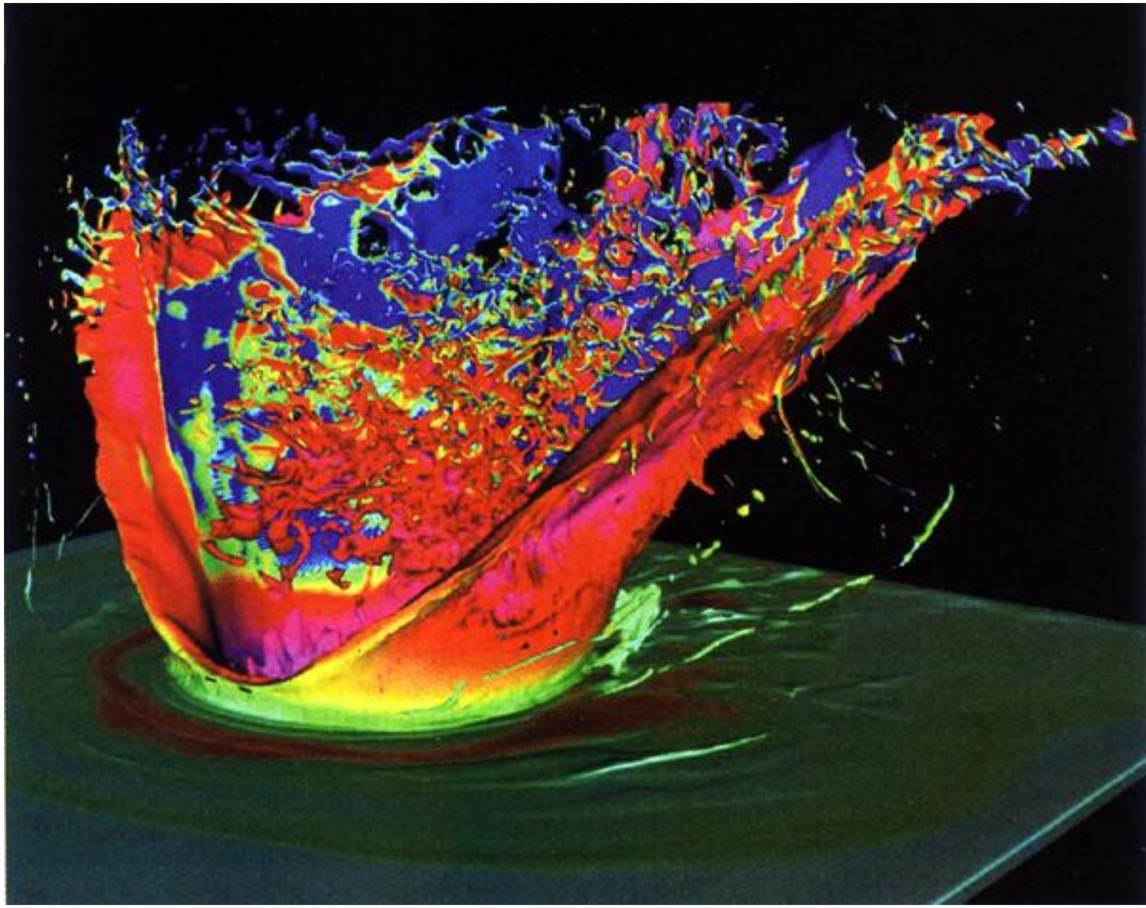


1E+008
1E+009
1E+010
1E+011
1E+012
1E+013
Annual Frequency of M (or greater)
0.1
0.01
0.001
0.0001
1E-005
1E-006
1E-007
A - World (20th Century)
E - Giant tsunamigenic submarine landslides 1925-2005
100 m CRATER AND
TUNGUSKA-TYPE EVENT
D - Volcano Flank Collapses 1550-2005
B - European Alps (A.D. 883-1987)
C - Southern Alps, New Zealand (~10,000 yrs)
500 m CRATER
1 km CRATER
IMPACT-GENERATED TSUNAMI
F - Mega-landslides on Canary Islands
Magnitude (M in m³)
STOREGGA



Era	Period		Epoch	Millions of years ago
Cenozoic	Quaternary		Holocene	0.01
			Pleistocene	1.8
	Tertiary		Pliocene	5.3
			Miocene	23.8
			Oligocene	33.7
			Eocene	54.8
			Paleocene	65.0
Mesozoic	Cretaceous			144
	Jurassic			206
	Triassic			248
Paleozoic	Permian			290
	Carboniferous	Pennsylvanian		323
		Mississippian		354
	Devonian			417
	Silurian			443
	Ordovician			490
	Cambrian			540
Precambrian				

GEOLOGICAL TIME – A FRAMEWORK FOR MEGA IMPACTS



K/T ASTEROID IMPACT – YUCATAN PENINSULA

Manicouagan Crater, Quebec (100 km in diameter); 214 million years old

Manicouagan Crater, Quebec (100 km in diameter); 214 million years old; view from ISS in 2012

ASTEROID IMPACT : VERY LOW PROBABILITY BUT EXTREMELY HIGH CONSEQUENCES = ?

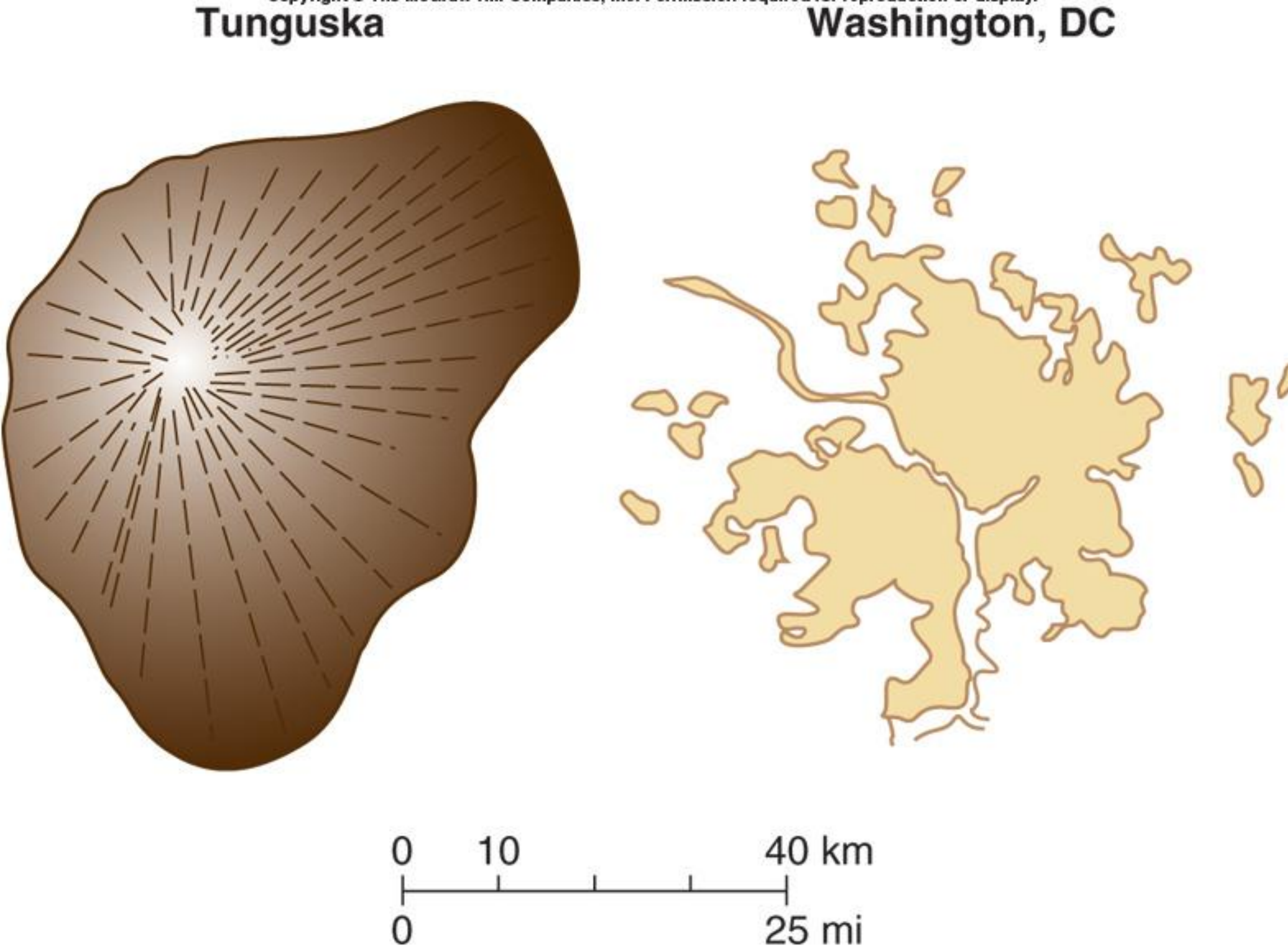
MITIGATION __________
NASA SPACEGUARD
http://impact.arc.nasa.gov/

EARTH IMPACTS BY ASTEROIDS

Tunguska 1908

1. **NASA SPACEGUARD SURVEY OF NEAR EARTH OBJECTS (NEOs) - APOPHIS**
2. **MAJOR GLOBAL CATASTROPHE WITH 1-2km (OR GREATER) DIAMETER OBJECT**
3. **PROTECTION-DESTRUCTION OR DEFLECTION**
4. **CRATERS ON EARTH SHOW PREHISTORIC RECORD OF IMPACT**
5. **TUNGUSKA – 1908 (15 Megatons); Forest destroyed over an area of 2100 km^3**

DISTRIBUTION OF KNOWN TERRESTRIAL IMPACT CRATERS (after R.A.F. Grieve, Geological Survey of Canada)

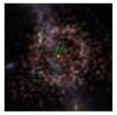

Tunguska
Washington, DC
0
10
40 km
0
25 mi

NASA and FEMA Rehearse for the Unthinkable: An Asteroid Strike on Los Angeles

By CHRISTOPHER MELE NOV. 14, 2016

An artist's concept of a near-Earth object. JPL-Caltech/NASA

RELATED COVERAGE



How Big Are Those Killer Asteroids? A Critic Says NASA Doesn't Know. MAY 23, 2016

Agencies, Hoping to Deflect Comets and Asteroids, Step Up Earth Defense JUNE 18, 2015

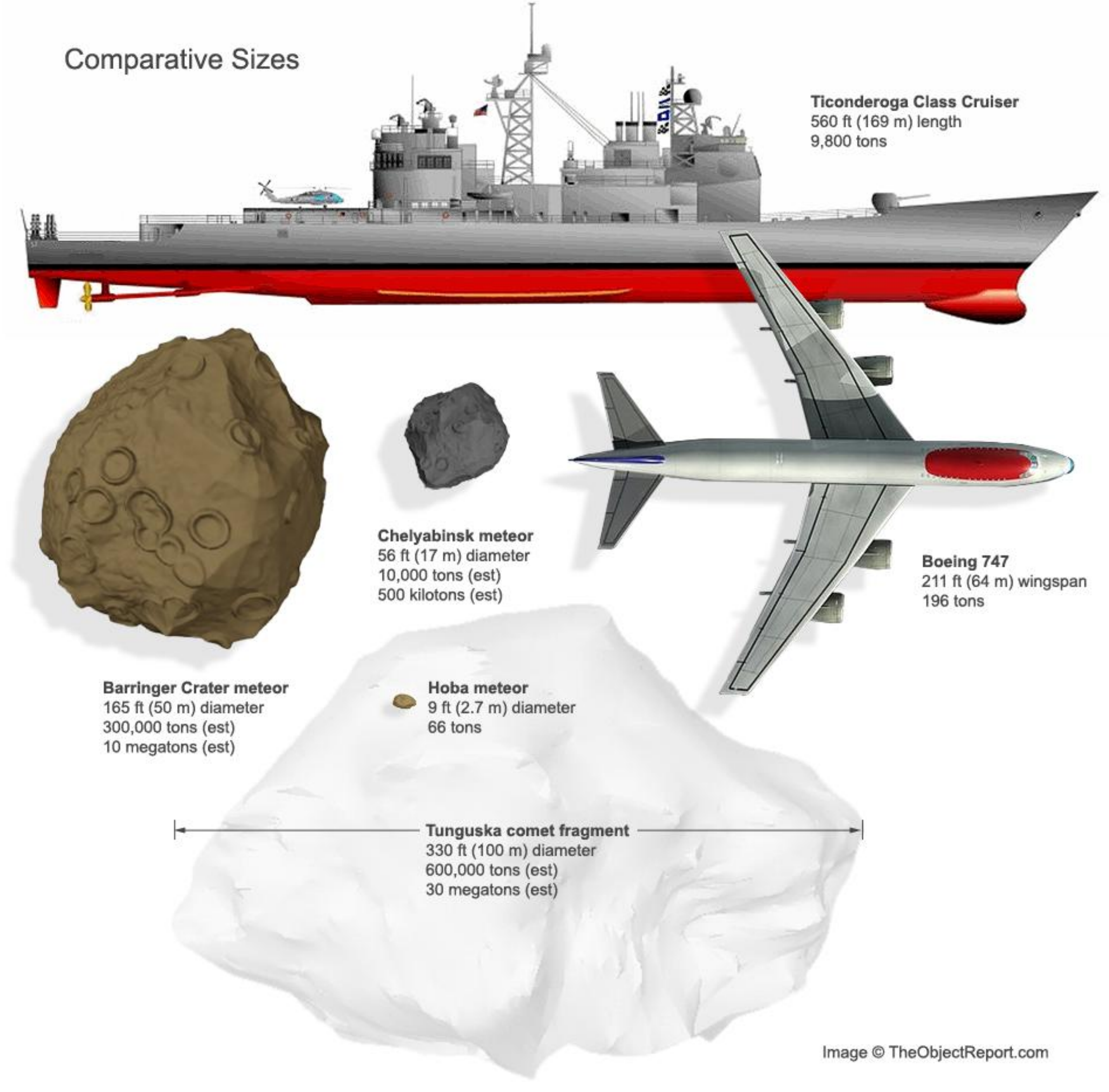
NASA Aims at an Asteroid Holding Clues to the Solar System's Roots SEPT. 5, 2016

TRILOBITES

How an Amateur Meteorite Hunter Tracked Down a Fireball MARCH 10, 2016

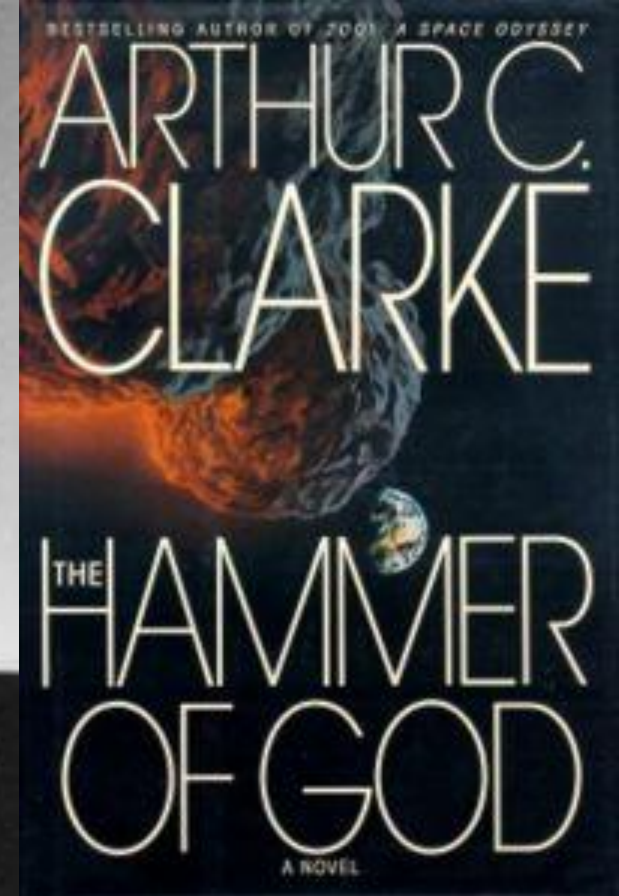
CHELYABINSK METEOR, RUSSIA: FEBRUARY 15, 2013

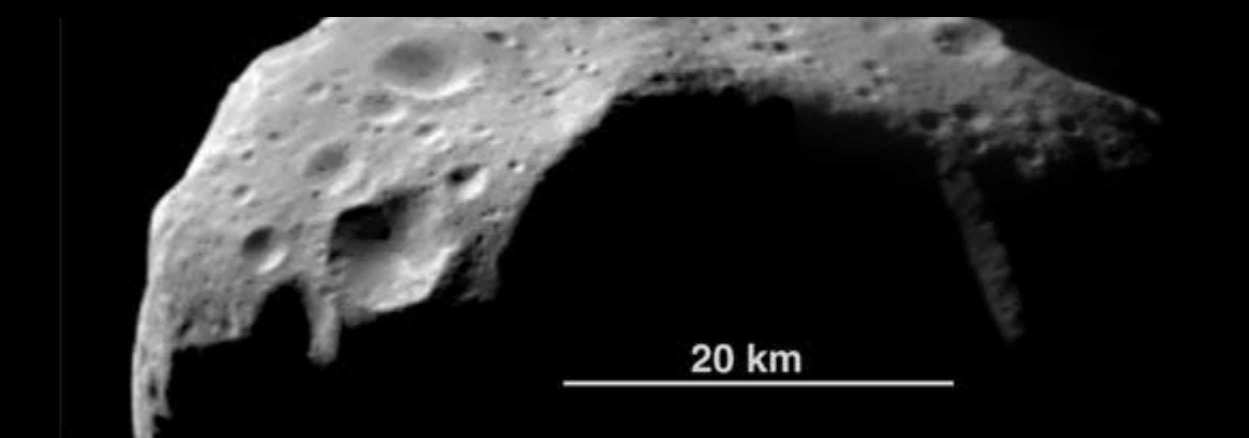
CHELYABINSK METEOR, RUSSIA: FEBRUARY 15, 2013



COMPARATIVE SIZES

Arthur C,
Clarke (1917-
2008)





Impacts on the Earth by asteroids and comets: assessing the hazard

Clark R. Chapman & David Morrison

There is a 1-in-10,000 chance that a large (~2-km diameter) asteroid or comet will collide with the Earth during the next century, disrupting the ecosphere and killing a large fraction of the world's population. Although impacts of this magnitude are so infrequent as to be beyond our personal experience, the long-term statistical hazard is comparable to that of many other, more familiar natural disasters, raising the question of whether mitigation measures should be considered.

Chapman and Morrison's paper in *Nature* in 1994

Aorounga Crater , Chad – 12.8 km in diameter <340 Ma

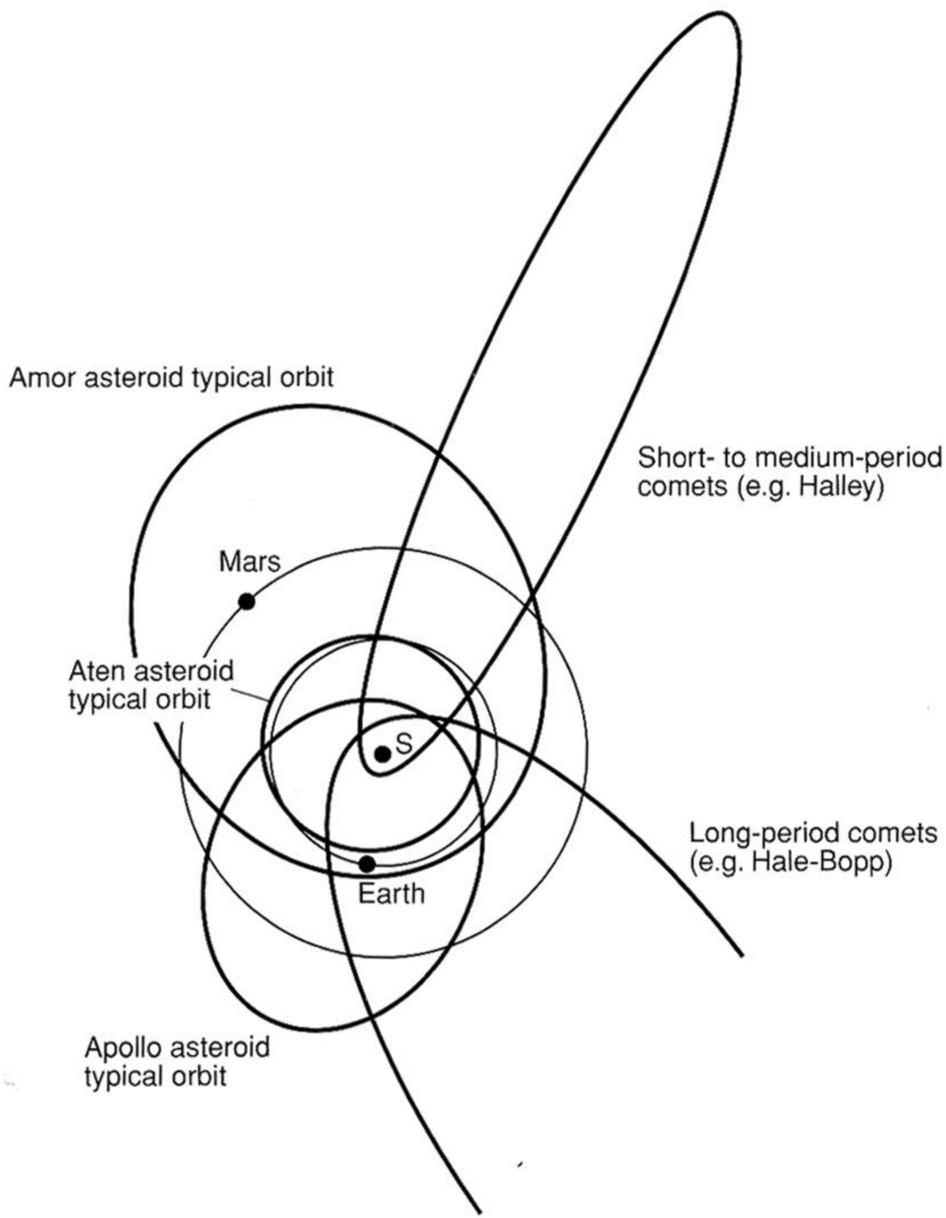
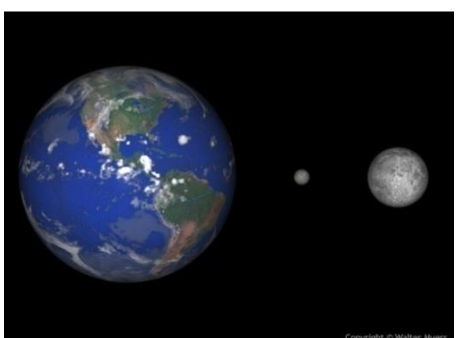


FIGURE 7.3 Orbital characteristics of Earth-threatening objects (not to scale).

NEOs – NEAR EARTH OBJECTS WHICH CONSIST OF NEAs (NEAR EARTH ASTEROIDS) AND SHORT PERIOD COMETS (e.g., HALLEY)

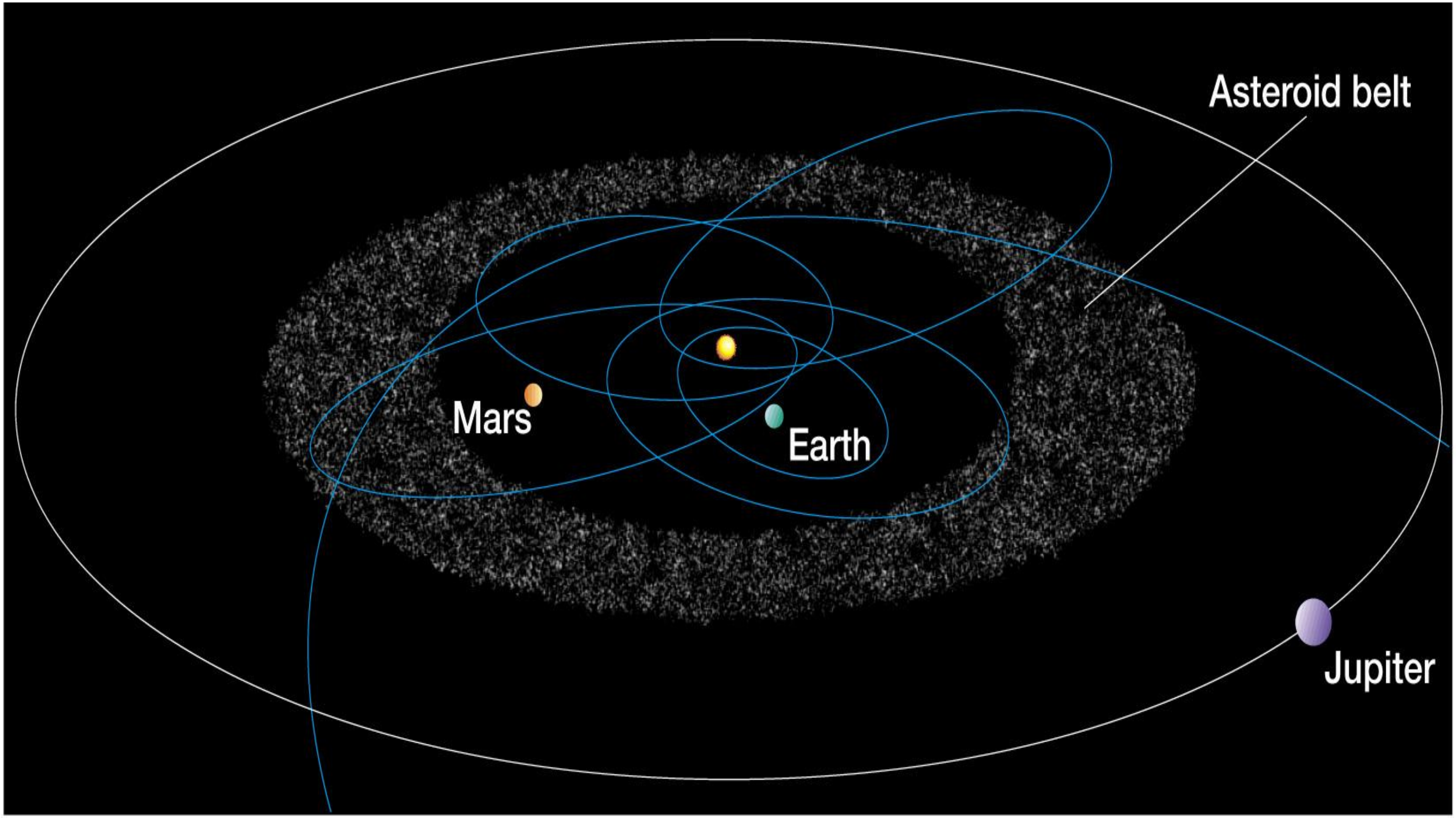
HAZARDS TO EARTH: ASTEROIDS

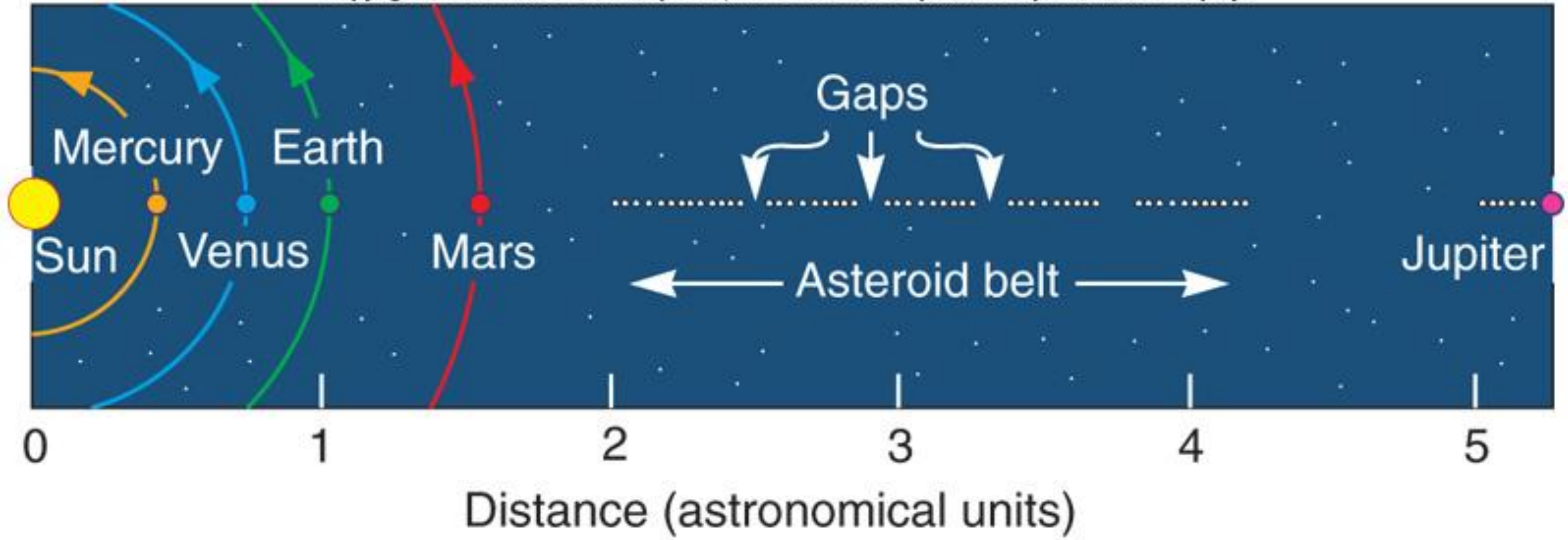
- **Asteroids**
  - **Most lie between Mars and Jupiter**
  - **Small bodies – largest (Ceres) is about 1000 km in diameter**
  - **Some have very eccentric orbits**
  - **Many of the recent impacts on the Earth and Moon were asteroids**
  - **Origin is uncertain**

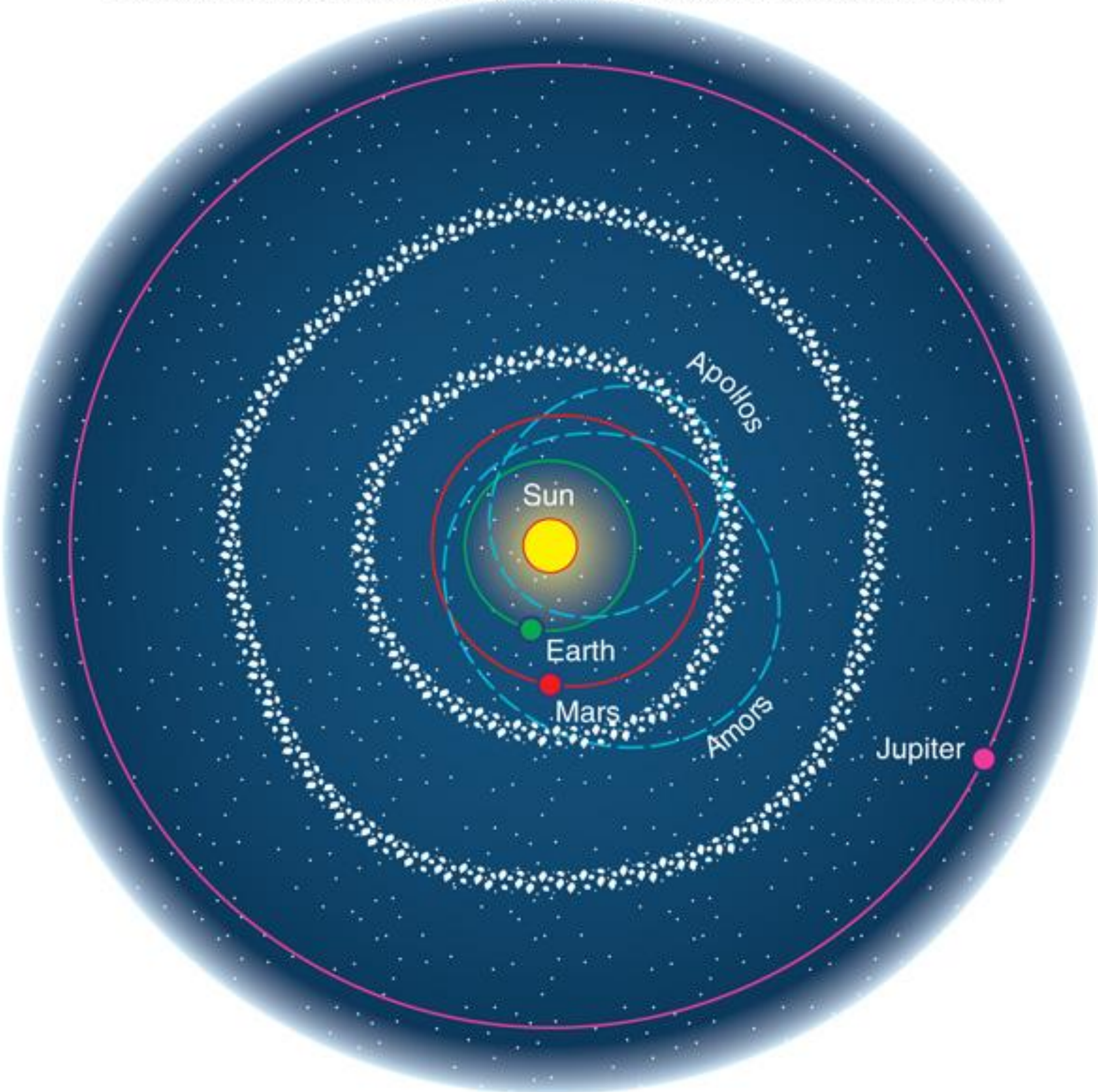


Asteroid 951 photographed by Galileo spacecraft – Longest dimension is 19 km

The asteroid belt




Gaps
Mercury
Earth
Sun
Venus
Mars
Asteroid belt
Jupiter
0
1
2
3
4
5
Distance (astronomical units)


Apollos
Sun
Earth
Mars
Amors
Jupiter

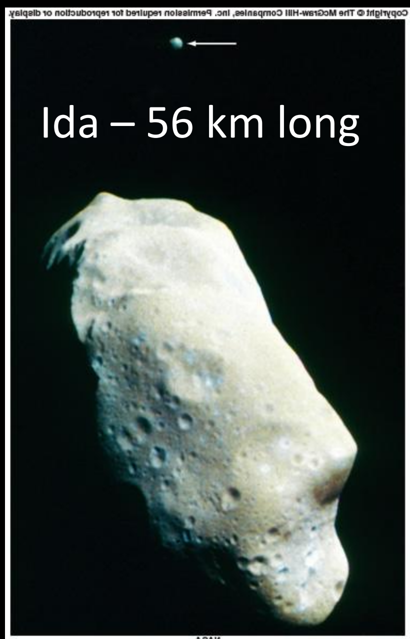
The potentially dangerous asteroid 2012 DA14

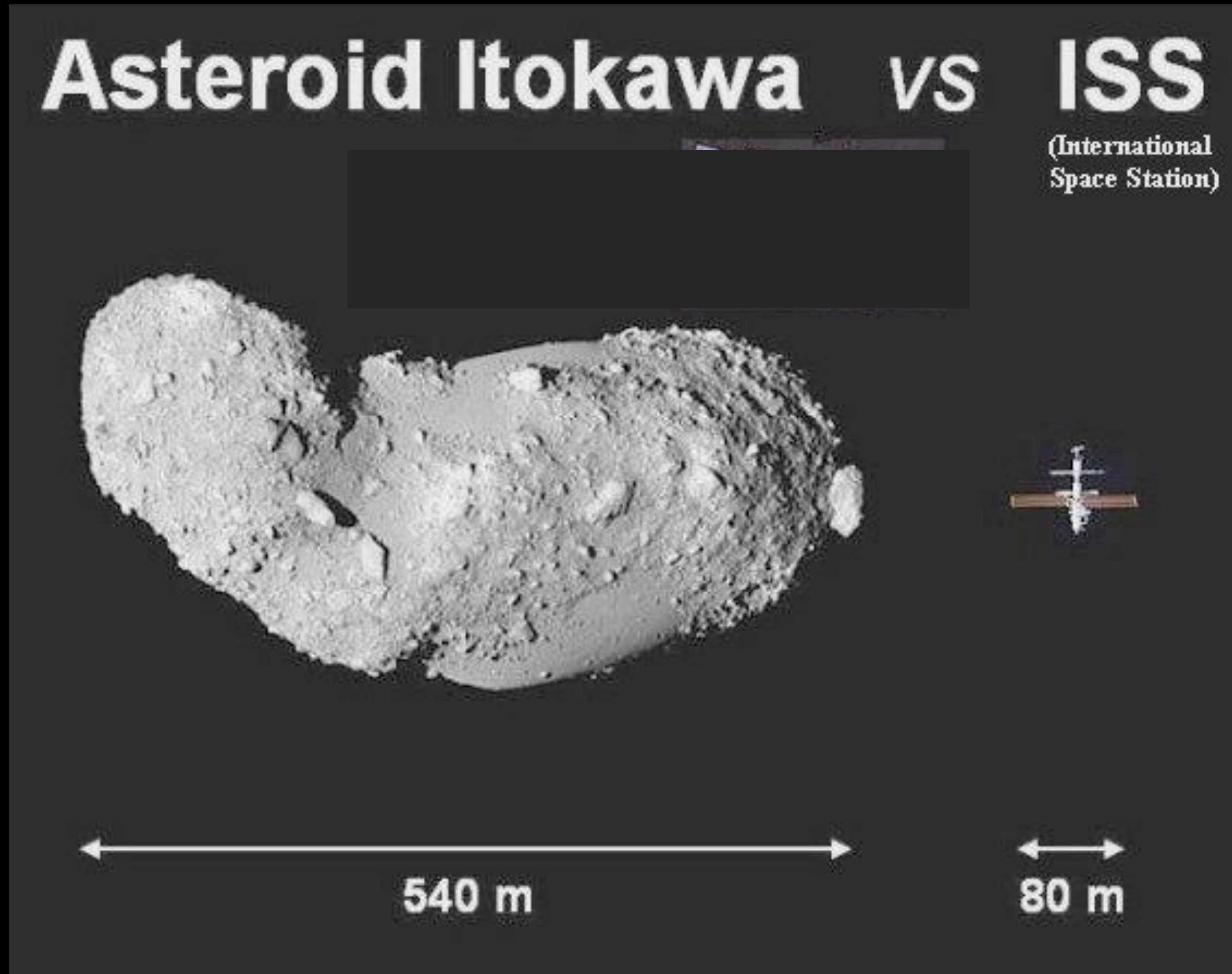
I. Wlodarczyk[*]
Chorzow Astronomical Observatory (MPC 553), Al. Planetarium 4, Chorzow 41-500, Poland

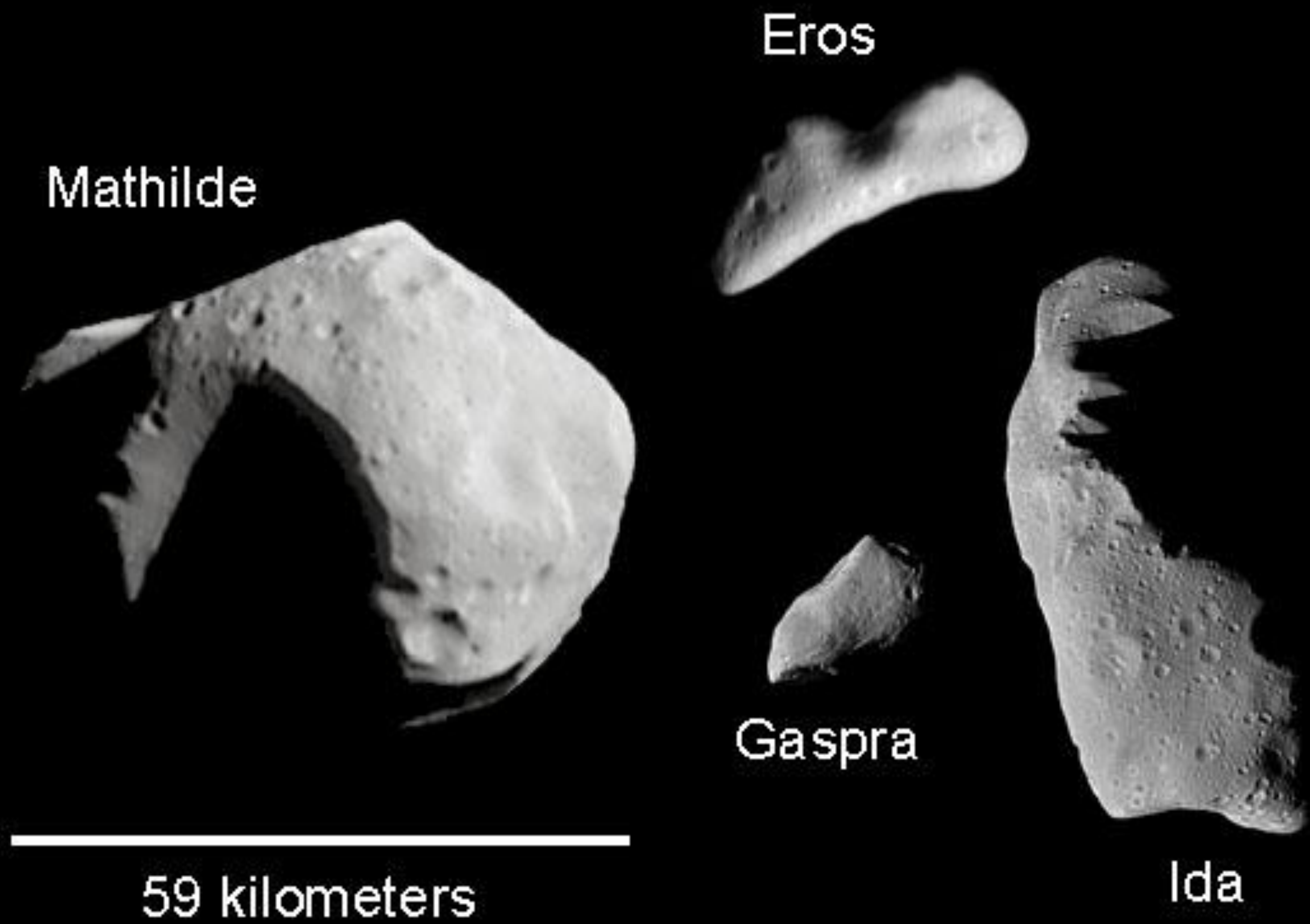
Accepted 2012 September 3. Received 2012 August 30; in original form 2012 June 8

ABSTRACT
We present computing methods that allow us to study the behaviour of the dynamically interesting potentially dangerous asteroid 2012 DA14. Using the freely available ORBFIT software, we can follow the orbit of the asteroid backward and forward in the future, searching for close approaches to the Earth that might lead to possible impacts. The possible impact orbit for 2026 is computed. We show that it should be possible to recover asteroid 2012 DA14, mainly in 2013 February. It is highly unlikely that asteroid 2012 DA14 will hit any geosynchronous satellites during its close approach on 2013 February 15.

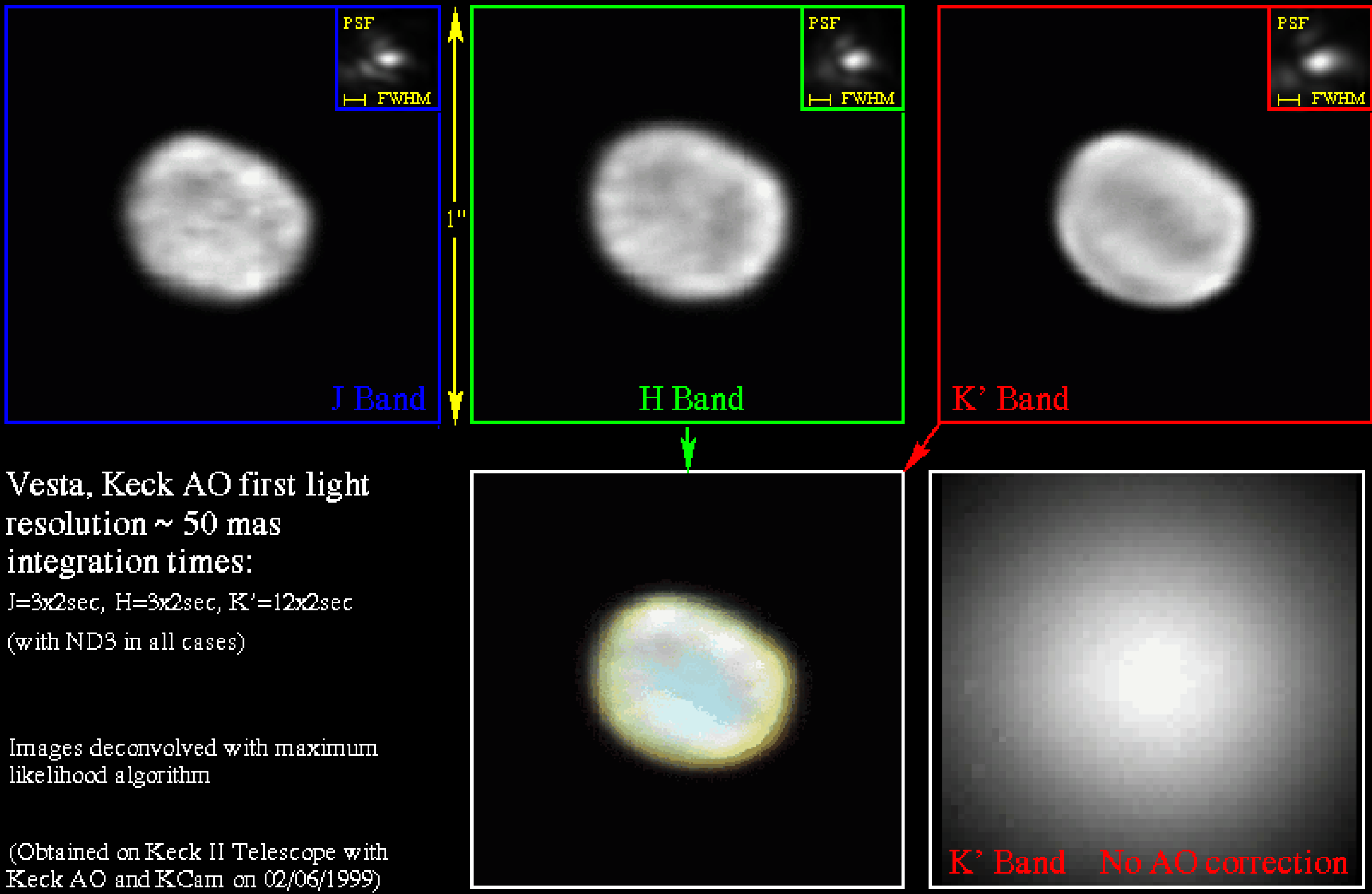
OTHER POTENTIALLY DANGEROUS ASTEROIDS WERE 2008TC3 and 2016UR36


Ida – 56 km long
NASA


Asteroid Itokawa vs ISS
(International Space Station)
540 m
80 m

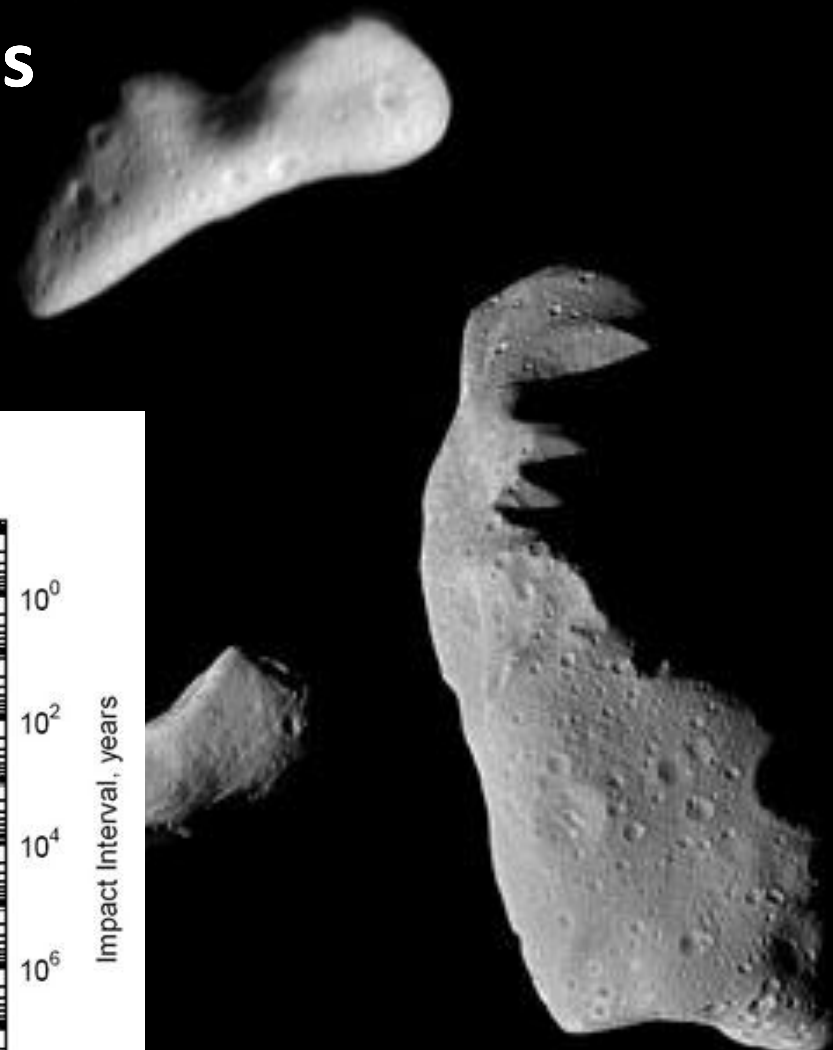

Eros
Mathilde
Gaspra
Ida
59 kilometers

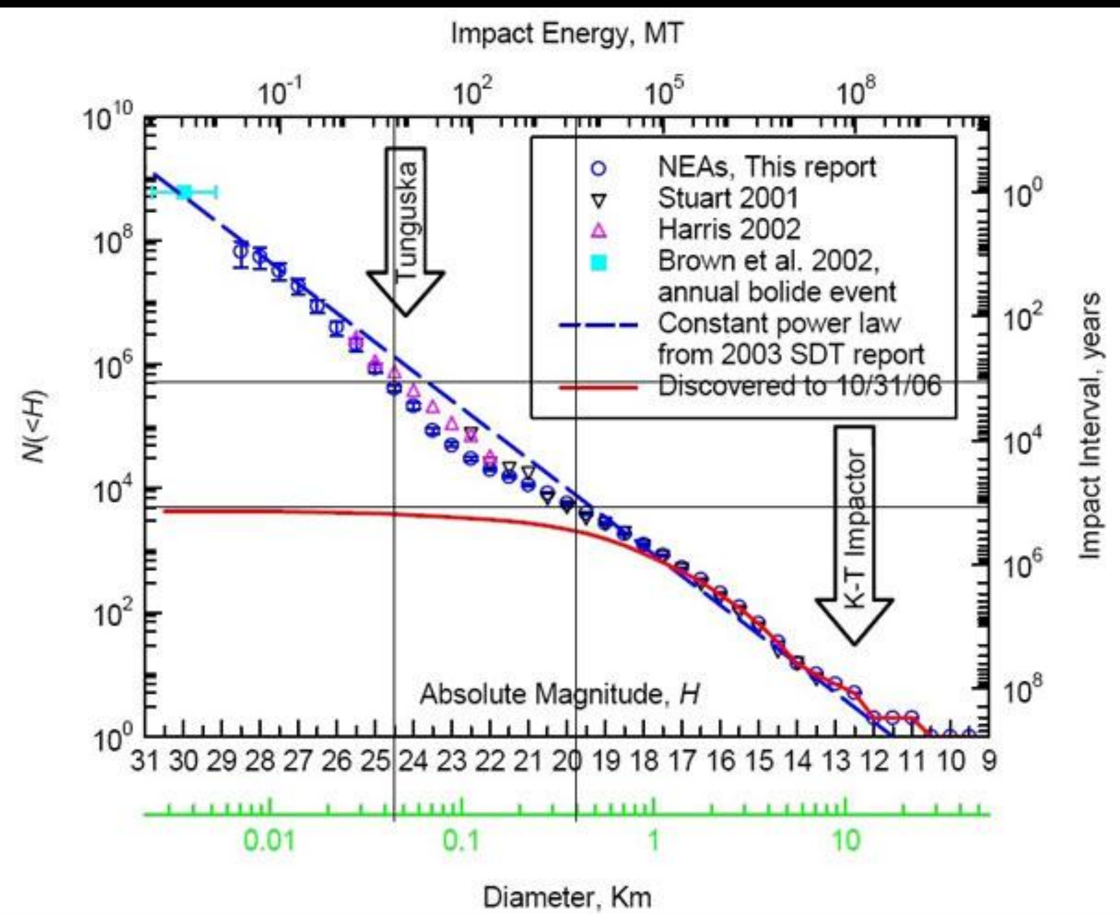
Mathilde

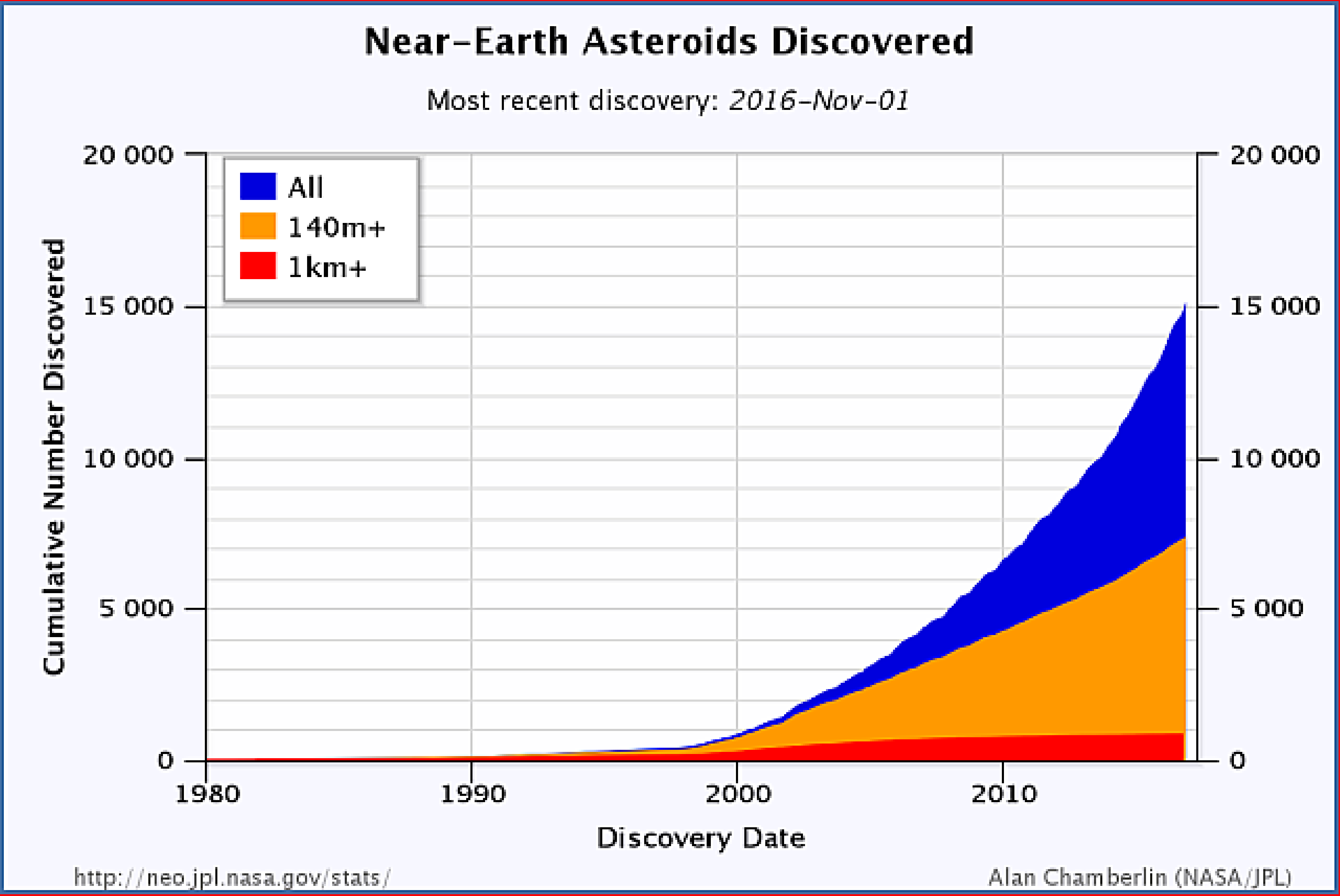


MAPPING AND DETECTION

SIZE DISTRIBUTION OF NEOs







Near-Earth Asteroids Discovered
Most recent discovery: 2016-Nov-01
All
140m+
1km+
Cumulative Number Discovered
0
5 000
10 000
15 000
20 000
1980
1990
2000
2010
Discovery Date
http://neo.jpl.nasa.gov/stats/
Alan Chamberlin (NASA/JPL)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

+ View the NASA Portal

Near Earth Object Program

NEO BASICS | SEARCH PROGRAMS | DISCOVERY STATISTICS | ACCESSIBLE NEAs | NEWS | FAQ

ORBIT DIAGRAMS | ORBIT ELEMENTS | CLOSE APPROACHES | IMPACT RISK | IMAGES | RELATED LINKS

Sentry Risk Table

- Removed Objects
- Introduction to Impact Monitoring
- Frequently Asked Questions
- Operational Notes

The following table lists potential future Earth impact events that the JPL Sentry System has detected based on currently available observations. Click on the object designation to go to a page with full details on that object.

Sentry is a highly automated collision monitoring system that continually scans the most current asteroid catalog for possibilities of future impact with Earth over the next 100 years. Whenever a potential impact is detected it will be analyzed and the results immediately published here, except in unusual cases where an IAU Technical Review is underway.

It is normal that, as additional observations become available, objects will disappear from this table whenever there are no longer any potential impact detections. For this reason we maintain a list of removed objects with the date of removal.

558 NEAs: Last Updated Mar 31, 2015

Sort by Palermo Scale (cum.) or by Object Designation

Recently Observed Objects (within past 60 days)

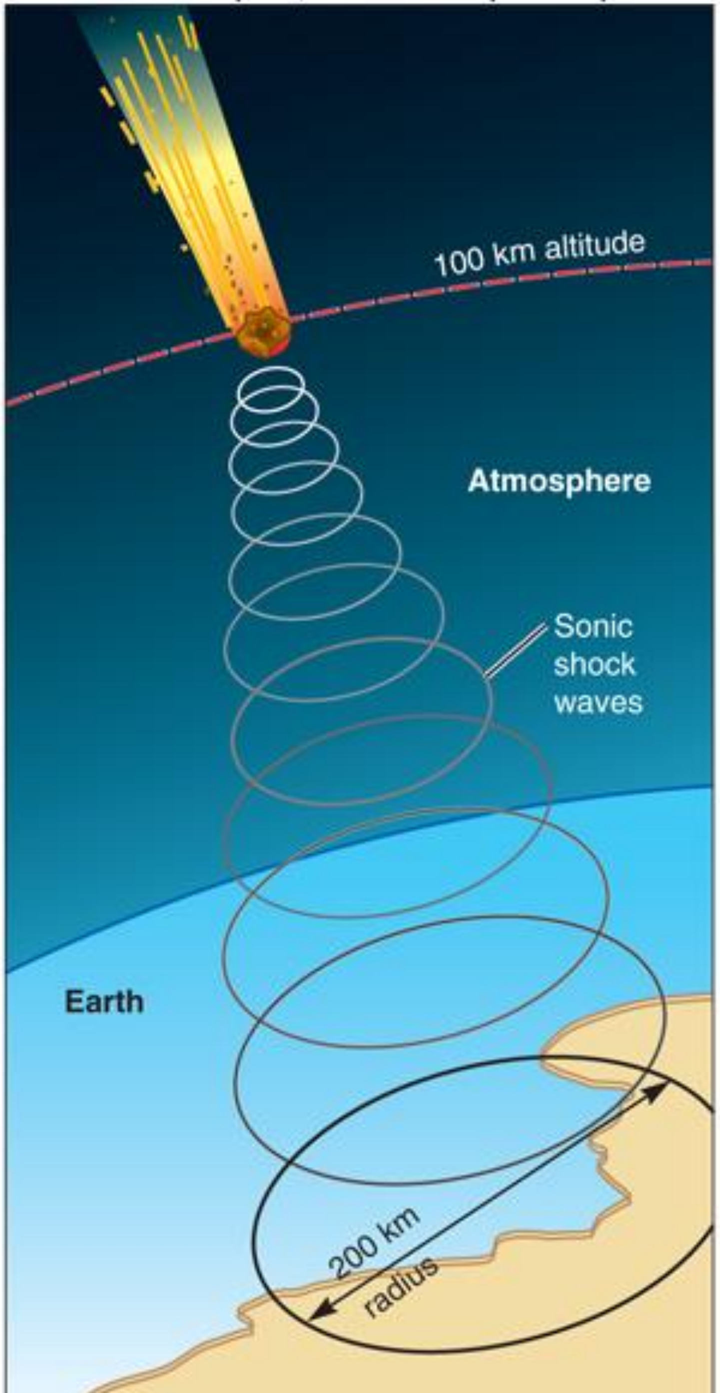
Object Designation	Year Range	Potential Impacts	Impact Prob. (cum.)	$V_{infinity}$ (km/s)	H (mag)	Est. Diam. (km)	Palermo Scale (cum.)	Palermo Scale (max.)	Torino Scale (max.)
2015 FL290	2082-2085	3	9.0e-07	10.82	22.0	0.140	-4.76	-5.04	0
2015 DA54	2107-2107	1	8.6e-08	23.13	20.8	0.230	-5.00	-5.00	0
2015 FP118	2021-2058	3	2.2e-09	11.73	19.6	0.410	-5.31	-5.34	0
2015 FG120	2062-2112	22	8.8e-07	8.43	23.1	0.080	-5.33	-5.70	0
2015 FN36	2100-2113	3	7.8e-07	22.04	23.9	0.057	-5.54	-5.69	0
2015 EO	2050-2077	8	6.7e-06	14.24	26.6	0.016	-5.91	-6.14	0

Sentry: Earth Impact Monitoring

Introduction | Object Table | VI Table | FAQ | Operational Notes | Removed Objects

Introduction

When interpreting Sentry pages, where information on known potential NEA impacts is posted, one must bear in mind that an Earth collision by a sizable NEA is a very low probability event. Objects normally appear on the Risk Page because their orbits can bring them close to the Earth's orbit and the limited number of available observations do not yet allow their trajectories to be well-enough defined. In such cases, there may be a wide range of possible future paths that can be fit to the existing observations, sometimes including a few that can intersect the Earth.



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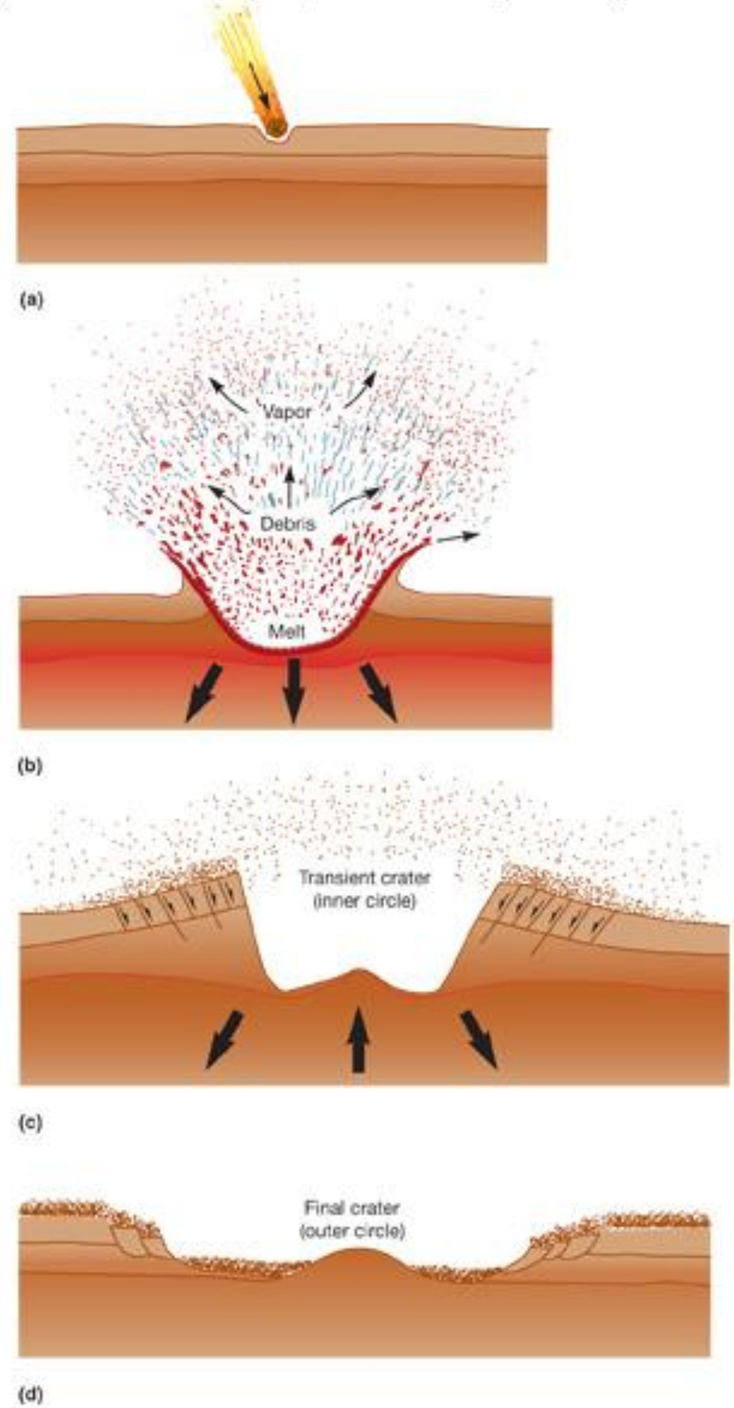
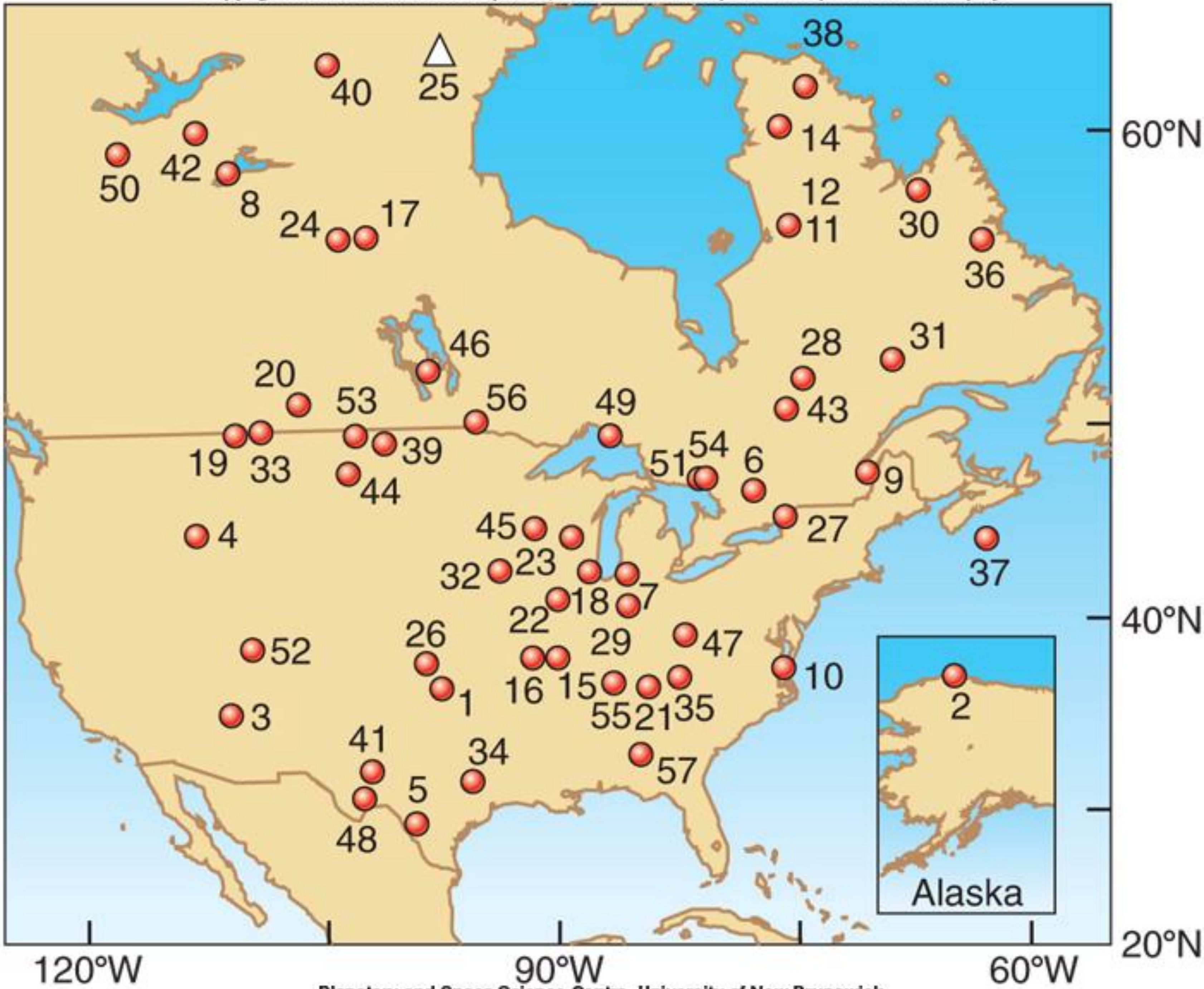
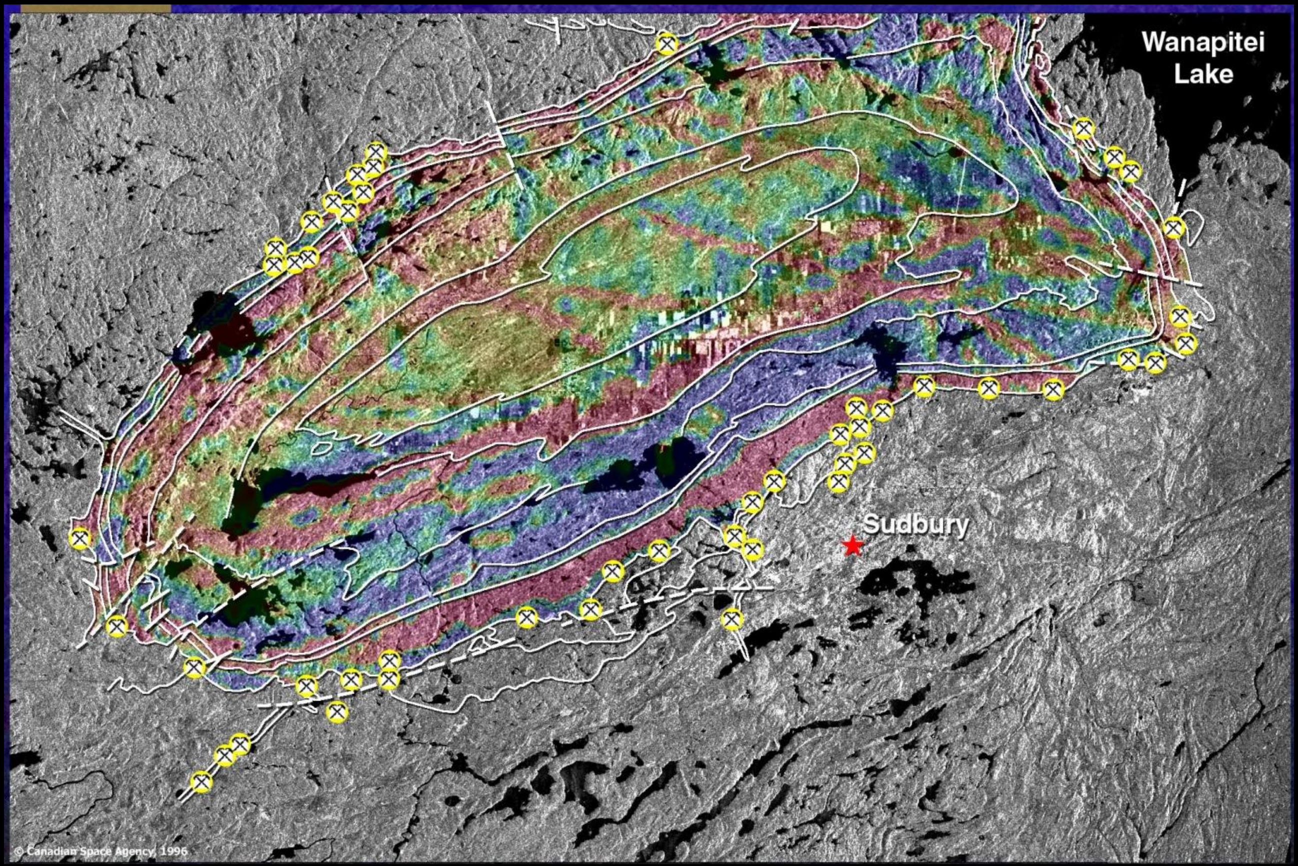


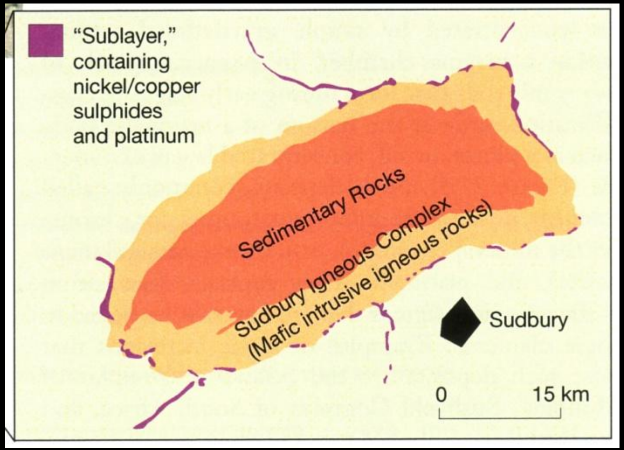


Planetary and Space Science Centre, University of New Brunswick



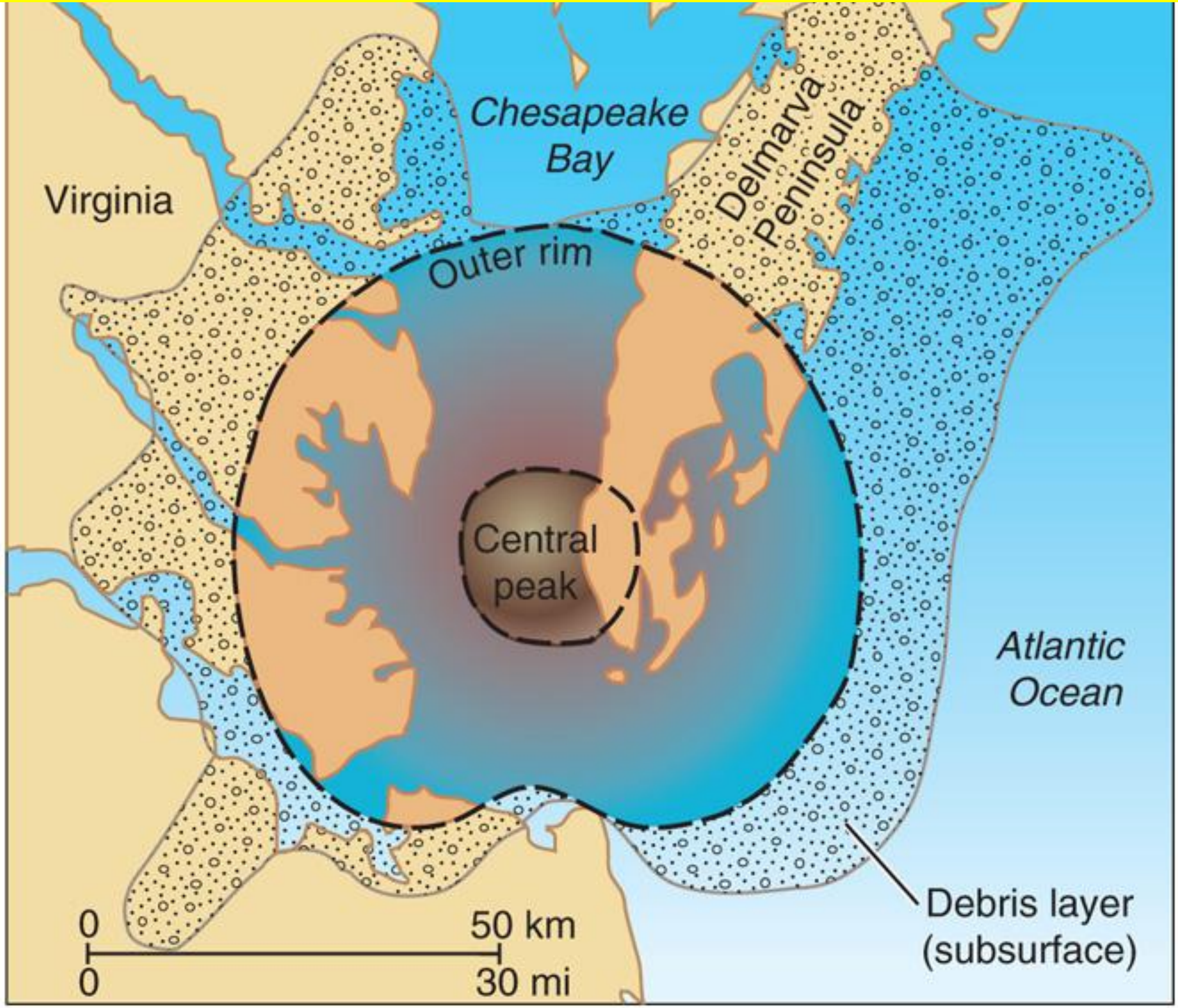
SUDBURY IMPACT STRUCTURE

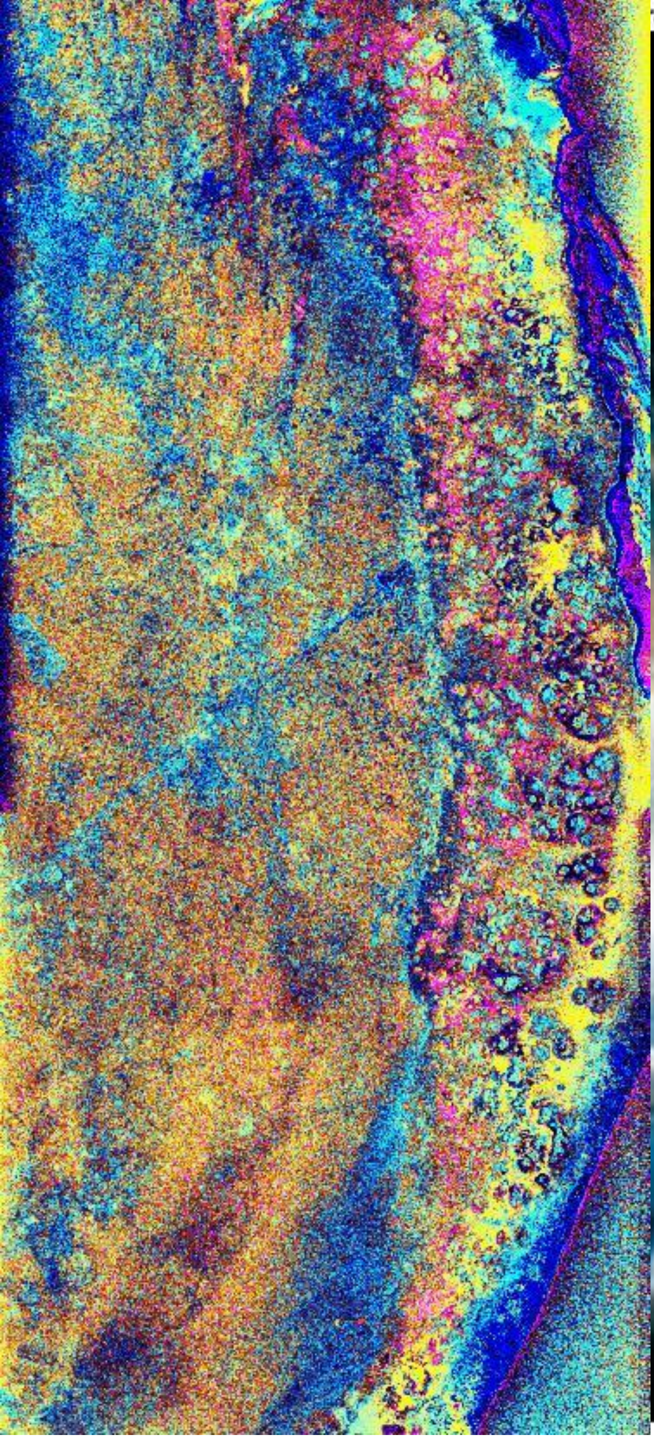
Yellow symbols are mineral properties

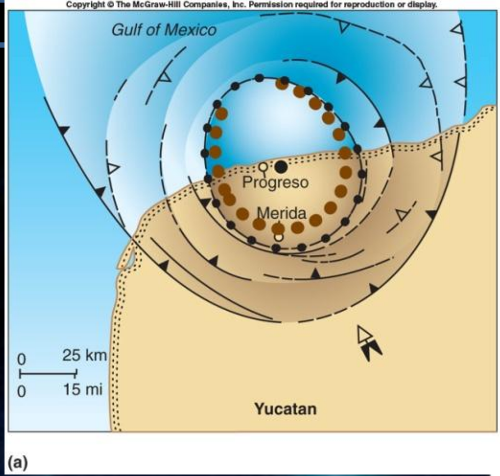


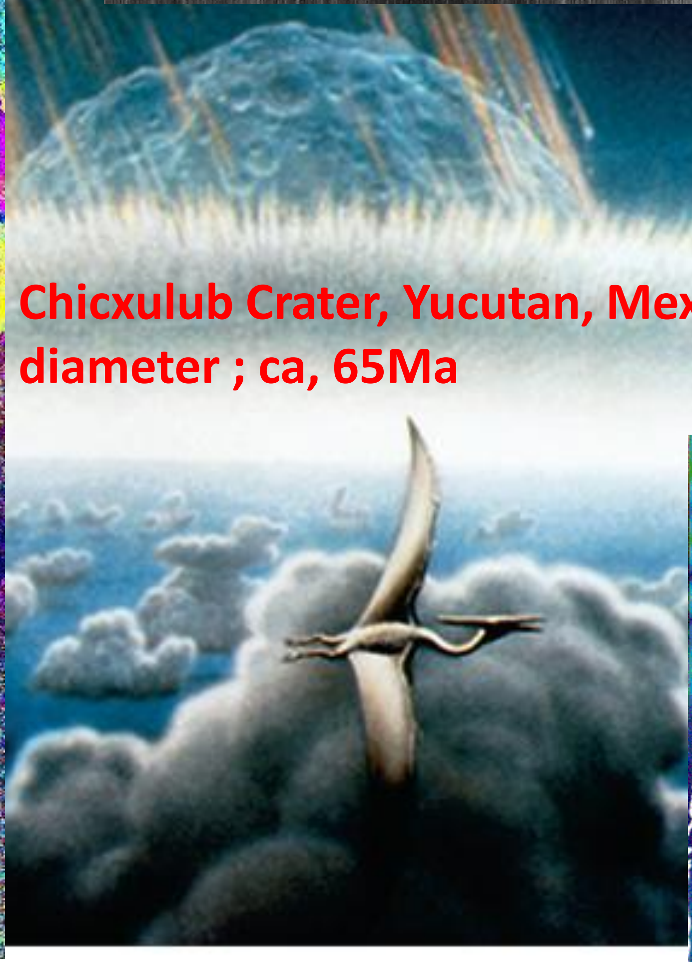
- NICKEL-BEARING ROCK CONTAINS SULPHIDES THAT CRYSTALLISED FROM IMMISCIBLE MAGMATIC FLUIDS
- NICKEL BEARING LIQUID ESCAPED FROM MAGMA AS A RESULT OF GIANT METEORITE IMPACT AND BECAME INJECTED AROUND IMPACT STRUCTURE
- IMPACT 1850 Ma ; 250 km IN DIAMETER

Origin of Chesapeake Bay 35 Ma – showered tektites over a massive area ; 90 km wide crater

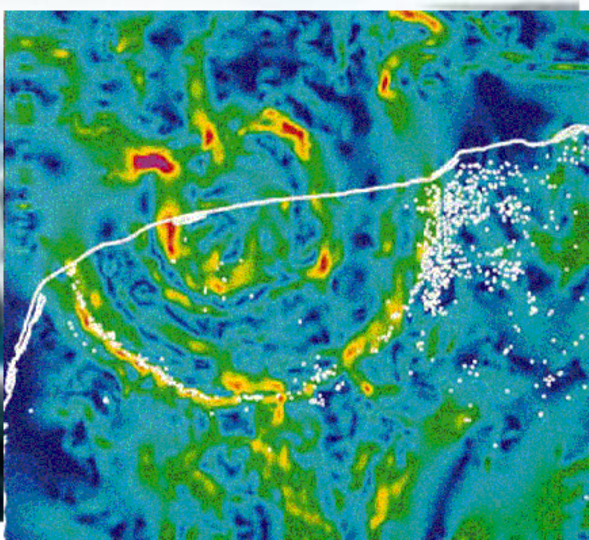


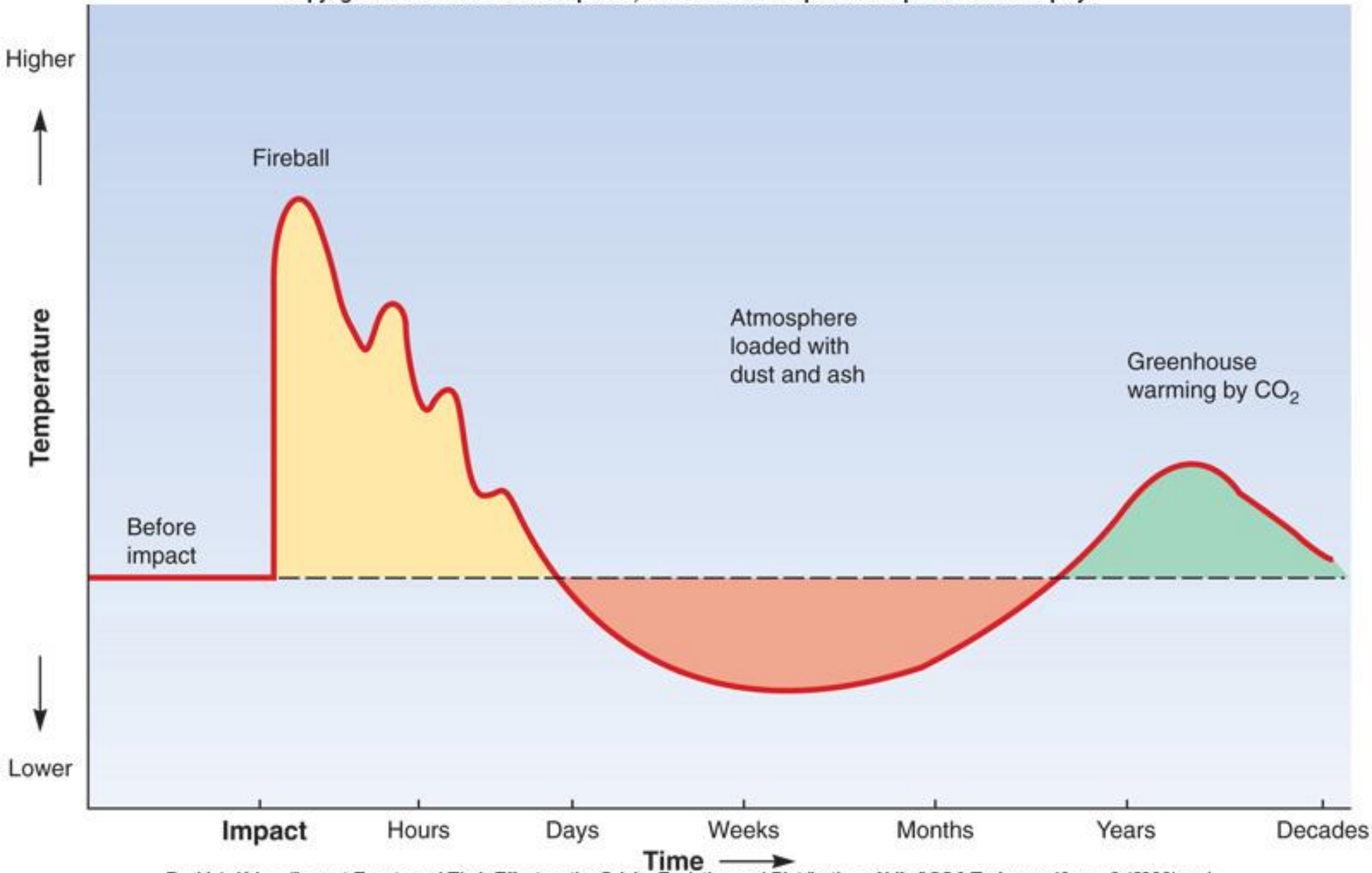






Chicxulub Crater, Yucutan, Mexico ; 180-300 km in diameter ; ca, 65Ma





David A. Kring, "Impact Events and Their Effect on the Origin, Evolution and Distribution of Life." **GSA Today,** *v. 10, no. 8 (2000), p.4*

IMPACT OF THE K/T EVENT ON EARTH''S ATMOSPHERE

Geophysical Research Letters, 2017

Quantifying the Release of Climate-Active Gases by Large Meteorite Impacts With a Case Study of Chicxulub

Natalia Artemieva[1], Joanna Morgan[2], and Expedition 364 Science Party[3]

[1]Planetary Science Institute, Tucson, AZ, USA, [2]Department of Earth Science and Engineering, Imperial College London, London, UK, [3]See section A2

Abstract Potentially hazardous asteroids and comets have hit Earth throughout its history, with catastrophic consequences in the case of the Chicxulub impact. Here we reexamine one of the mechanisms that allow an impact to have a global effect—the release of climate-active gases from sedimentary rocks. We use the SOVA hydrocode and model ejected materials for a sufficient time after impact to quantify the volume of gases that reach high enough altitudes (> 25 km) to have global consequences. We vary impact angle, sediment thickness and porosity, water depth, and shock pressure for devolatilization and present the results in a dimensionless form so that the released gases can be estimated for any impact into a sedimentary target. Using new constraints on the Chicxulub impact angle and target composition, we estimate that 325 ± 130 Gt of sulfur and 425 ± 160 Gt CO_2 were ejected and produced severe changes to the global climate.

Plain language Summary Potentially hazardous asteroids and comets have hit Earth throughout its history, with catastrophic consequences in the case of the Chicxulub impact 66 Myr ago. Here we reexamine one of the mechanisms that allow an impact to have a global effect—the release of climate-active gases from terrestrial sedimentary rocks after the high-velocity impact. We estimate that 325 ± 130 Gt of sulfur and 425 ± 160 Gt CO_2 were ejected into the atmosphere at velocities > 1 km/s. These numbers have to be used in global climate models to quantify possible changes of solar irradiation, surface temperature, and duration of stressful conditions for biota.

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL074879

Key Points:
- We use a hydrocode to model shock pressures, ejection velocities, and amount of gases released from sedimentary rocks after large impacts
- We use new constraints on impact angle and target composition to

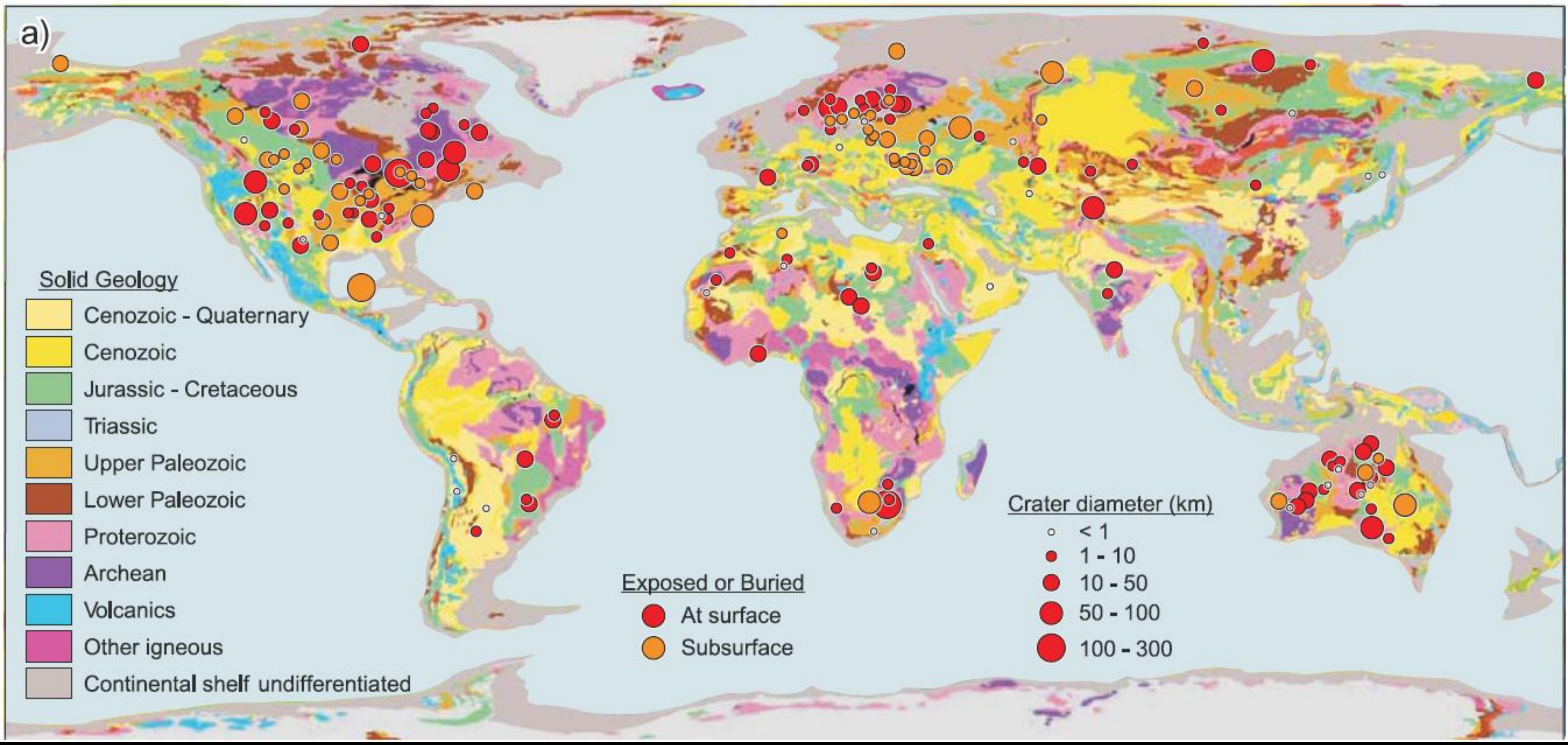
Quantifying the Release of Climate-Active Gases by Large Meteorite Impacts With a Case Study of Chicxulub

Natalia Artemieva[1], Joanna Morgan[2], and Expedition 364 Science Party[3]

[1]Planetary Science Institute, Tucson, AZ, USA, [2]Department of Earth Science and Engineering, Imperial College London, London, UK, [3]See section A2

The hazardous effects of impacts became a topic of great interest following the realization that the Earth was hit by a large asteroid or comet ~ 66 Ma and that this impact coincided with the K-Pg mass extinction (Alvarez et al., 1980). It is obvious why a large impact might be locally devastating, with the emission of high levels of thermal radiation from the impact plume, the generation of hurricane-force winds, and potential to cause tsunamis and landslides (Bourgeois et al., 1988; Bralower et al., 1998; Collins et al., 2005; Ward & Asphaug, 2000). For an impact to cause a mass extinction it must have global consequences. Proposed kill mechanisms for the K-Pg mass extinction include the following: short-term cooling and darkness produced by dust, soot, and sulfur in the atmosphere (Alvarez et al., 1980; Brett, 1992; Pierazzo et al., 1998; Sigurdsson et al., 1992; Toon et al., 1982); long-term warming from the release of massive volumes of CO_2 (O'Keefe & Ahrens, 1989; Pope et al., 1994); ocean acidification (e.g., D'Hondt et al., 1994); and global firestorms ignited when ejecta heats up as it reenters the Earth's atmosphere and emits thermal radiation (Melosh et al., 1990; Morgan et al., 2013; Wolbach et al., 1985).

DISTRIBUTION OF KNOWN TERRESTRIAL IMPACT CRATERS (after R.A.F. Grieve, Geological Survey of Canada)



Global distribution of 176 major asteroid craters mapped to date (from Stewart, 2011)

SIZE DISTRIBUTION OF CRATERS ON EARTH

Barringer Crater, AZ

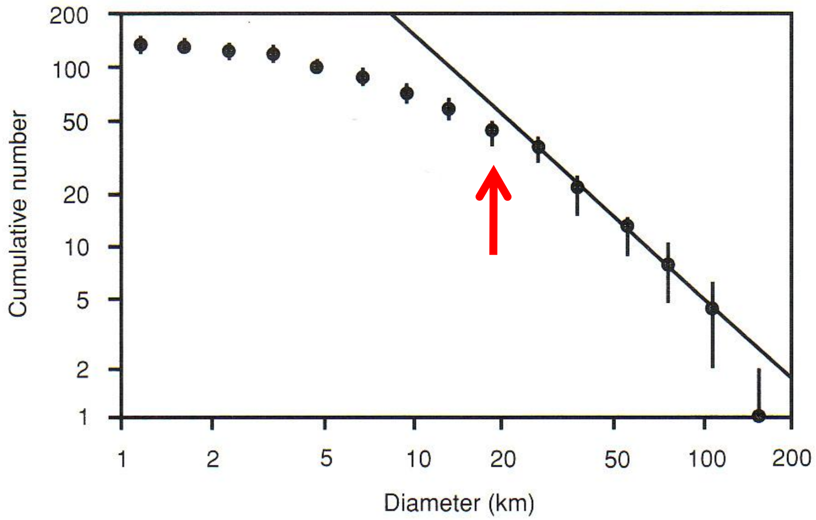
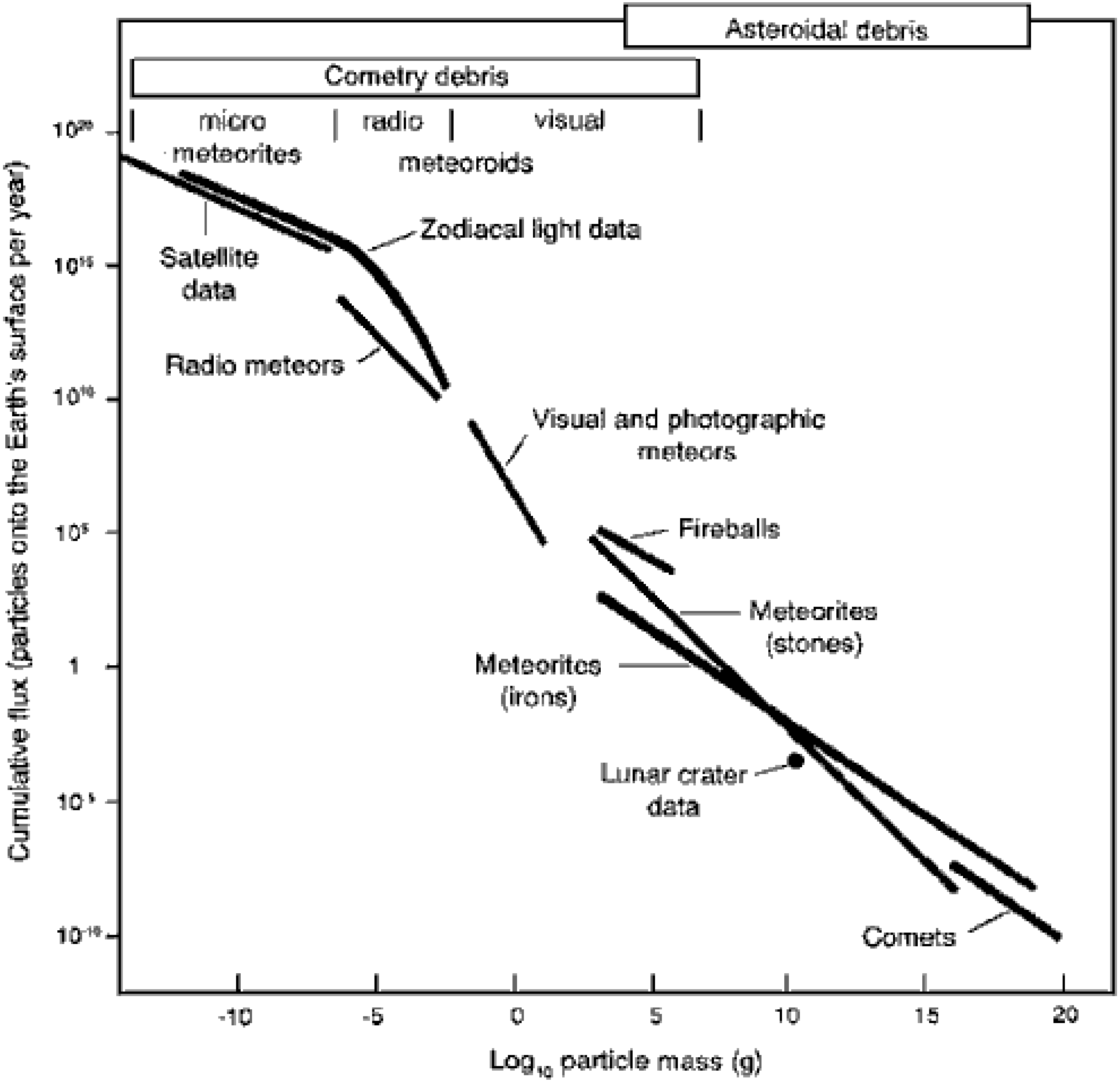
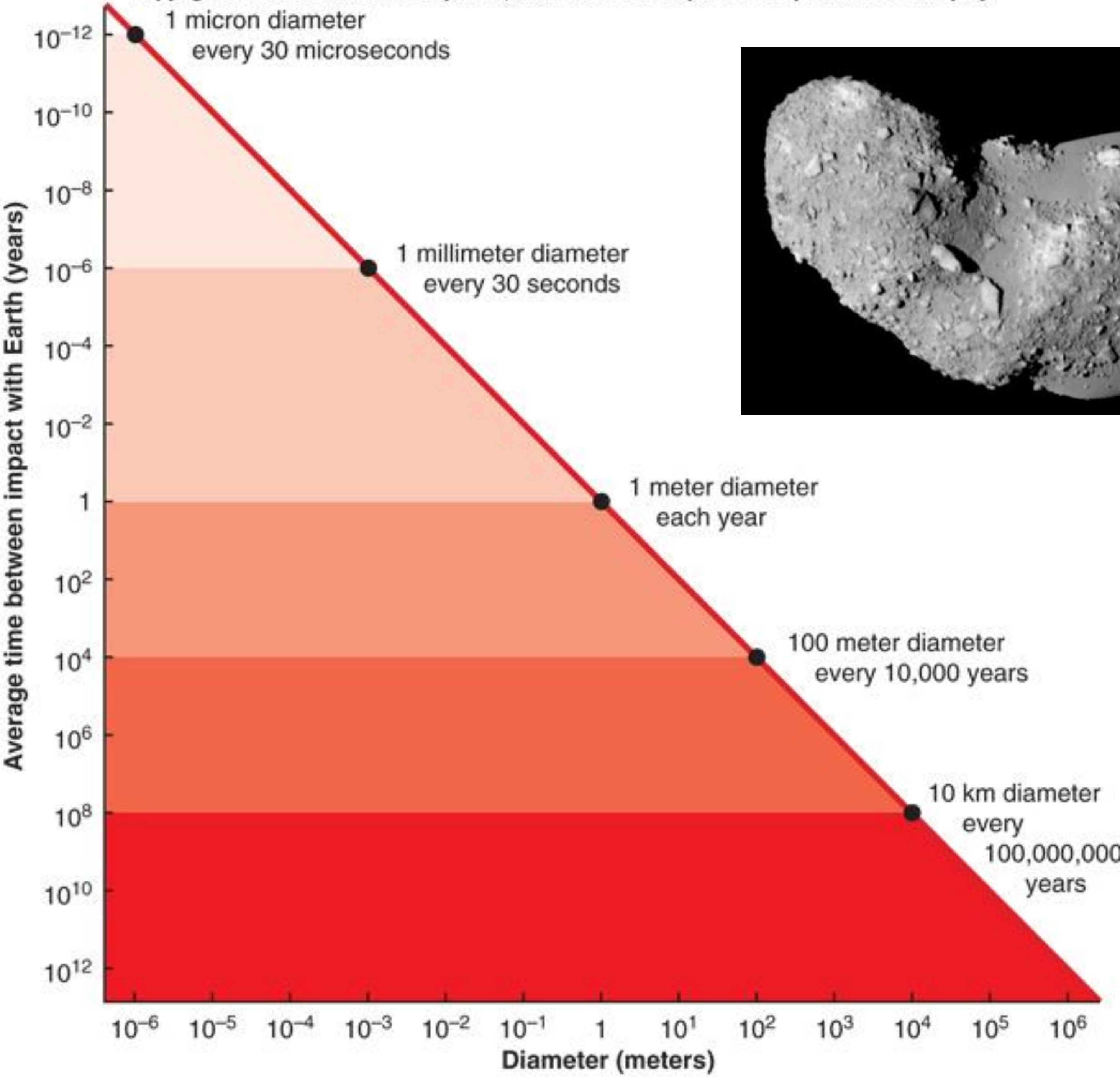
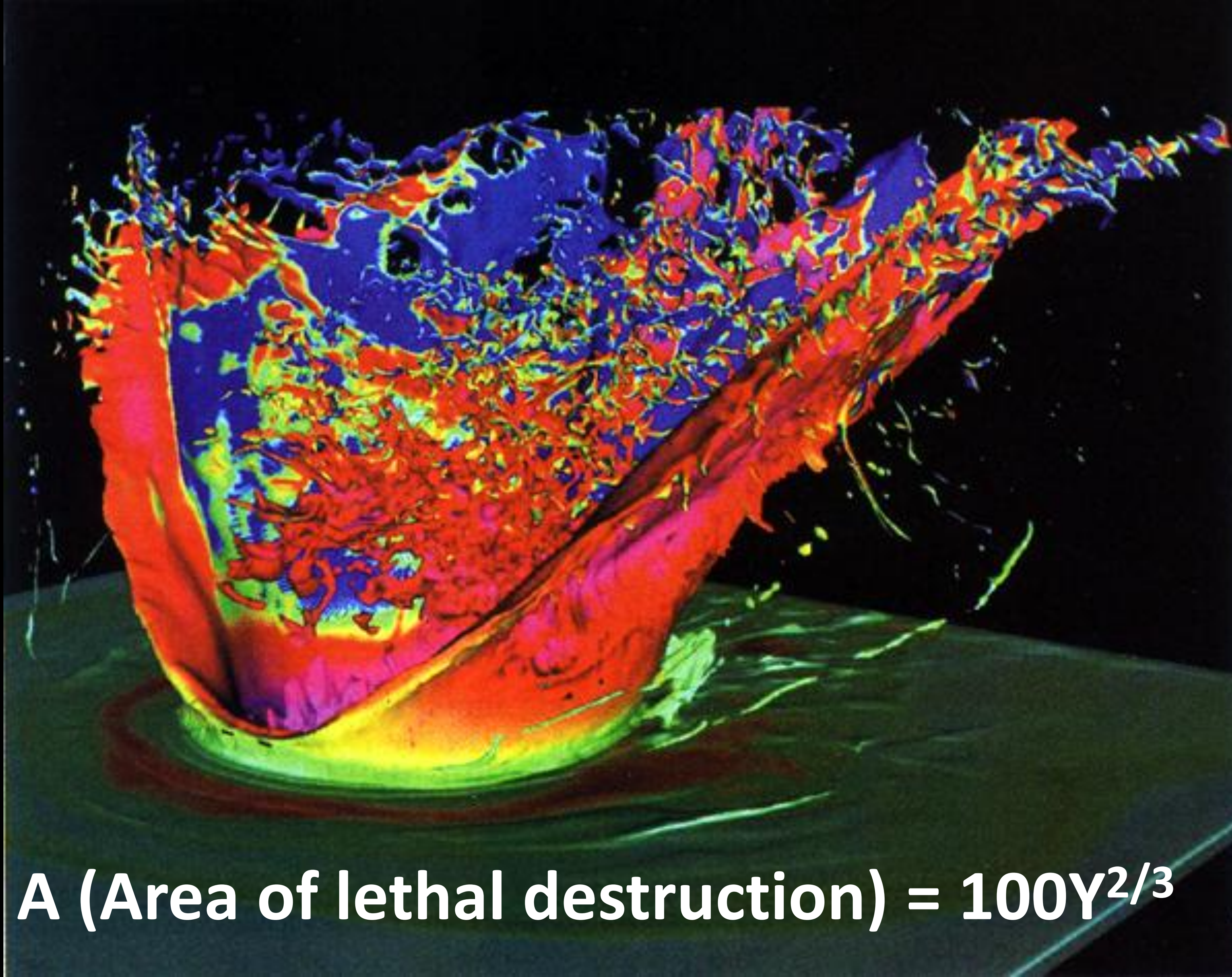


FIGURE 7.5 Cumulative size–frequency curve for terrestrial impact craters. Note the lower than expected number of smaller craters that starts to become apparent for diameters of less than around 25 km. (From Grieve, 1997)



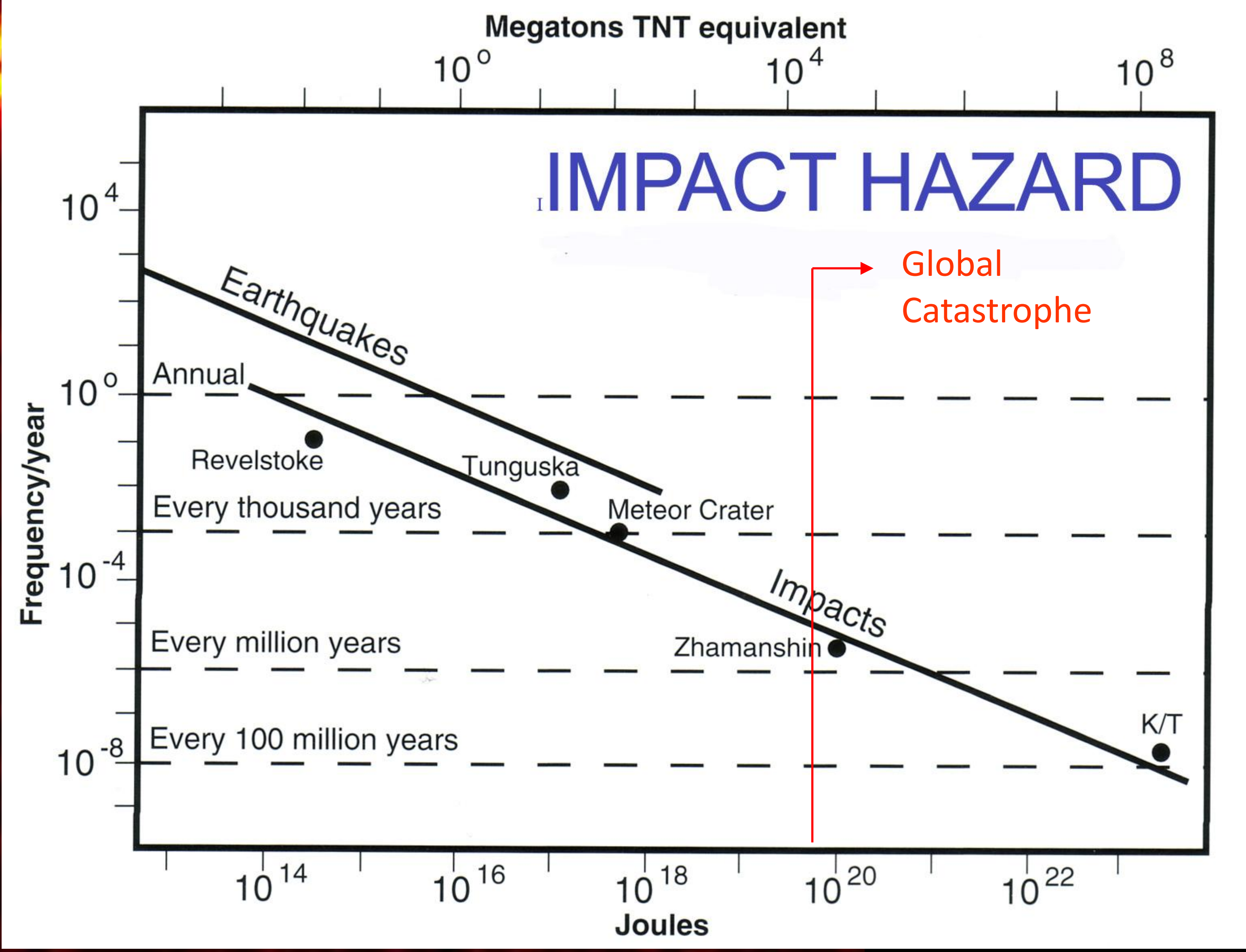
Asteroidal debris
Cometry debris
micro
radio
visual
micro meteorites
meteoroids
Zodiacal light data
Satellite data
Radio meteors
Visual and photographic meteors
Fireballs
Meteorites (stones)
Meteorites (irons)
Lunar crater data
Comets
Cumulative flux (particles onto the Earth's surface per year)
Log10 particle mass (g)
1
-10
-5
0
5
10
15
20

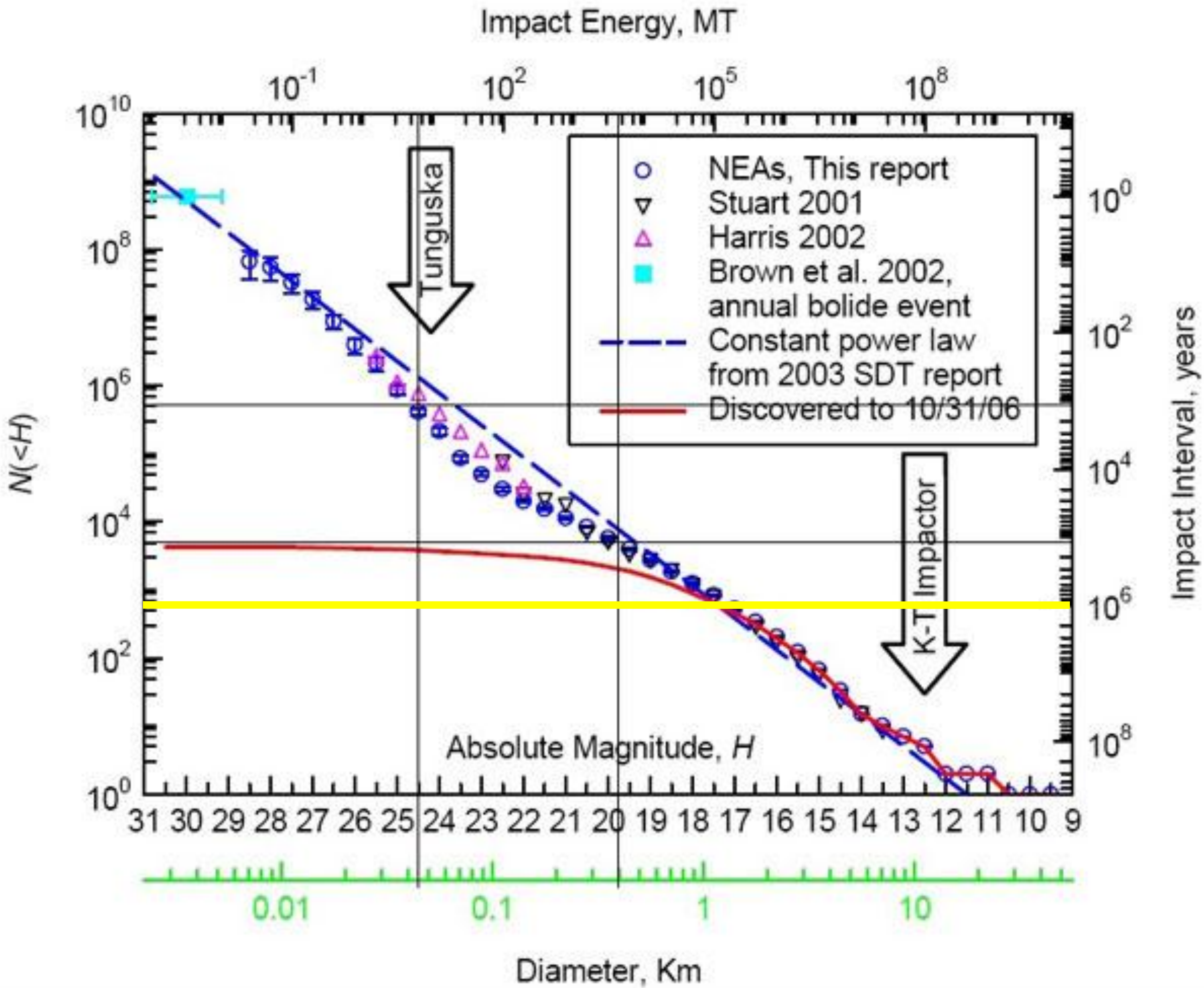

1 micron diameter
every 30 microseconds
1 millimeter diameter
every 30 seconds
1 meter diameter
each year
100 meter diameter
every 10,000 years
10 km diameter
every
100,000,000
years
Average time between impact with Earth (years)
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Diameter (meters)



A (Area of lethal destruction) = $100Y^{2/3}$

(after Grieve, 2001)





Impact Energy, MT
10^-1
10^2
10^5
10^8
10^10
10^8
10^6
10^4
10^2
10^0
N(<H)
Tunguska
NEAs, This report
Stuart 2001
Harris 2002
Brown et al. 2002, annual bolide event
Constant power law from 2003 SDT report
Discovered to 10/31/06
K-T Impactor
10^0
10^2
10^4
10^6
10^8
Impact Interval, years
Absolute Magnitude, H
31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9
0.01
0.1
1
10
Diameter, Km

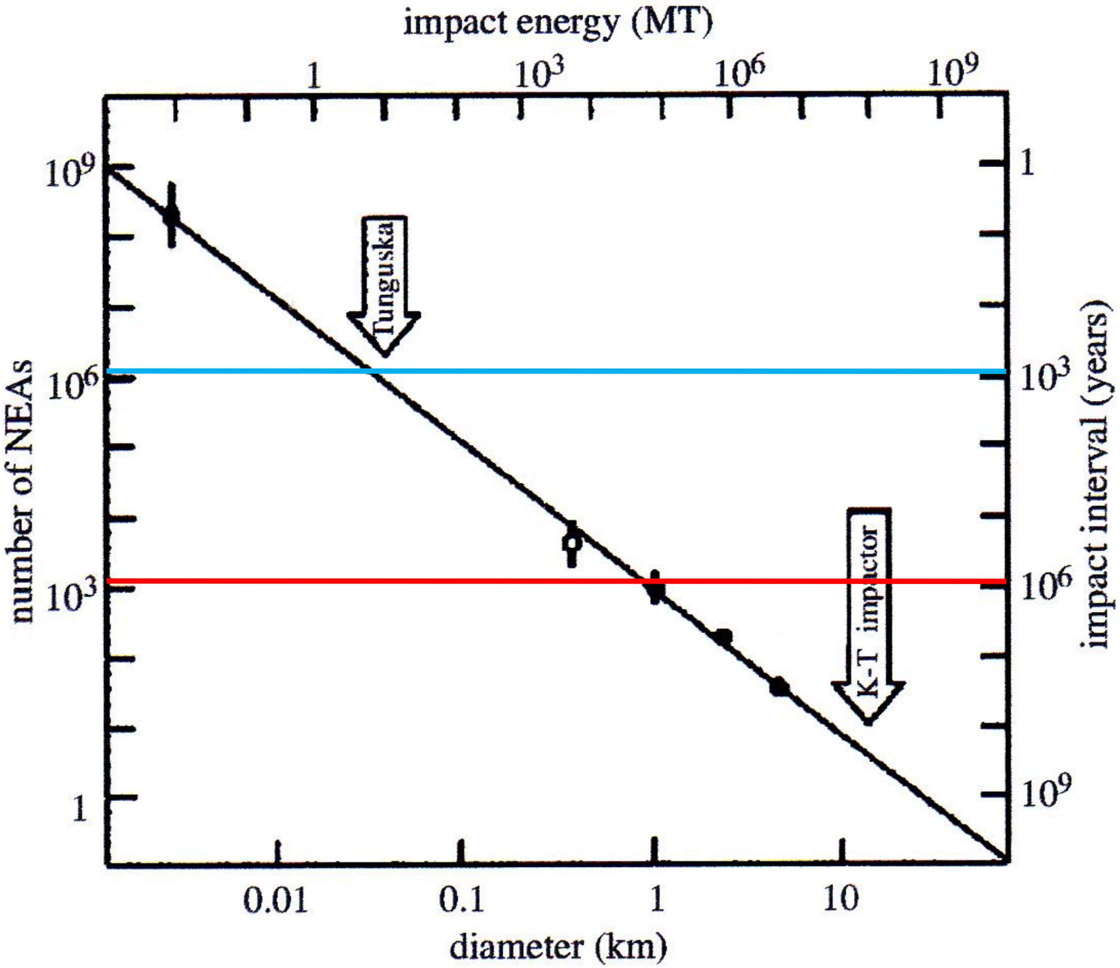
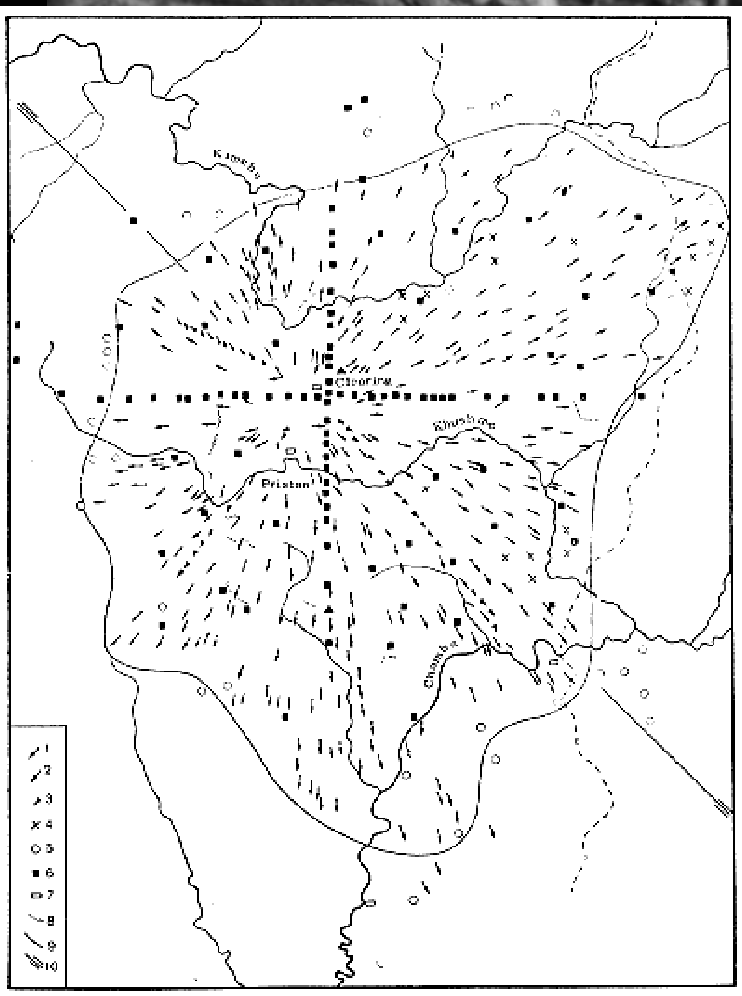


Figure 1. Power-law fit to the average impact frequency for the whole Earth as a function of impact energy in megatonnes of TNT. The scale at the bottom gives approximate equivalent diameters for an asteroid with nominal orbit and density. The four data points representing diameters from 30 m to 5 km (using the lower scale) are derived from current surveys of asteroids in near-Earth orbits. The data point at about 10 kilotonnes of energy is an estimate from observations of bright bolides in the upper atmosphere. Within the estimated uncertainties (perhaps as large as a factor of 3 in impact frequency), this curve is also consistent with historic average impact rates estimated from cratering on the Earth and Moon. **(after Morrison, 2006)**

RECONSTRUCTION OF 1908 TUNGUSKA EVENT IN 1961



TUNGUSKA IMPACTOR SIZE REVISION

The 1908 Tunguska airburst from a small asteroid has generally been estimated to have had an energy of 10-15 megatons. The corresponding size for a rocky impactor is roughly 60 meters in diameter. Mark Boslough of Sandia Laboratory, however, has generated new supercomputer simulations that suggest a smaller Tunguska explosion. In part his models require less energy in the explosion because he includes the substantial downward momentum of the rocky impactor, rather then modeling it as a stationary explosion. If this revision (down to an estimated energy of 3-5 megatons, and a corresponding diameter perhaps as low as 40 m) is correct, the expected frequency of such impacts changes, from once in a couple of millennia to once in a few hundred years. If smaller impactors can do the damage previously associated with larger ones, of course, the total hazard from such impacts is increased. Below is a press release from Sandia and a newspaper article discussing this new work.

David Morrison (Dec 2007)

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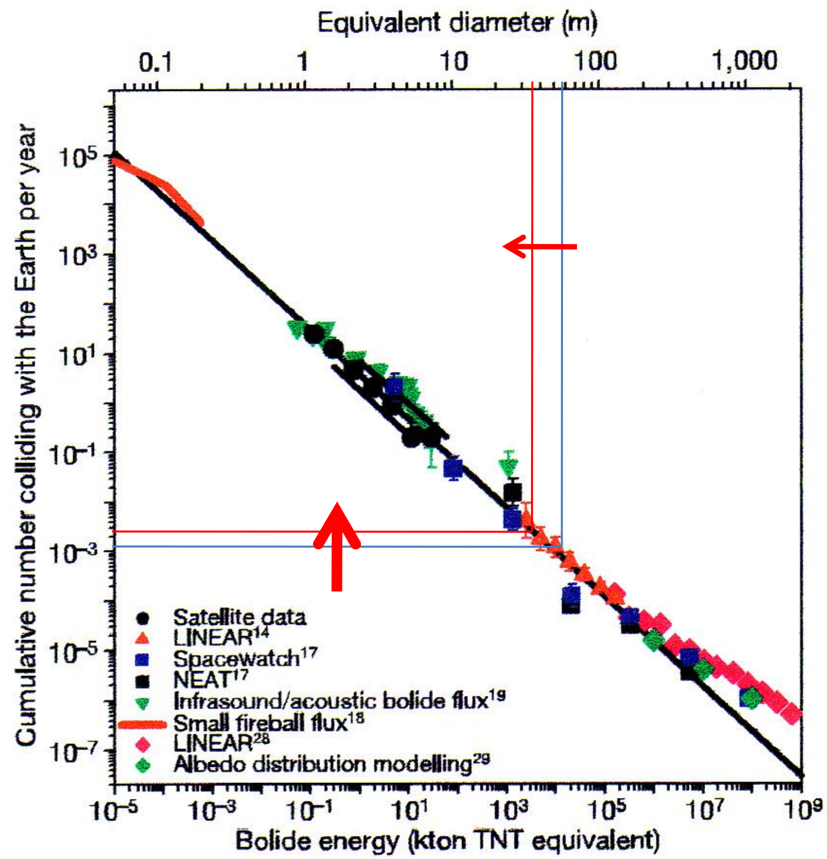
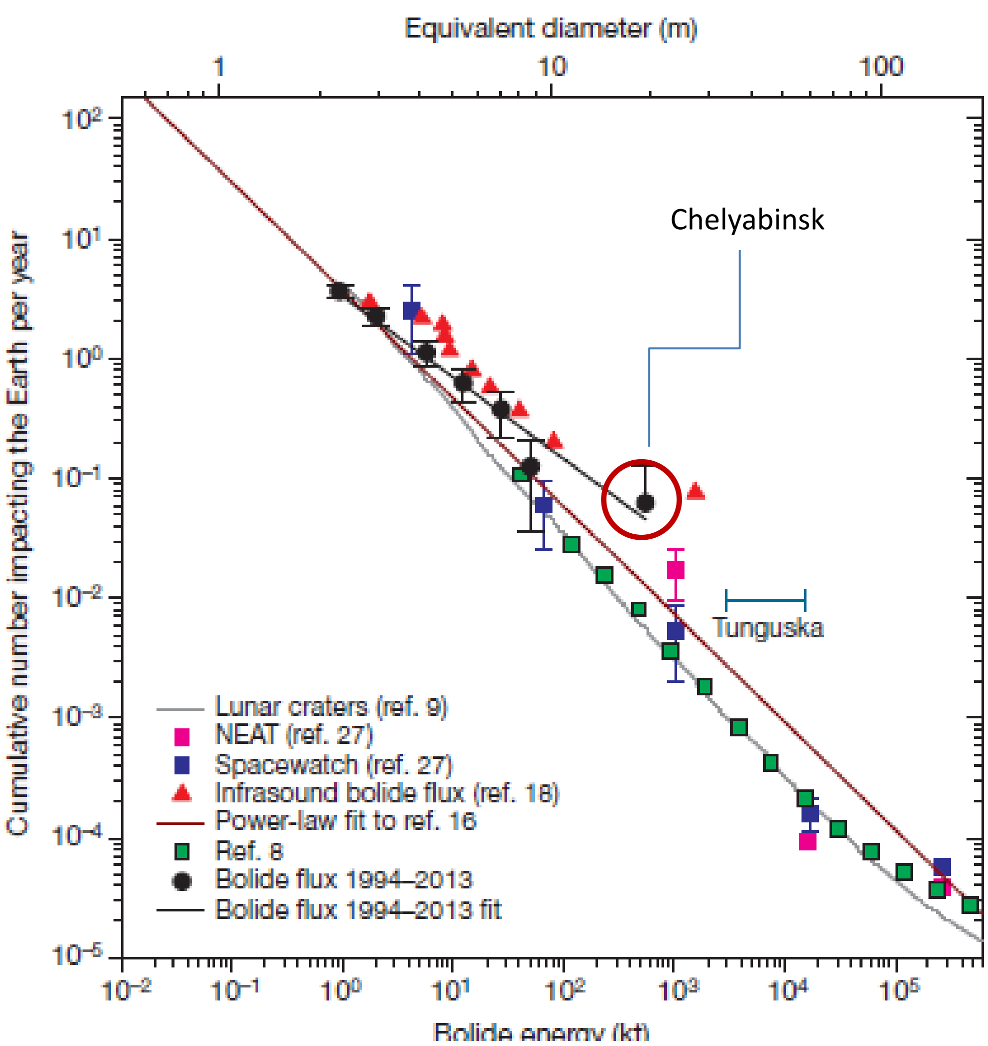


Figure 4 The flux of small near-Earth objects colliding with the Earth. Data are shown over a range of 14 magnitudes of energy. In addition to data shown in Fig. 3, this plot also shows the Earth collision hazard in the 1,000 Mton and larger energy range, based on modelling the albedo distribution of near-Earth asteroids[29]. At smaller sizes, the power-law number distribution derived from a decade-long survey of ground-based observations of fireballs[18] is indicated.

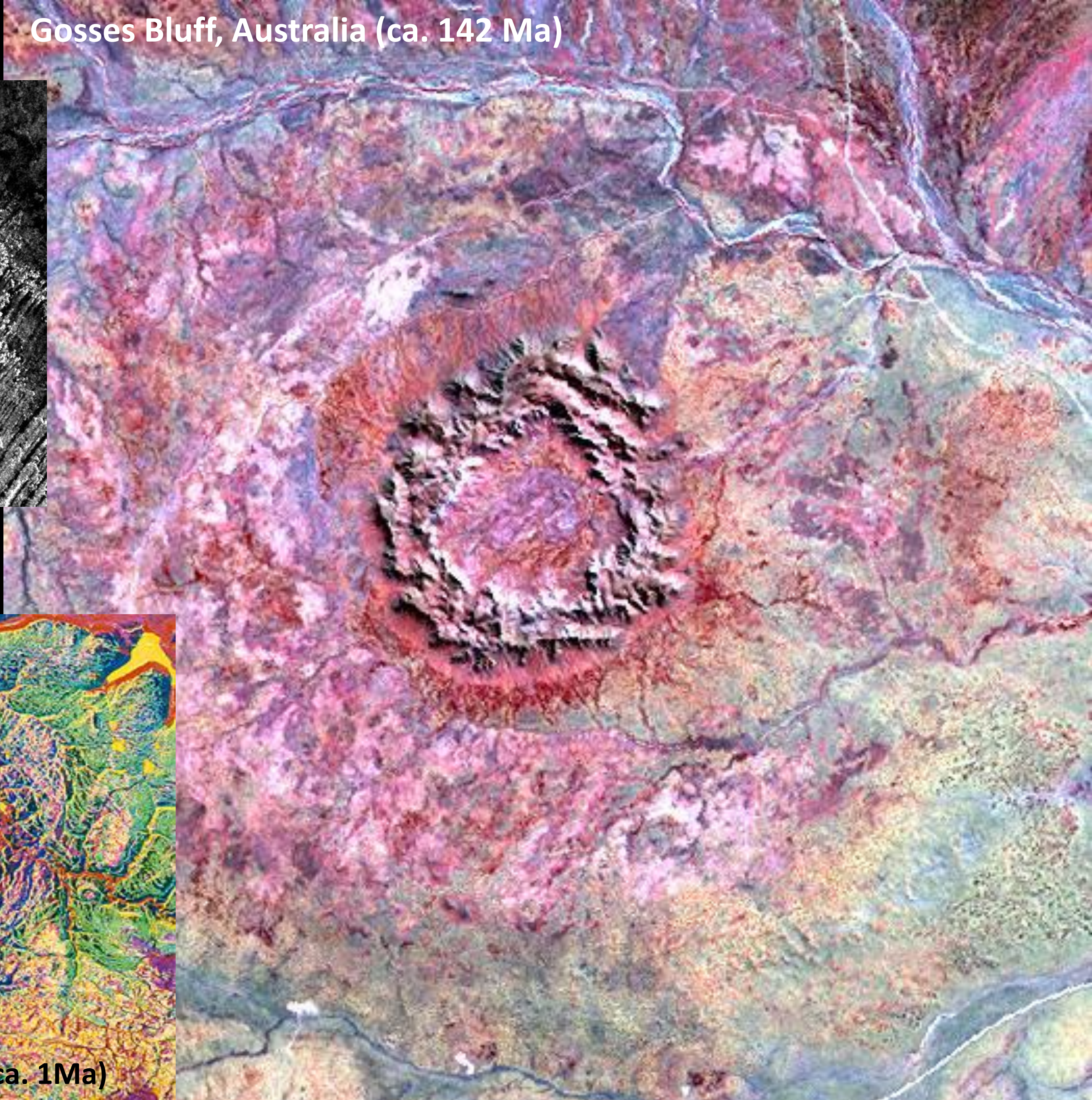
A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors

P. G. Brown[1,2], J. D. Assink[3], L. Astiz[4], R. Blaauw[5], M. B. Boslough[6], J. Borovička[7], N. Brachet[3], D. Brown[8], M. Campbell-Brown[1], L. Ceranna[9], W. Cooke[10], C. de Groot-Hedlin[4], D. P. Drob[11], W. Edwards[12], L. G. Evers[13,14], M. Garces[15], J. Gill[1], M. Hedlin[4], A. Kingery[16], G. Laske[4], A. Le Pichon[3], P. Mialle[8], D. E. Moser[5], A. Saffer[10], E. Silber[1], P. Smets[13,14], R. E. Spalding[6], P. Spurný[7], E. Tagliaferri[17], D. Uren[1], R. J. Weryk[1], R. Whitaker[18] & Z. Krzeminski[1]

Most large (over a kilometre in diameter) near-Earth asteroids are now known, but recognition that airbursts (or fireballs resulting from nuclear-weapon-sized detonations of meteoroids in the atmosphere) have the potential to do greater damage[1] than previously thought has shifted an increasing portion of the residual impact risk (the risk of impact from an unknown object) to smaller objects[2]. Above the threshold size of impactor at which the atmosphere absorbs sufficient energy to prevent a ground impact, most of the damage is thought to be caused by the airburst shock wave[3], but owing to lack of observations this is uncertain[4,5]. Here we report an analysis of the damage from the airburst of an asteroid about 19 metres (17 to 20 metres) in diameter southeast of Chelyabinsk, Russia, on 15 February 2013, estimated to have an energy equivalent of approximately 500 ($\pm$100) kilotons of trinitrotoluene (TNT, where 1 kiloton of TNT $=4.185\times10^{12}$ joules). We show that a widely referenced technique[4–6] of estimating airburst damage does not reproduce the observations, and that the mathematical relations[7] based on the effects of nuclear weapons—almost always used with this technique—overestimate blast damage. This suggests that earlier damage estimates[5,6] near the threshold impactor size are too high. We performed a global survey of airbursts of a kiloton or more (including Chelyabinsk), and find that the number of impactors with diameters of tens of metres may be an order of magnitude higher than estimates based on other techniques[8,9]. This suggests a non-equilibrium (if the population were in a long-term collisional steady state the size-frequency distribution would either follow a single power law or there must be a size-dependent bias in other surveys) in the near-Earth asteroid population for objects 10 to 50 metres in diameter, and shifts more of the residual impact risk to these sizes.



CHELYABINSK 2013 – IMPLICATIONS FOR MAGNITUDE AND FREQUENCY



Gosses Bluff, Australia (ca. 142 Ma)

Zhamanshin, Kazakhstan (ca. 1Ma)

Largest-ever meteorite crater found in Australian outback

Scientists say underground 'scars' in central Australia mark the largest meteorite crater ever found

Tectonophysics 643 (2015) 55–72

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/tecto

Geophysical anomalies and quartz deformation of the Warburton West structure, central Australia

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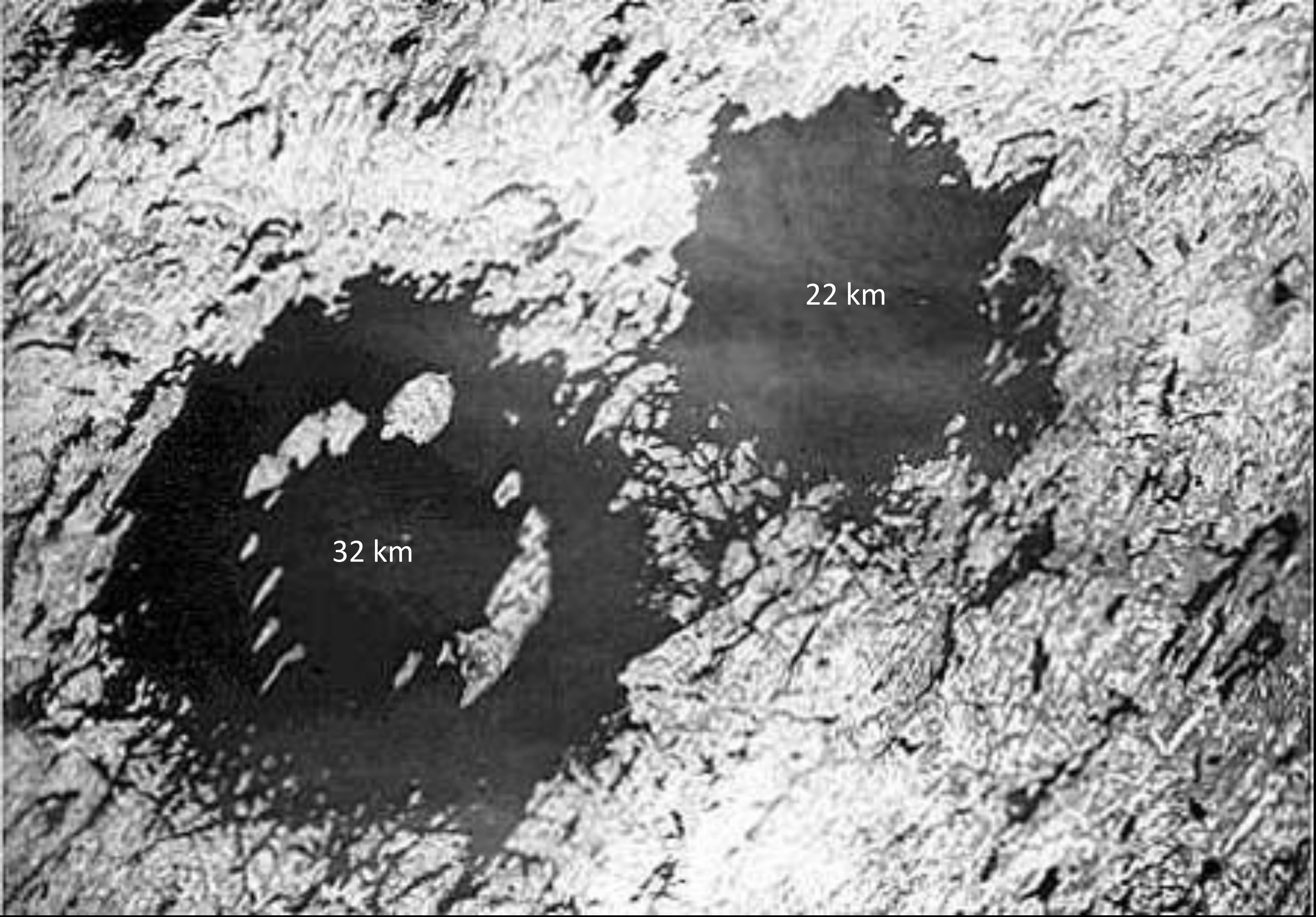
[f] Research School of Earth Science, Canberra, Australia



Clearwater Lakes, Quebec; Double impact at 250 Ma

Table 7.3 Impact scales, energies and predicted fatality rates for three different estimates of the global threshold (After Chapman and Morrison, 1994)

Type of event	Diameter of impactor	Energy (Mt)	Frequency (years)	Deaths
Tunguska-scale event	50–300 m	9–2000	250	5×10^3
Large sub-global events	300–600 m	$2000–1.5 \times 10^4$	35×10^3	3×10^5
(3 estimates)	300 m to 1.5 km	$2000–2.5 \times 10^5$	25×10^3	5×10^5
	300 m to 5 km	$2000–10^7$	25×10^3	1.2×10^6
Low global threshold	>600 m	1.5×10^4	7×10^4	1.5×10^9
Nominal global threshold	>1.5 km	2×10^5	5×10^5	1.5×10^9
High global threshold	>5 km	10^7	6×10^6	1.5×10^9
Rare K/T-scale events	>10 km	10^8	10^8	5×10^9

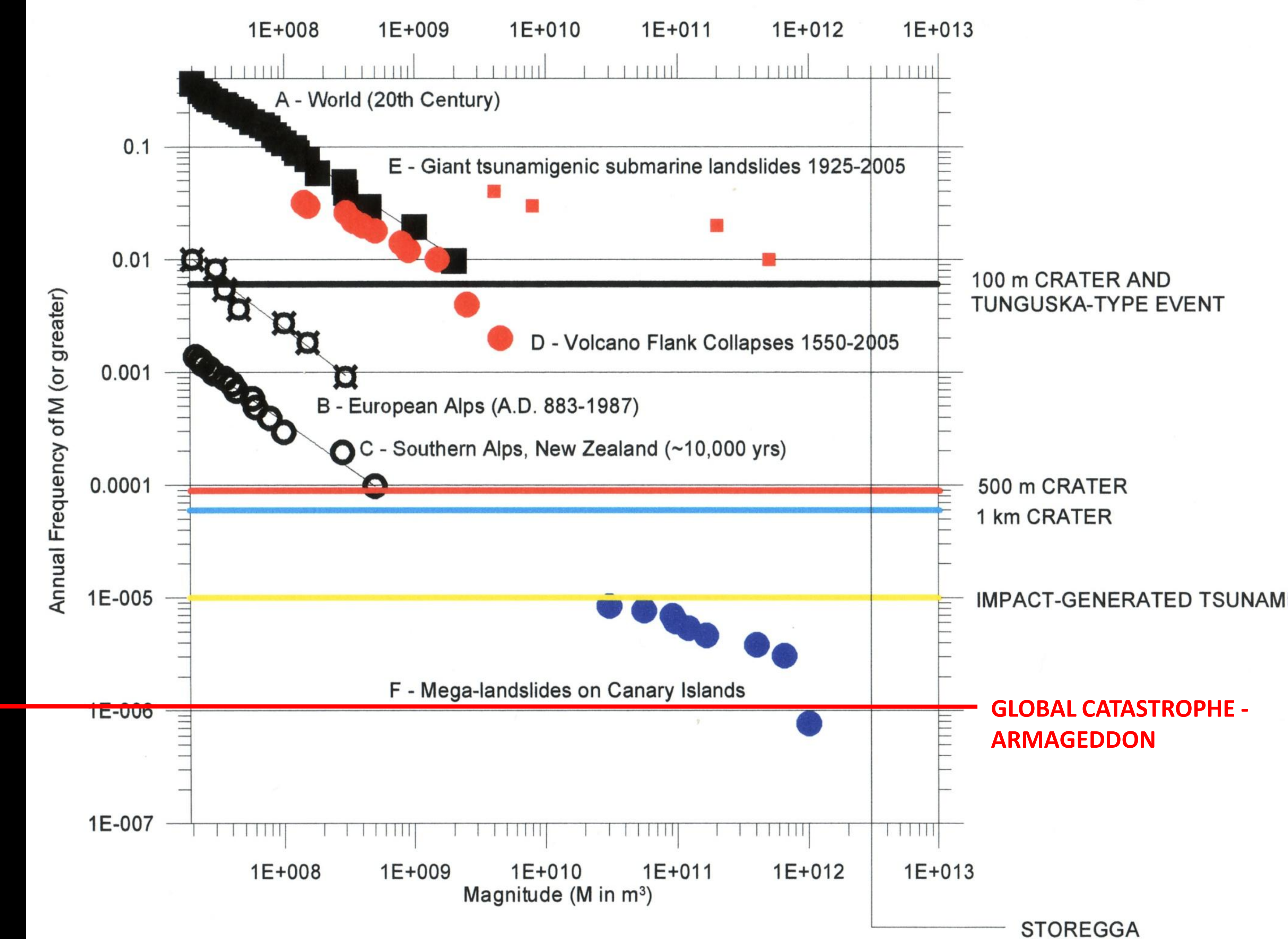

1E+008
1E+009
1E+010
1E+011
1E+012
1E+013
A - World (20th Century)
E - Giant tsunamigenic submarine landslides 1925-2005
0.1
0.01
0.001
0.0001
1E-005
1E-006
1E-007
Annual Frequency of M (or greater)
100 m CRATER AND
TUNGUSKA-TYPE EVENT
D - Volcano Flank Collapses 1550-2005
B - European Alps (A.D. 883-1987)
C - Southern Alps, New Zealand (~10,000 yrs)
500 m CRATER
1 km CRATER
IMPACT-GENERATED TSUNAMI
F - Mega-landslides on Canary Islands
GLOBAL CATASTROPHE -
ARMAGEDDON
Magnitude (M in m³)
STOREGGA

TABLE 17.5

Table 17.5

Frequency of Impacts and Annual Risks of Death

For Tunguska-sized events:	
Average interval between impacts	300 years
Average interval for populated areas only	3,000 years
Average interval for urban areas	100,000 years
Average interval for US urban areas only	1,000,000 years
Total annual probability of death	1/30,000,000

Source: D. Morrison (1992).

TABLE 17.6

Odds of Dying in the United States from Selected Causes

Cause of Death	Odds of Happening
Motor vehicle accident	1 in 100
Murder	1 in 300
Fire	1 in 800
Firearms accident	1 in 2,500
Asteroid/Comet impact (lower limit)	**1 in 3,000**
Electrocution	1 in 5,000
Airplane crash	1 in 20,000
Flood	1 in 30,000
Tornado	1 in 60,000
Venomous bite or sting	1 in 100,000
Asteroid/Comet impact (upper limit)	**1 in 250,000**
Fireworks accident	1 in 1,000,000
Food poisoning by botulism	1 in 3,000,000

Source: C. Chapman (2003).

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Sentry Risk Table

- Removed Objects
- Introduction to Impact Monitoring
- Frequently Asked Questions
- Operational Notes

The following table lists potential future Earth impact events that the JPL Sentry System has detected based on currently available observations. Click on the object designation to go to a page with full details on that object.

Sentry is a highly automated collision monitoring system that continually scans the most current asteroid catalog for possibilities of future impact with Earth over the next 100 years. Whenever a potential impact is detected it will be analyzed and the results immediately published here, except in unusual cases where an IAU Technical Review is underway.

It is normal that, as additional observations become available, objects will disappear from this table whenever there are no longer any potential impact detections. For this reason we maintain a list of removed objects with the date of removal.

558 NEAs: Last Updated Mar 31, 2015

Sort by Palermo Scale (cum.) or by Object Designation

Recently Observed Objects (within past 60 days)

Object Designation	Year Range	Potential Impacts	Impact Prob. (cum.)	$V_{infinity}$ (km/s)	H (mag)	Est. Diam. (km)	Palermo Scale (cum.)	Palermo Scale (max.)	Torino Scale (max.)
2015 FL290	2082-2085	3	9.0e-07	10.82	22.0	0.140	-4.76	-5.04	0
2015 DA54	2107-2107	1	8.6e-08	23.13	20.8	0.230	-5.00	-5.00	0
2015 FP118	2021-2058	3	2.2e-09	11.73	19.6	0.410	-5.31	-5.34	0
2015 FG120	2062-2112	22	8.8e-07	8.43	23.1	0.080	-5.33	-5.70	0
2015 FN36	2100-2113	3	7.8e-07	22.04	23.9	0.057	-5.54	-5.69	0
2015 EO	2050-2077	8	6.7e-06	14.24	26.6	0.016	-5.91	-6.14	0


Off World
NASA's Scout Space Monitoring System Gave 5 Days Warning of Passing Asteroid
P.Carril/ESA

A close encounter: Nasa's new 'Scout' asteroid-spotter catches a large space rock hurtling towards Earth

- The asteroid, named 2016 UR36, was first detected on October 25
- Nasa was able to predict where it was headed thanks to its new tool
- Huge asteroid passed Earth at a comfortable distance of 310,000 miles

Daily Mail, October 31, 2016

THE TORINO SCALE

Assessing Asteroid/Comet Impact Predictions

No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Certain Collisions	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing a global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

Fig. 2. Public description for the Torino Scale, revised from Binzel (2000) to better describe the attention or response that is merited for each category.

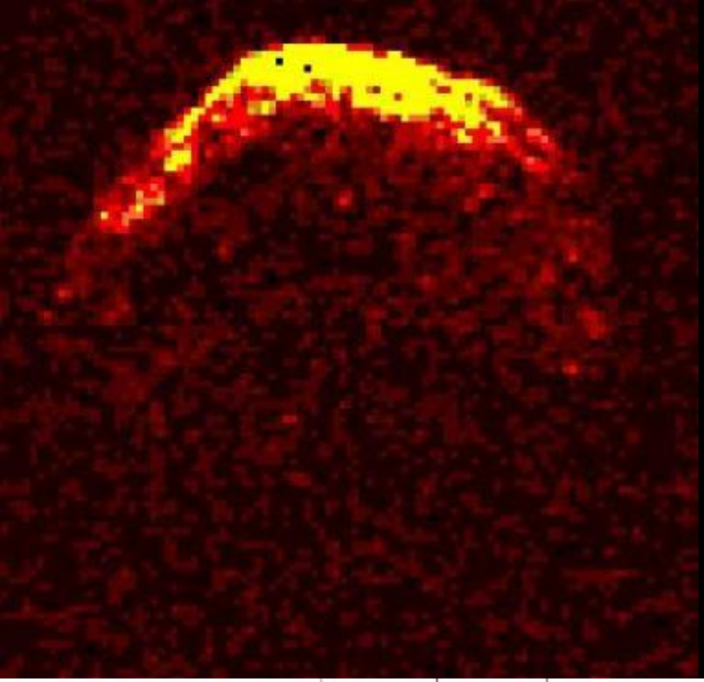
TABLE 17.4

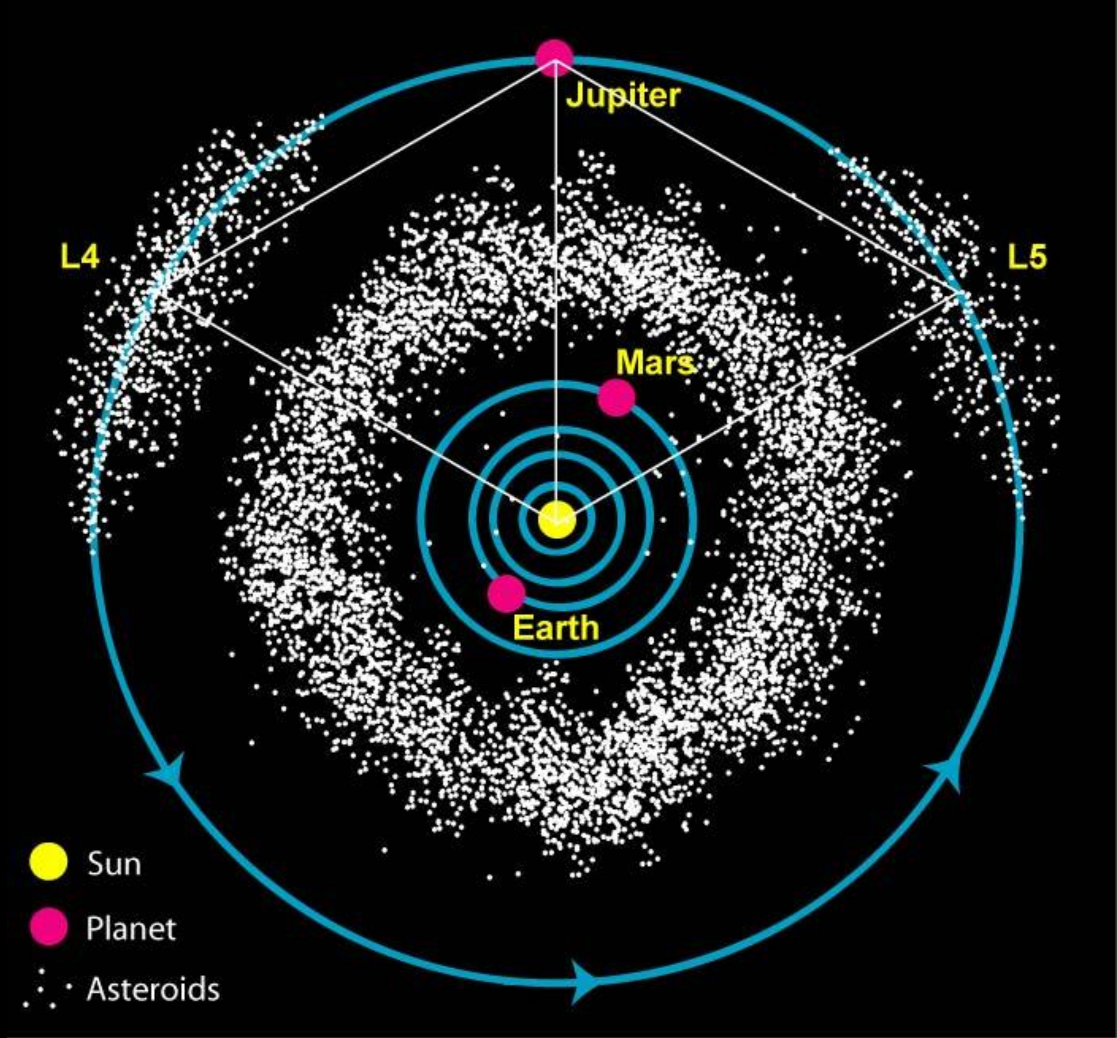
The Torino Scale

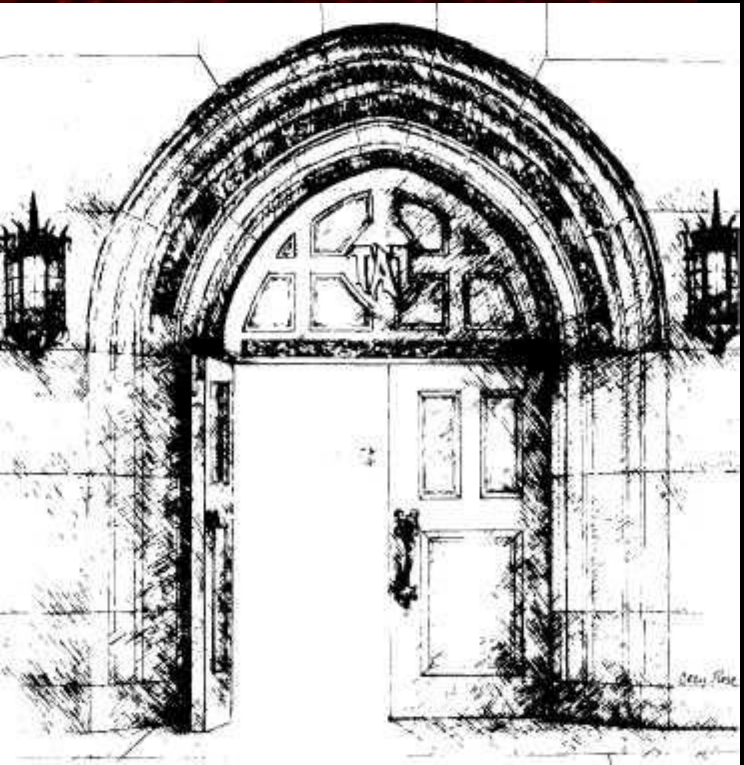
Assessing Comet and Asteroid Impact Hazards

Events with no likely consequences (White zone)	
0	No collision hazard, or object is small.
Events meriting careful monitoring (Green zone)	
1	Collision is extremely unlikely.
Events of concern (Yellow zone)	
2	Collision is very unlikely.
3	Close encounter with >1% chance of local destruction.
4	Close encounter with >1% chance of regional devastation.
Threatening events (Orange zone)	
5	Significant threat of regional devastation.
6	Significant threat of global catastrophe.
7	Extremely significant threat of global catastrophe.
Certain collisions (Red zone)	
8	Collision will cause localized destruction (one event each 50 to 1,000 years).
9	Collision will cause regional devastation (one event each 1,000 to 100,000 years).
10	Collision will cause global catastrophe (one event each 100,000 years).

99942



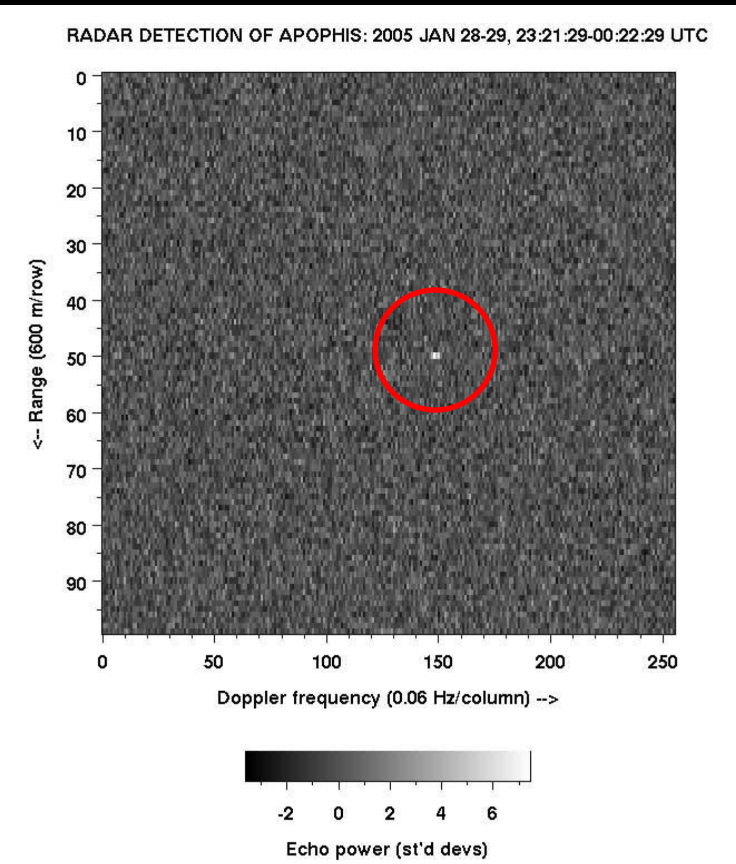




APOPHIS 2029 & 2036

APOPHIS – EGYPTIAN GOD OF CHAOS AND DESTRUCTION (SNAKE DEMON)

APOPHIS ENCOUNTER 1 – FRIDAY 13 APRIL 2029
APOPHIS ENCOUNTER 2 – EASTER SUNDAY 13 APRIL 2036



210-330 m in diameter

Available online at www.sciencedirect.com

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Icarus 193 (2008) 1–19

www.elsevier.com/locate/icarus

Predicting the Earth encounters of (99942) Apophis

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[b] *Arecibo Observatory, National Astronomy and Ionosphere Center, HC03 Box 53995, Arecibo, PR 00612, USA*
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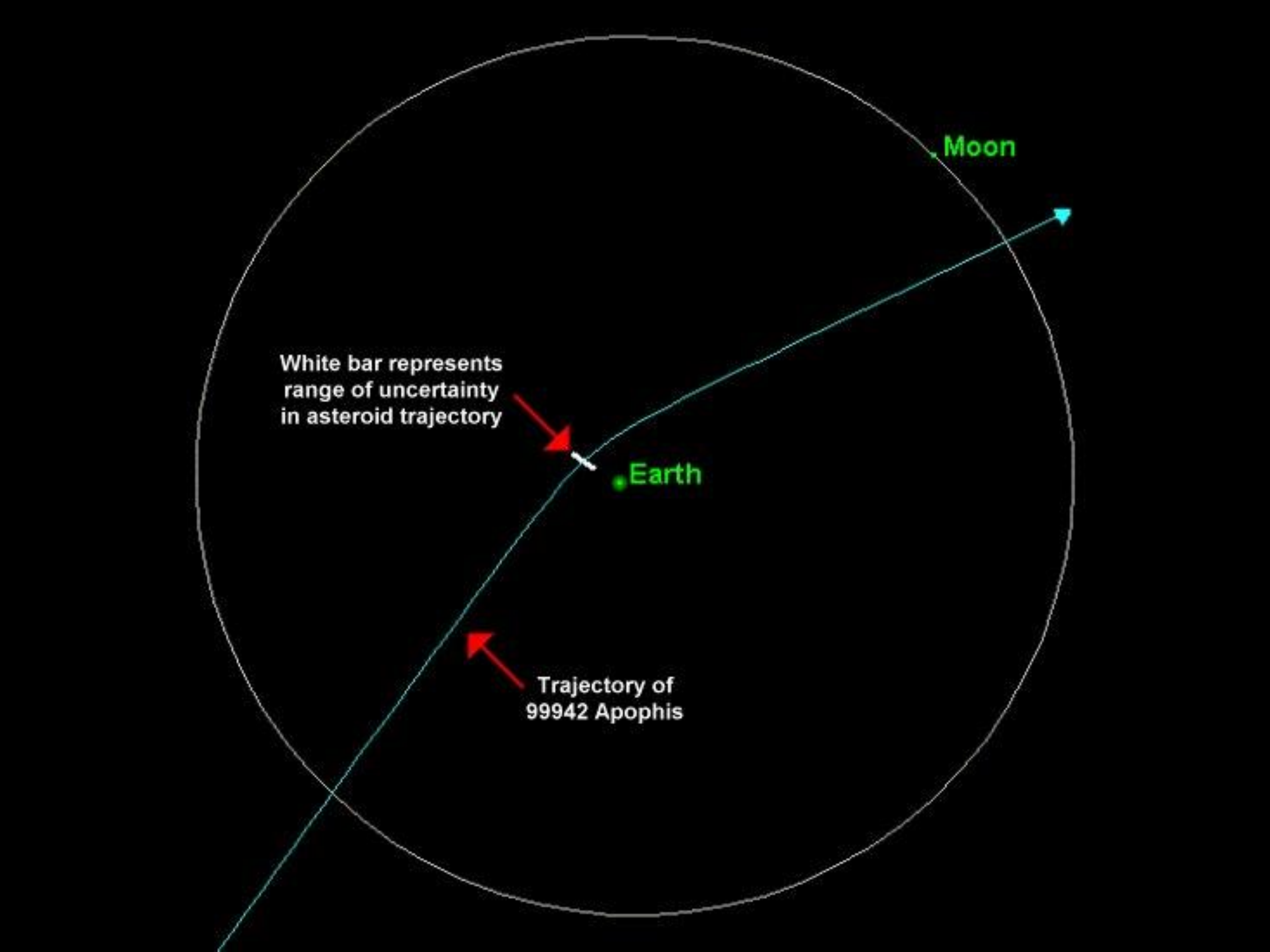
Received 18 July 2007; revised 5 September 2007

Available online 9 October 2007

Abstract

Arecibo delay–Doppler measurements of (99942) Apophis in 2005 and 2006 resulted in a five standard-deviation trajectory correction to the optically predicted close approach distance to Earth in 2029. The radar measurements reduced the volume of the statistical uncertainty region entering the encounter to 7.3% of the pre-radar solution, but increased the trajectory uncertainty growth rate across the encounter by 800% due to the closer predicted approach to the Earth. A small estimated Earth impact probability remained for 2036. With standard-deviation plane-of-sky position uncertainties for 2007–2010 already less than 0.2 arcsec, the best near-term ground-based optical astrometry can only weakly affect the trajectory estimate. While the potential for impact in 2036 will likely be excluded in 2013 (if not 2011) using ground-based optical measurements, approximations within the Standard Dynamical Model (SDM) used to estimate and predict the trajectory from the current era are sufficient to obscure the difference between a predicted impact and a miss in 2036 by altering the dynamics leading into the 2029 encounter. Normal impact probability assessments based on the SDM become problematic without knowledge of the object's physical properties; impact could be excluded while the actual dynamics still permit it. Calibrated position uncertainty intervals are developed to compensate for this by characterizing the minimum and maximum effect of physical parameters on the trajectory. Uncertainty in accelerations related to solar radiation can cause between 82 and 4720 Earth-radii of trajectory change relative to the SDM by 2036. If an actionable hazard exists, alteration by 2–10% of Apophis' total absorption of solar radiation in 2018 could be sufficient to produce a six standard-deviation trajectory change by 2036 given physical characterization; even a 0.5% change could produce a trajectory shift of one Earth-radius by 2036 for all possible spin-poles and likely masses. Planetary ephemeris uncertainties are the next greatest source of systematic error, causing up to 23 Earth-radii of uncertainty. The SDM Earth point-mass assumption introduces an additional 2.9 Earth-radii of prediction error by 2036. Unmodeled asteroid perturbations produce as much as 2.3 Earth-radii of error. We find no future small-body encounters likely to yield an Apophis mass determination prior to 2029. However, asteroid (144898) 2004 VD17, itself having a statistical Earth impact in 2102, will probably encounter Apophis at 6.7 lunar distances in 2034, their uncertainty regions coming as close as 1.6 lunar distances near the center of both SDM probability distributions.

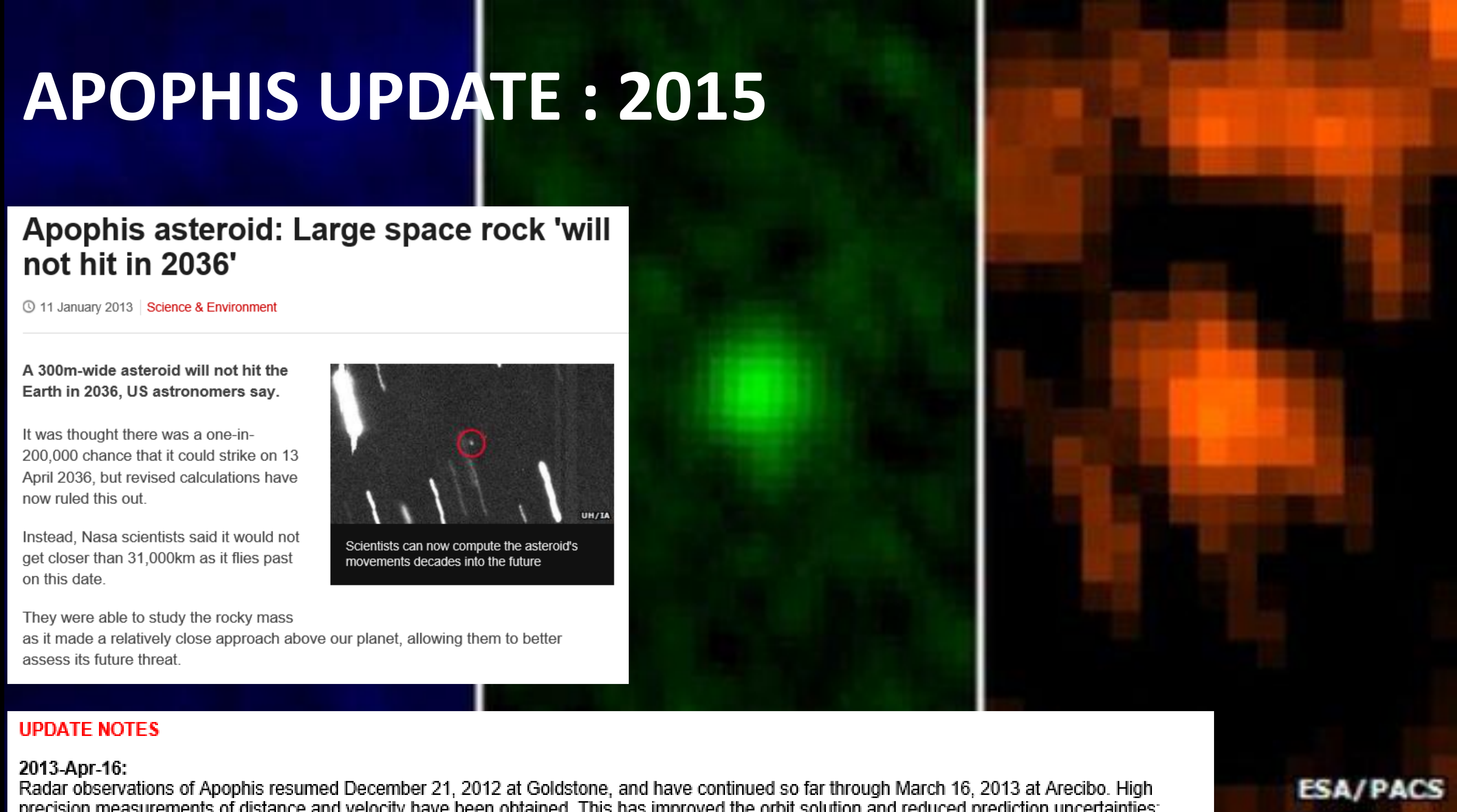
Keywords: Asteroids; Asteroids, dynamics; Radar observations; Near-Earth objects; Orbit determination


Moon
White bar represents range of uncertainty in asteroid trajectory
Earth
Trajectory of 99942 Apophis

APOPHIS UPDATE : 2011

- NASA'S RECALCULATION IN 2009 INDICATES SIGNIFICANTLY REDUCED LIKELIHOOD OF HAZARDOUS ENCOUNTER WITH EARTH IN 2036
- CHANCES OF EARTH ENCOUNTER DROPPED FROM 1/45,000 TO 1/4,000,000 (ABOUT 1,000 TIMES LESS)

APOPHIS UPDATE : 2015



Apophis asteroid: Large space rock 'will not hit in 2036'

11 January 2013 | Science & Environment

A 300m-wide asteroid will not hit the Earth in 2036, US astronomers say.

Scientists can now compute the asteroid's movements decades into the future

It was thought there was a one-in-200,000 chance that it could strike on 13 April 2036, but revised calculations have now ruled this out.

Instead, Nasa scientists said it would not get closer than 31,000km as it flies past on this date.

They were able to study the rocky mass as it made a relatively close approach above our planet, allowing them to better assess its future threat.

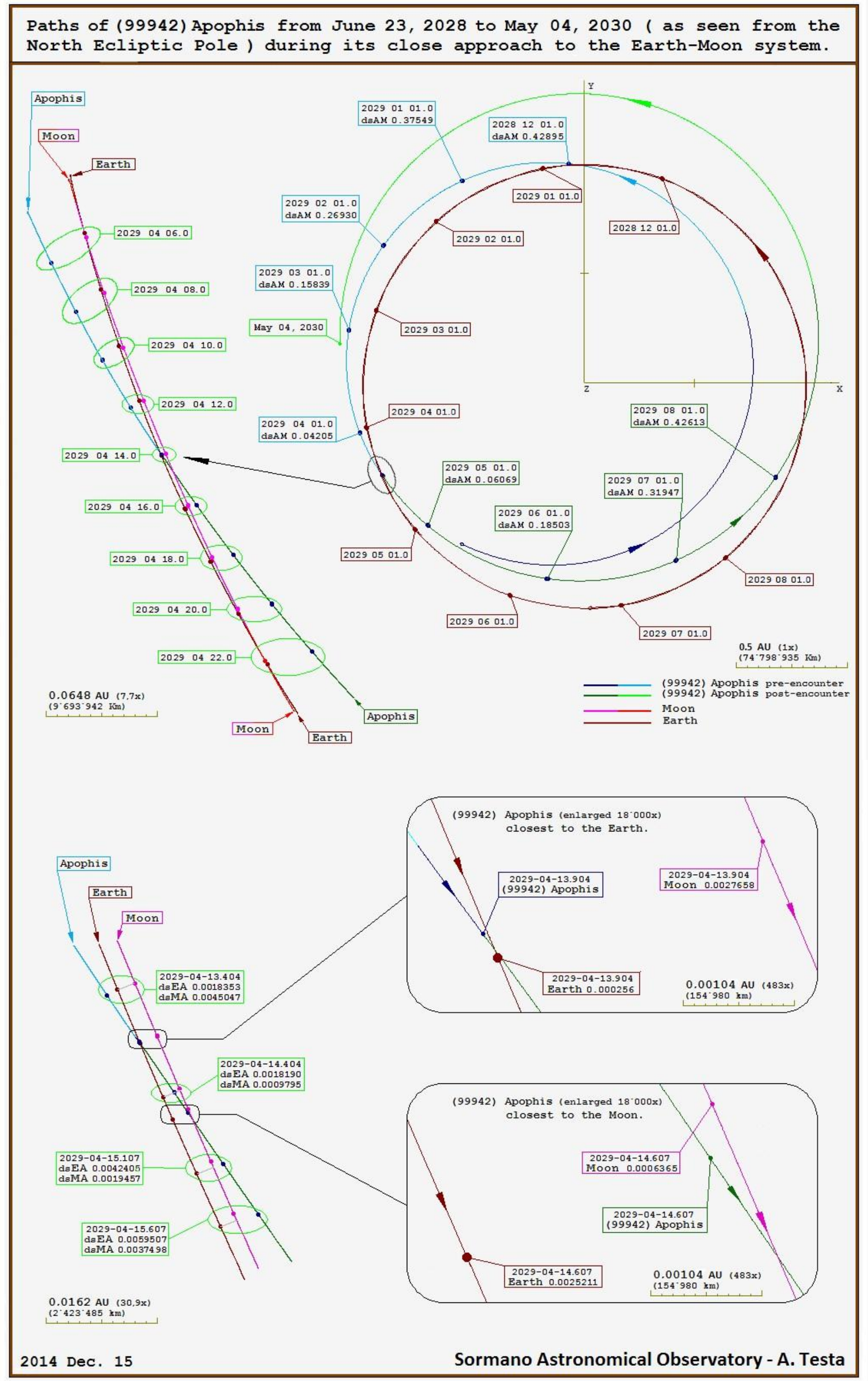
UPDATE NOTES

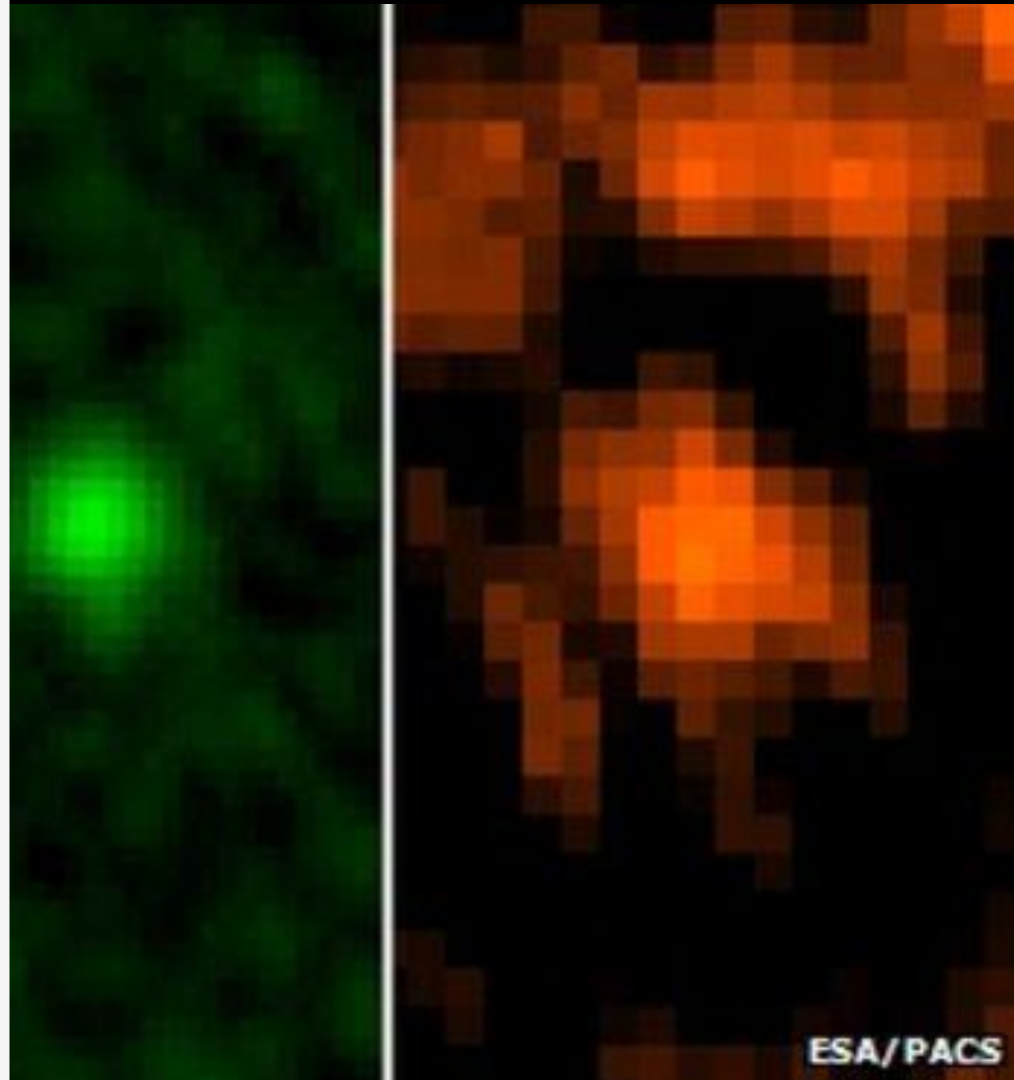
2013-Apr-16:
Radar observations of Apophis resumed December 21, 2012 at Goldstone, and have continued so far through March 16, 2013 at Arecibo. High precision measurements of distance and velocity have been obtained. This has improved the orbit solution and reduced prediction uncertainties:

#1) The echo was strong enough that low-resolution (few pixel) imaging was obtained at Goldstone, revealing the elongated shape of Apophis as it rotated. Equipment problems at Arecibo prevented the higher resolution characterization that had been planned.

#2) Trajectory predictions based on the gravity-only orbit solution described in the 2008 Icarus paper were found to be correct to within 18 mm/s per second and 132 km after predicting ahead six years. These are statistically small prediction errors; 0.75-sigma in Doppler and 0.57-sigma in range. There are no observational indications of non-gravitational forces acting on Apophis over 2004-2013.

The new radar data, along with new optical astrometry, permits refinement of the 2036 Earth encounter, now nominally predicted to occur at a distant 0.388 au (about 150 lunar distances). This is 22% further away than the paper's nominal prediction of 0.317 au, though well within the statistical uncertainties of that solution (s142).





APOPHIS IMPACT HAZARD ASSESSMENT

APOPHIS UPDATE : 2017

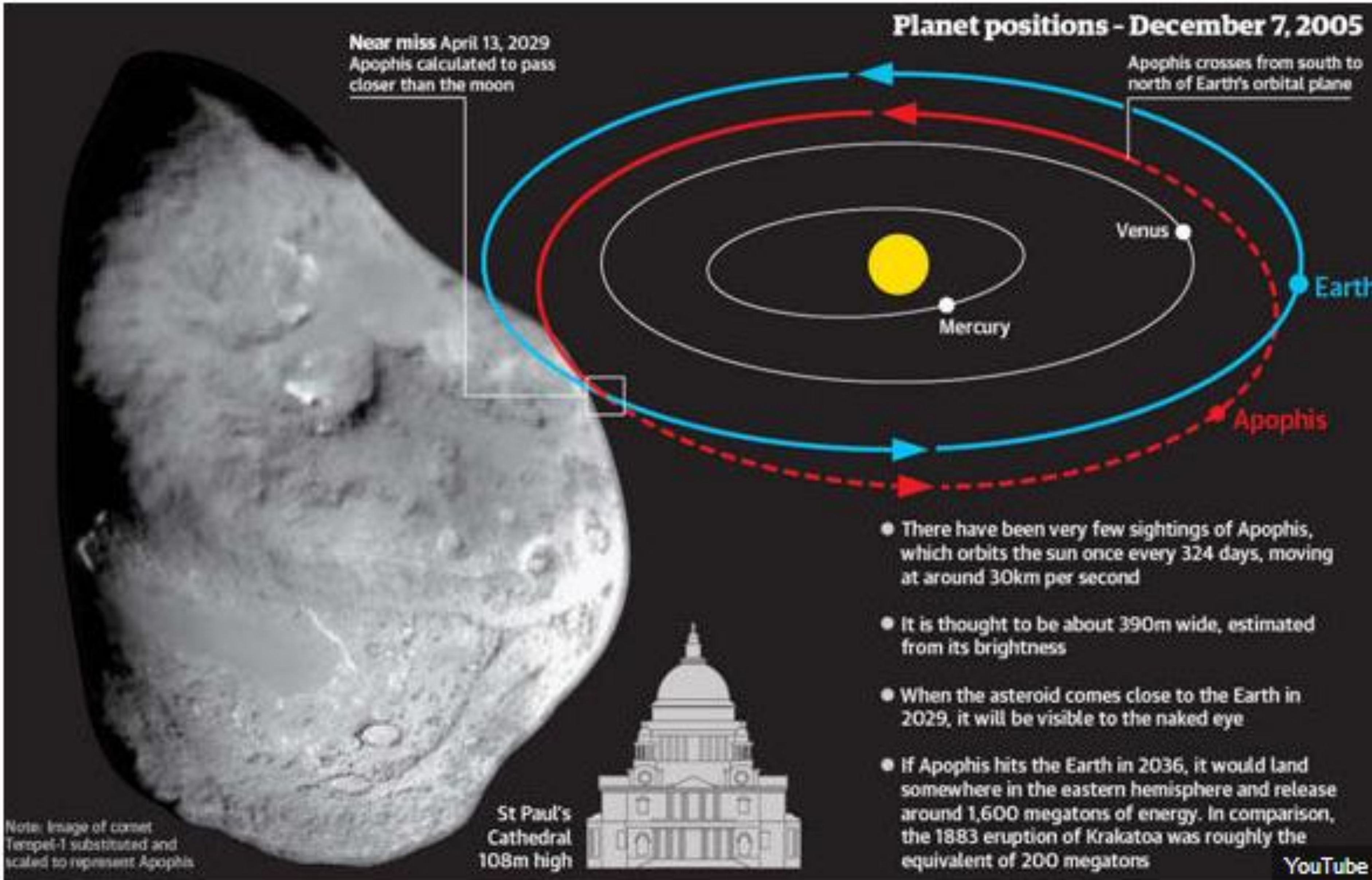
Predicting Apophis' Earth Encounters in 2029 and 2036

UPDATE! (April 2013) See notes below for preliminary 2012-2013 radar results and news

SUMMARY

Researchers at NASA/JPL, Caltech, and Arecibo Observatory have released the results of radar observations of the potentially hazardous asteroid 99942 Apophis, along with an in-depth analysis of its motion. The research will affect how and when scientists measure, predict, or consider modifying the asteroid's motion. The paper has been accepted for publication in the science journal "Icarus" and was presented at the AAS/DPS conference in Orlando, Florida in October of 2007. The Apophis study was led by Jon Giorgini, a senior analyst in JPL's Solar System Dynamics group and member of the radar team that observed Apophis.

The analysis of Apophis previews situations likely to be encountered with NEAs yet to be discovered: a close approach that is not dangerous (like Apophis in 2029) nonetheless close enough to obscure the proximity and the danger of a later approach (like Apophis in 2036) by amplifying trajectory prediction uncertainties caused by difficult-to-observe physical characteristics interacting with solar radiation as well as other factors.


Planet positions - December 7, 2005
Near miss April 13, 2029
Apophis calculated to pass closer than the moon
Apophis crosses from south to north of Earth's orbital plane
Venus
Earth
Mercury
Apophis
There have been very few sightings of Apophis, which orbits the sun once every 324 days, moving at around 30km per second
It is thought to be about 390m wide, estimated from its brightness
When the asteroid comes close to the Earth in 2029, it will be visible to the naked eye
If Apophis hits the Earth in 2036, it would land somewhere in the eastern hemisphere and release around 1,600 megatons of energy. In comparison, the 1883 eruption of Krakatoa was roughly the equivalent of 200 megatons
St Paul's Cathedral 108m high
Note: Image of comet Tempel-1 substituted and scaled to represent Apophis
YouTube

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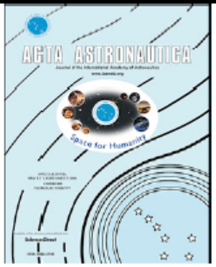

Options and uncertainties in planetary defense: Mission planning and vehicle design for flexible response

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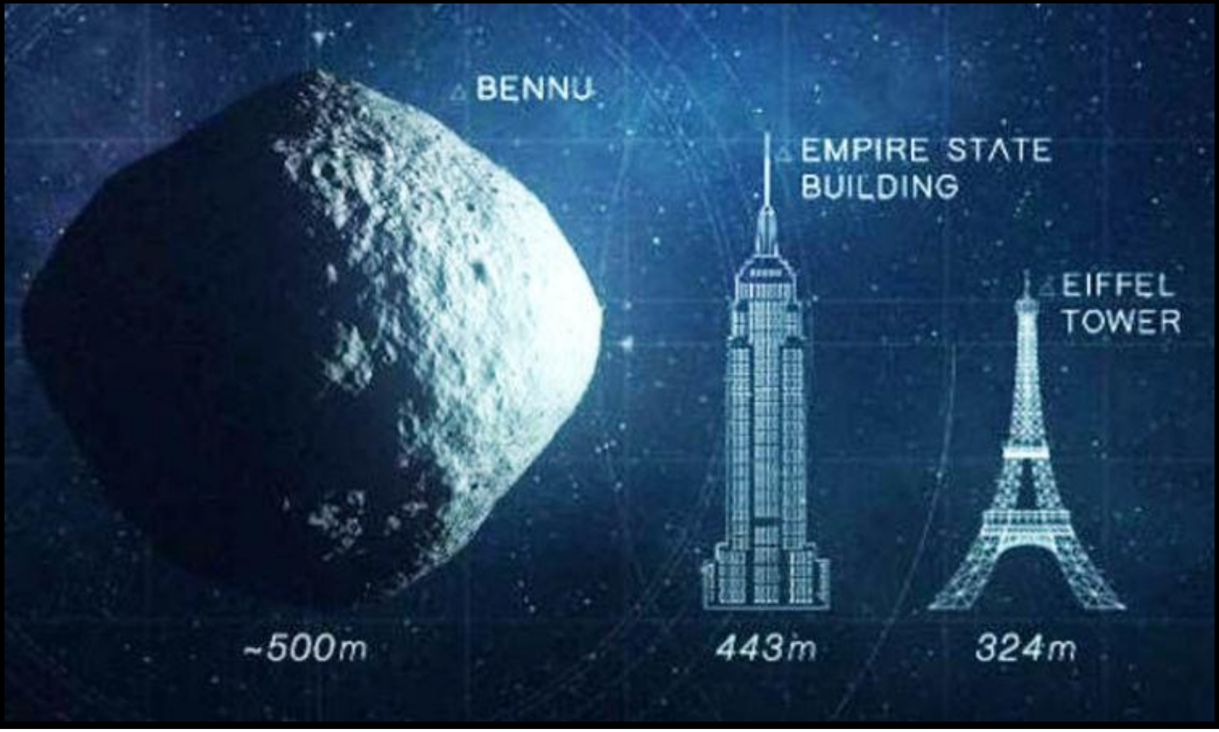


ASTEROID BENNU: NASA WANTS TO USE NUCLEAR WEAPONS TO DEFLECT 1,600-FOOT SPACE ROCK

BY KATHERINE HIGNETT ON 3/9/18 AT 7:49 AM

Recent Bennu Press Stories Need Correction

Mar 24, 2018 • Paul Chodas • Center for NEO Studies (CNEOS)

Several news stories circulating over the past week reporting on the possibility of asteroid Bennu impacting the Earth need some correction. These stories name 2135 as the year when asteroid Bennu has a small chance of impacting the Earth, but that is incorrect. In fact, as shown by our Sentry impact monitoring system analysis for Bennu (reported by CNEOS and a paper published in Icarus in 2014), the earliest possible year in which the asteroid could hit our planet is 2175, and the chance of the impact happening in that year is 1 in 24,000. The stories state the odds of Bennu hitting our planet as "about 1 in 2,700" and imply this is the impact probability for a single year. But, in fact, those odds are the cumulative probability of impact over all years between 2175 and 2199.

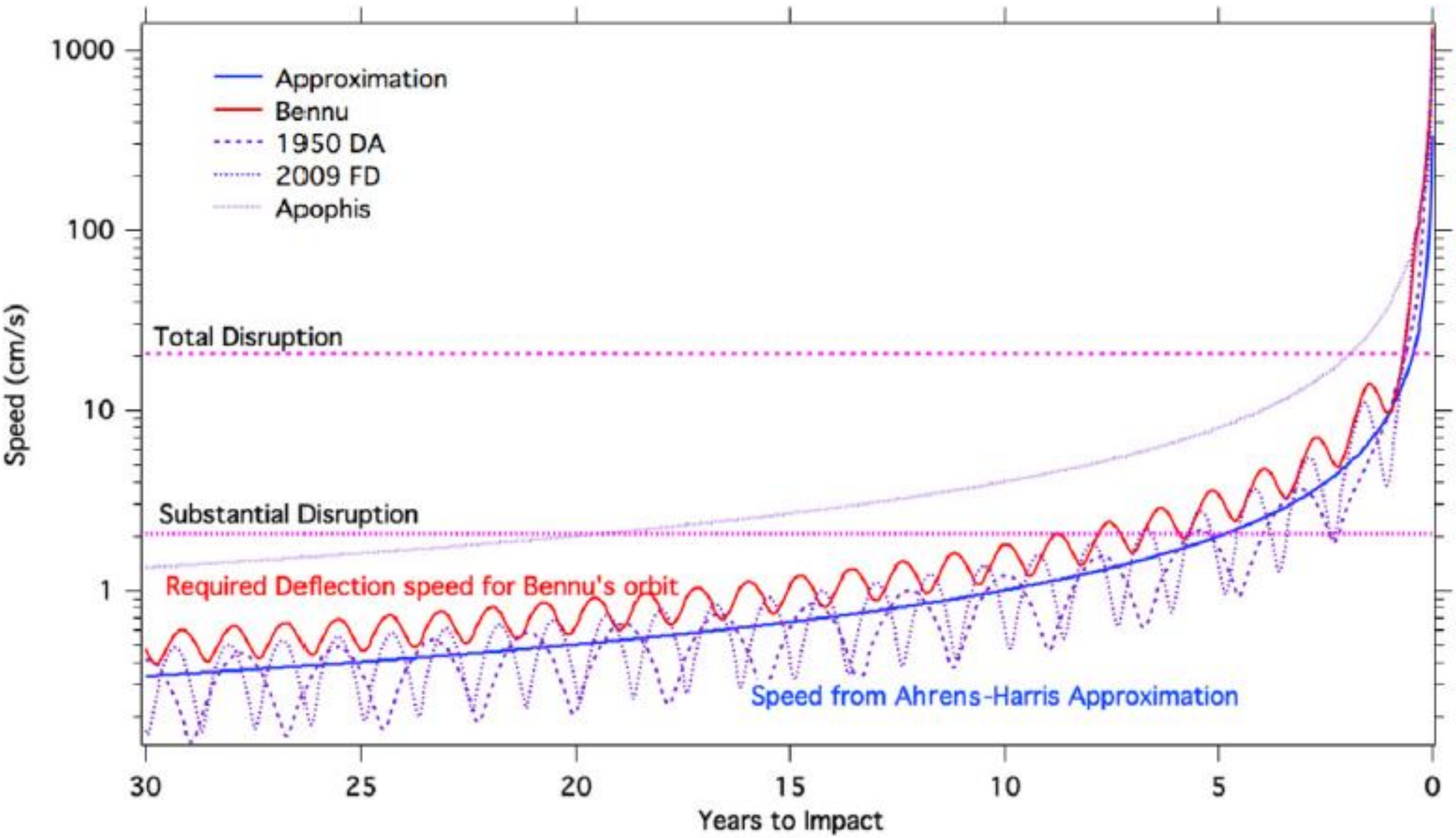


Fig. 1. Required deflection Δv ("speed") versus time for a Bennu-like orbit.

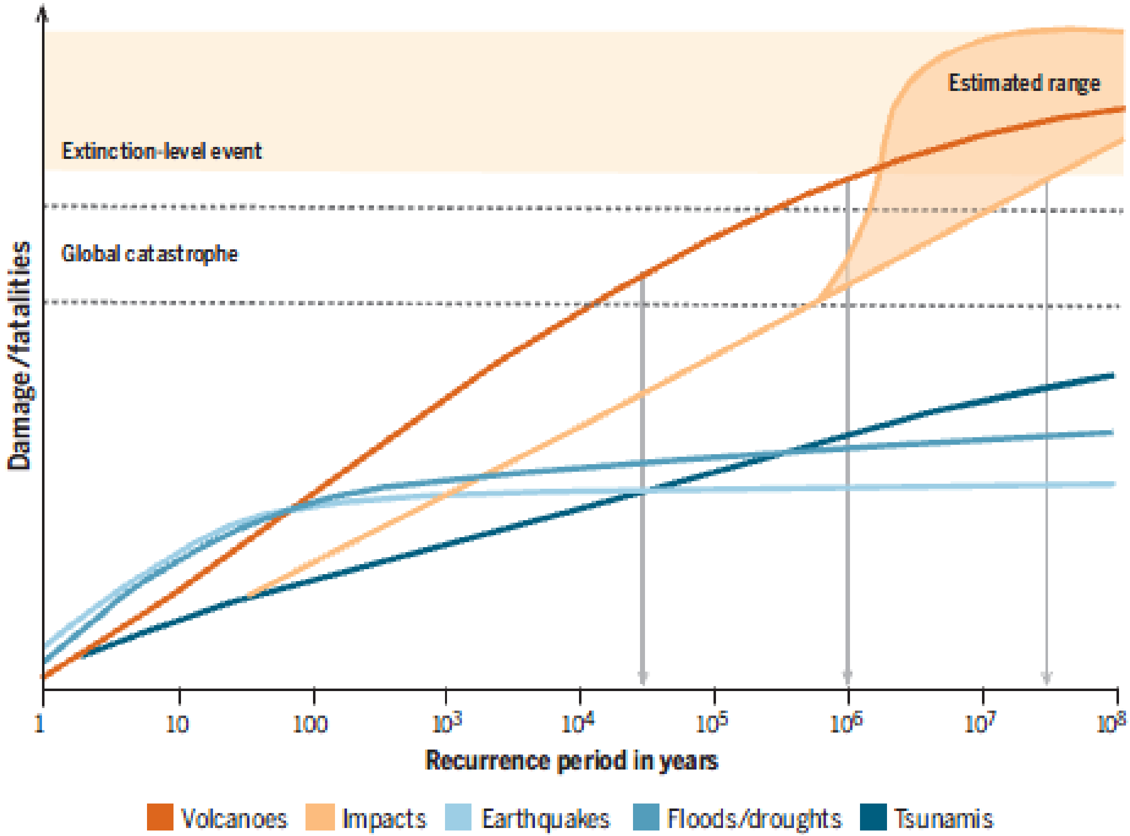
THINKING THE UNTHINKABLE

Rare cataclysms are hard to study and plan for, but they may be too dangerous to ignore

Just a matter of time

Over thousands to millions of years, supervolcanoes and extraterrestrial impactors pose the greatest threats to humanity (top graph). Yet researchers and planners focus almost exclusively on more common hazards with only moderately severe conseqences (second and third graphs).

Relative severity over time



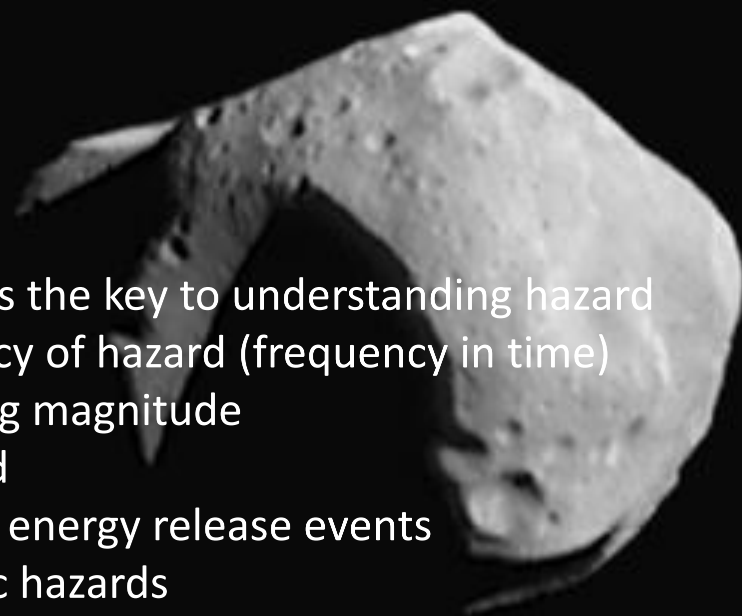
TŌHOKU EARTHQUAKE AND TSUNAMI
東北地方太平洋沖地震

MARCH 2011

A magnitude 9.0 undersea megathrust earthquake struck off the coast of Japan, 154 kilometers from the Fukushima Daiichi Nuclear Power Plant. The plant was automatically shut down following the earthquake and backup generators started the cooling process. 41 minutes later, powerful tsunami waves reached the plant at heights of up to 14 meters. A seawall was designed to protect the plant from a worst-case tsunami of 6 meters. The waves inundated the Fukushima facility, disabling the backup generators. What is your view of the risk within a resilient risk management framework?

READ MORE>>

EARTH 270 v. 2018: 15 SUMMARY POINTS



1. Understanding process is the key to understanding hazard
2. Magnitude and frequency of hazard (frequency in time)
3. Importance of measuring magnitude
4. The geography of hazard
5. Catastrophic hazards as energy release events
6. Geologic v. Atmospheric hazards
7. Disasters and population
8. Disasters and atmospheric change
9. The importance of earthquakes, tsunamis, and hurricanes
10. Technology in mapping, detection, and warning
11. Satellite technology in evaluation/assessment
12. Losses – loss of life and economic losses
13. Mitigation strategies (Warning?)
14. Resistance
15. The problem of high magnitude-low (very low) probability events