

# Near Earth Objects

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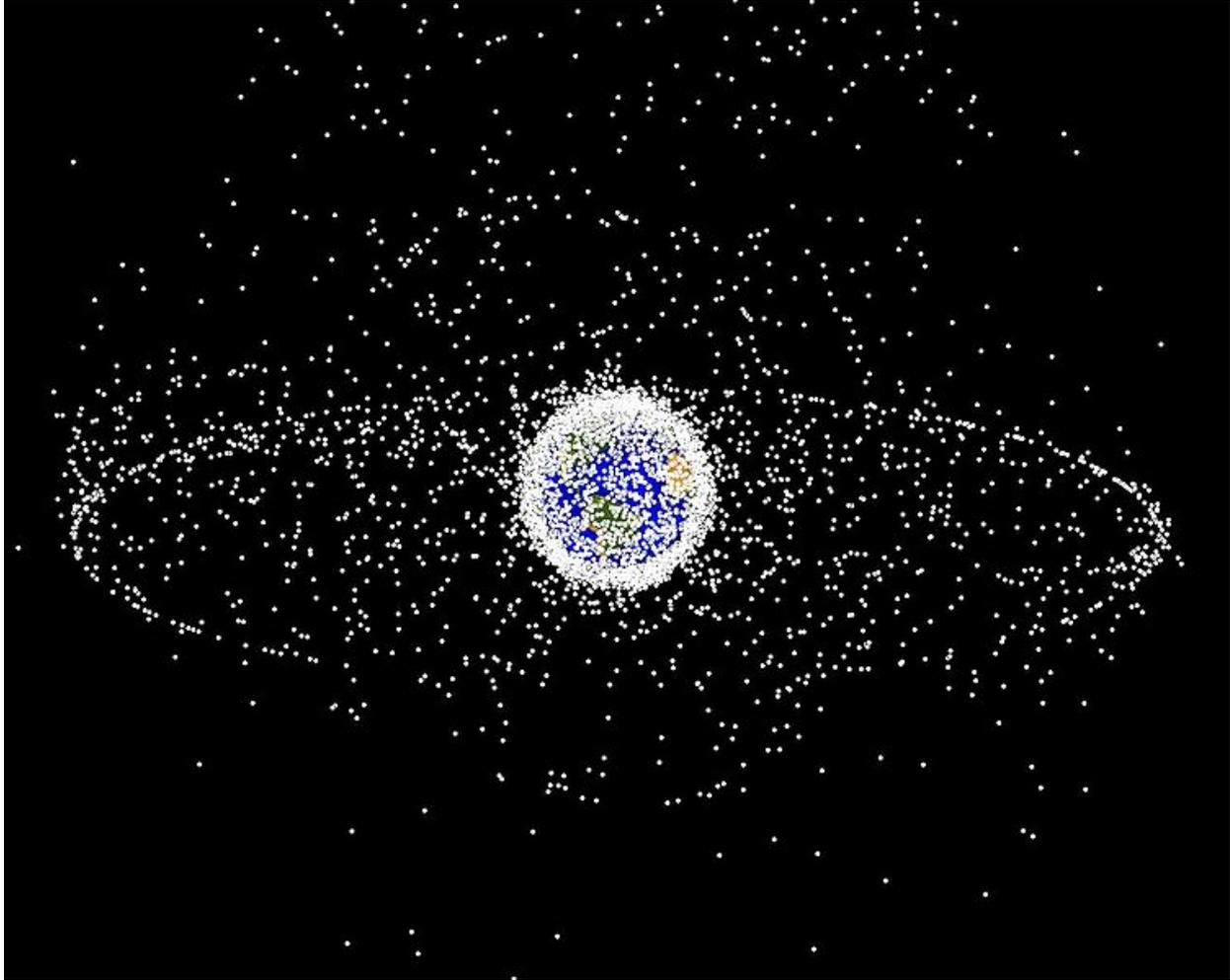
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## Chapter- 1

# Near-Earth Object



Asteroid 4179 Toutatis is a potentially hazardous object that has passed within 2.3 lunar distances



Earth's artificial satellites form a halo of space debris

A **near-Earth object (NEO)** is a Solar System object whose orbit brings it into close proximity with the Earth. All NEOs have a perihelion distance  $< 1.3$  AU. They include a few thousand near-Earth asteroids (NEAs), near-Earth comets, a number of solar-orbiting spacecraft, and meteoroids large enough to be tracked in space before striking the Earth. It is now widely accepted that collisions in the past have had a significant role in shaping the geological and biological history of the planet. NEOs have become of increased interest since the 1980s because of increased awareness of the potential danger some of the asteroids or comets pose to the Earth, and active mitigations are being researched. A study showed that the United States and China are the nations most vulnerable to a meteor strike.

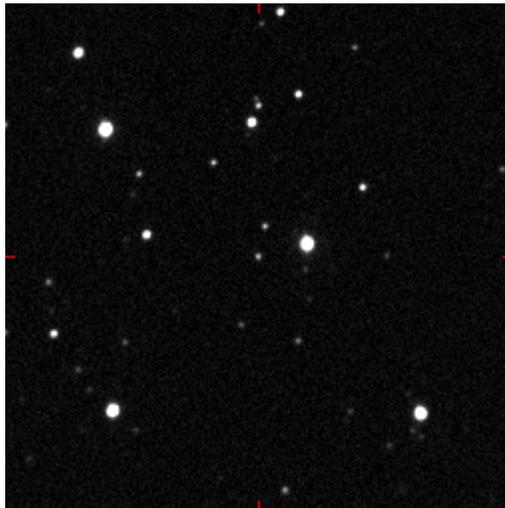
Those NEOs that are asteroids (NEA) have orbits that lie partly between 0.983 and 1.3 astronomical units away from the Sun. When an NEA is detected it is submitted to the Harvard Minor Planet Center for cataloging. Some near-Earth asteroids' orbits intersect that of Earth's so they pose a collision danger. The United States, European Union and other nations are currently scanning for NEOs in an effort called Spaceguard. In the United States, NASA has a congressional mandate to catalogue all NEOs that are at least 1 kilometer wide, as the impact of

such an object would be expected to produce severe to catastrophic effects. As of October 2008, 982 of these mandated NEOs have been detected. It was estimated in 2006 that 20% of the mandated objects have not yet been found. Efforts are under way to use an existing telescope in Australia to cover the ~30% of the sky that has not yet been surveyed.

Potentially hazardous objects (PHOs) are currently defined based on parameters that measure the object's potential to make threatening close approaches to the Earth. Mostly objects with an Earth minimum orbit intersection distance (MOID) of 0.05 AU or less and an absolute magnitude (H) of 22.0 or less (a rough indicator of large size) are considered PHOs. Objects that cannot approach closer to the Earth (i. e. MOID) than 0.05 AU (roughly 7,480,000 km or 4,650,000 mi), or are smaller than about 150 m (500 ft) in diameter (i. e. H = 22.0 with assumed albedo of 13%), are not considered PHOs. The NASA Near Earth Object Catalog also includes the approach distances of asteroids and comets measured in Lunar Distances, and this usage has become the more usual unit of measure used by the press and mainstream media in discussing these objects.

Some NEOs are of high interest because they can be physically explored with lower mission velocity even than the Moon, due to their combination of low velocity with respect to Earth ( $\Delta V$ ) and small gravity, so they may present interesting scientific opportunities both for direct geochemical and astronomical investigation, and as potentially economical sources of extraterrestrial materials for human exploitation. This makes them an attractive target for exploration. As of 2008, two near-Earth objects have been visited by spacecraft: 433 Eros, by NASA's Near Earth Asteroid Rendezvous probe, and 25143 Itokawa, by the JAXA Hayabusa mission.

## Close approaches



Flyby of Asteroid 2004 FH. The other object that flashes by is an artificial satellite

On August 10, 1972 a meteor that became known as The Great Daylight 1972 Fireball was witnessed by many people moving north over the Rocky Mountains from the U.S. Southwest to Canada. It was an Earth-grazing meteoroid that passed within 57 kilometres (about 34 miles) of

the Earth's surface. It was filmed by a tourist at the Grand Teton National Park in Wyoming with an 8-millimeter color movie camera.

On March 23, 1989 the 300 meter (1,000-foot) diameter Apollo asteroid 4581 Asclepius (1989 FC) missed the Earth by 700,000 kilometers (400,000 miles) passing through the exact position where the Earth was only 6 hours before. If the asteroid had impacted it would have created the largest explosion in recorded history, thousands of times more powerful than the Tsar Bomba, the most powerful nuclear bomb ever exploded by man. It attracted widespread attention as early calculations had its passage being as close as 64,000 km (40,000 miles) from the Earth, with large uncertainties that allowed for the possibility of it striking the Earth.

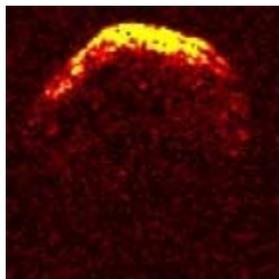
On March 18, 2004, LINEAR announced a 30 meter asteroid 2004 FH, which would pass the Earth that day at only 42,600 km (26,500 miles), about one-tenth the distance to the moon, and the closest miss ever noticed. They estimated that similar sized asteroids come as close about every two years.

On March 31, 2004, two weeks after 2004 FH, meteoroid 2004 FU<sub>162</sub> set a new record for closest recorded approach, passing Earth only 6,500 km (4,000 miles) away (about one-sixtieth of the distance to the Moon). Because it was very small (6 meters/20 feet), FU<sub>162</sub> was detected only hours before its closest approach. If it had collided with Earth, it probably would have harmlessly disintegrated in the atmosphere.

On March 2, 2009, near-Earth asteroid 2009 DD45 flew by Earth at about 13:40 UT. The estimated distance from Earth was 72,000 km (44,740 miles), approximately twice the height of a geostationary communications satellite. The estimated size of the space rock was about 35 meters (115 feet) wide.

On January 13, 2010 at 12:46 UT, near-Earth asteroid 2010 AL30 passed at about 122,000 km (76,000 mi). It was approximately 10–15 m (33–49 ft) wide. If 2010 AL30 had entered the Earth's atmosphere, it would have created an air burst equivalent to between 50 kT and 100 kT (kilotons of TNT). The Hiroshima "Little Boy" atom bomb had a yield between 13-18kT.

## Future impacts



Radar image of Asteroid 1950 DA

Although there have been a few false alarms, a number of objects have been known to be threats to the Earth. (89959) 2002 NT7 was the first asteroid with a positive rating on the Palermo Technical Impact Hazard Scale, with approximately one in a million on a potential impact date of February 1, 2019.

Asteroid (29075) 1950 DA was lost after its discovery in 1950 since not enough observations were made to allow plotting of its orbit, and then rediscovered on December 31, 2000. The chance it will impact Earth on March 16, 2880 during its close approach has been estimated as 1 in 300. This chance of impact for such a large object is roughly 50% greater than that for all other such objects combined between now and 2880. It has a diameter of about a kilometer (0.6 miles).

The asteroids 99942 Apophis (provisionally known as 2004 MN4), 2007 VK184, and 2008 AF4 have had above-normal rankings on the Torino Scale.

## Chapter- 2

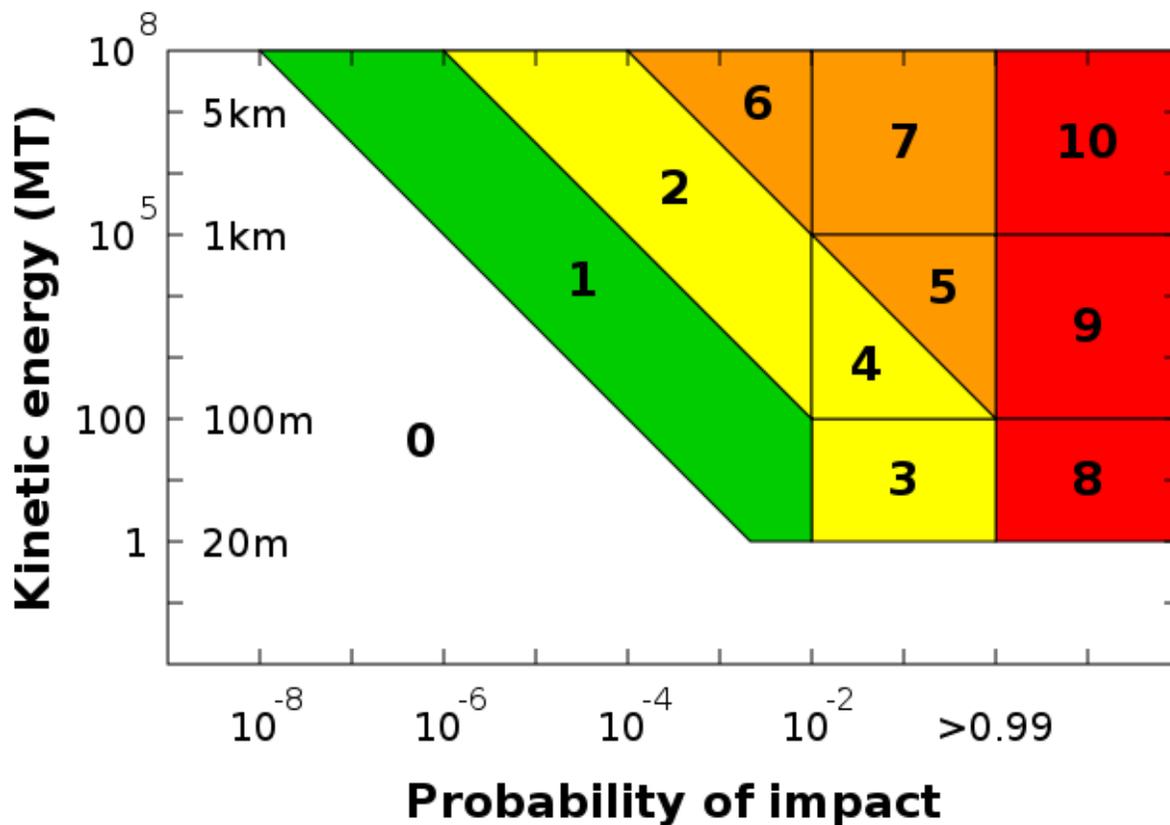
# Risk Scales for Categorizing the Impact Hazard Associated with Near-Earth Objects

## Torino Scale

The **Torino Scale** is a method for categorizing the impact hazard associated with near-Earth objects (NEOs) such as asteroids and comets. It is intended as a tool for astronomers and the public to assess the seriousness of collision predictions, by combining probability statistics and known kinetic damage potentials into a single threat value. The Palermo Technical Impact Hazard Scale is a similar, but more complex scale.

## Overview

The Torino Scale uses a scale from 0 to 10. A 0 indicates an object has a negligibly small chance of collision with the Earth, compared with the usual "background noise" of collision events, or is too small to penetrate the Earth's atmosphere intact. A 10 indicates that a collision is certain, and the impacting object is large enough to precipitate a global disaster. Only integer values are used.



Torino Scale. The scale in metres is the approximate diameter of an asteroid with a typical collision velocity.

An object is assigned a 0 to 10 value based on its collision probability and its kinetic energy (expressed in megatons of TNT).

## History

The Torino Scale was created by Professor Richard P. Binzel in the Department of Earth, Atmospheric, and Planetary Sciences, at the Massachusetts Institute of Technology (MIT). The first version, called "A Near-Earth Object Hazard Index", was presented at a United Nations conference in 1995 and was published by Binzel in the subsequent conference proceedings (*Annals of the New York Academy of Sciences*, volume 822, 1997.)

A revised version of the "Hazard Index" was presented at a June 1999 international conference on NEOs held in Torino (Turin), Italy. The conference participants voted to adopt the revised version, where the bestowed name "Torino Scale" recognizes the spirit of international cooperation displayed at that conference toward research efforts to understand the hazards posed by NEOs. ("Torino Scale" is the proper usage, not "Turin Scale.")

Due to exaggerated press coverage of Level 1 asteroids such as 2003 QQ<sub>47</sub>, a rewording of the Torino Scale was published in 2005, adding more details and renaming the categories: in particular, Level 1 was changed from "Events meriting careful monitoring" to "Normal".

## Current Torino Scale

The Torino Scale also uses a color code scale: white, green, yellow, orange, red. Each color code has an overall meaning:

### NO HAZARD (white)

The likelihood of a collision is zero, or is so low as to be effectively zero. Also applies to

0. small objects such as meteors and bodies that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.

### NORMAL (green)

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 (yellow)

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 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 public and by public officials is merited if the encounter is less than a decade away.

### THREATENING (orange)

5. A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether 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 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 a collision will occur.

### **CERTAIN COLLISIONS (red)**

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 thousand 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 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.

## **Objects with high Torino ratings**

The current record for highest Torino rating is held by 99942 Apophis, an about 350 m near-Earth asteroid, which was later downgraded to 0. On December 23, 2004, NASA's Near Earth Object Program Office announced that Apophis (then known only by its provisional designation 2004 MN<sub>4</sub>) was the first object to reach a level 2 on the Torino Scale, and it was subsequently upgraded to level 4. It is now expected to pass the Earth on Friday, April 13, 2029 quite closely but with no possibility of an impact. Future uncertainties in the orbit of Apophis will occur because of gravitational deflection during the 2029 encounter, so a Torino rating of 1 (for an encounter in 2036) applied until August 2006, when Apophis was downgraded to 0.

Prior to Apophis, no NEO had ever been given a Torino Scale value higher than 1. In February 2006, the rating for 2004 VD<sub>17</sub> was upgraded to a value of 2 due to a possible encounter in the year 2102, making it the second asteroid to ever be given a Torino Scale value higher than 1. Additional observations of 2004 VD<sub>17</sub> resulted in a downgrade to 0.

1950 DA is rated above Level 0 by NEODYs, it is rated Level 2. It, however, is not listed by the Sentry program because its risk is not within 100 years.

2007 VK<sub>184</sub> is the second object, an asteroid, which is listed on the Near Earth Object Risk List with a Torino Scale of Level 1. The object was discovered on November 12, 2007, by the Catalina Sky Survey. According to the Near-Earth Object list, 101 observations over 60 days suggest 2007 VK<sub>184</sub> has a probability of 1 in 3,030 chance to hit the Earth during June 2048. These figures translate into a 0.033% chance to hit (or 99.967% to miss). The asteroid is estimated to have a diameter of 130 meters, and travels through space with a speed of 15.63 km/s relative to the Earth.

2008 AF<sub>4</sub> is another object on the Torino Scale of 1. It is thought to have a 1 in 909,000 chance of impacting the Earth in 2096, 2099, or 2100. It was downgraded to 0 by 14 February 2008.

2009 KK, discovered in May 2009, was rated with a value of 1. It was downgraded to 0 on 17 June 2009.

2009 WM<sub>1</sub>, discovered on November 17, 2009, was rated with a value of 1. It was downgraded to 0 by the end of November.

2009 YG, discovered on December 17, 2009, was rated with a value of 1. It was downgraded to 0 by the end of December.

2005 YU<sub>55</sub>, in February 2010 was rated with a value of 1. It was downgraded to 0 on 9 April 2010.

## Palermo Technical Impact Hazard Scale

The **Palermo Technical Impact Hazard Scale** is a logarithmic scale used by astronomers to rate the potential hazard of impact of a near-earth object (NEO). It combines two types of data—probability of impact, and estimated kinetic yield—into a single "hazard" value. A rating of 0 means the hazard is as likely as the **background hazard** (defined as the average risk posed by objects of the same size or larger over the years until the date of the potential impact). A rating of +2 would indicate the hazard is 100 times more likely than a random background event. Scale values less than -2 reflect events for which there are no likely consequences, while Palermo Scale values between -2 and 0 indicate situations that merit careful monitoring. A similar but less complex scale is the Torino Scale, which is used for simpler descriptions in the non-scientific media.

The scale compares the likelihood of the detected potential impact with the average risk posed by objects of the same size or larger over the years until the date of the potential impact. This average risk from random impacts is known as the background risk. The Palermo Scale value,  $P$ , is defined as the base 10 logarithm of the ratio of the impact probability  $p_i$  to the background impact probability over the time in years  $T$  to the event:

$$P = \log_{10} \frac{p_i}{f_B T}$$

The annual background impact frequency is defined for this purpose as:

$$f_B = 0.03E^{-0.8}$$

where the energy threshold  $E$  is measured in megatons.

The near-Earth object (89959) 2002 NT<sub>7</sub> was the first near-Earth object detected by NASA's latest NEO program to be given a positive rating on the scale of 0.06, indicating a higher than background threat. The value was subsequently lowered after more measurements were taken and 2002 NT<sub>7</sub> is no longer considered to pose any risk.

As of September 2006, the record for Palermo scale values is held by asteroid (29075) 1950 DA, with a value of 0.17 for a possible collision in the year 2880.

For a brief period in late December 2004, asteroid 99942 Apophis (then known only by its provisional designation 2004 MN<sub>4</sub>) held the record for Palermo scale values, with a value of 1.10 for a possible collision in the year 2029. The 1.10 value indicated that a collision with this object was considered to be almost 12.6 times more likely than a random background event: 1 in 37 instead of 1 in 472. With further observations, the possibility of a 2029 impact was eliminated, but as of October 2006 a cumulative Palermo rating of  $-2.52$  applies, largely due to a possible event in 2036.

## Chapter- 3

# Historic Impacts

## Tunguska event



Trees knocked over by the Tunguska blast. Photograph from the Soviet Academy of Science 1927 expedition led by Leonid Kulik



The Southern swamp — the hypocenter of the Tunguska explosion, in 2008



Tunguska in 2006

The **Tunguska event**, or **Tunguska explosion**, was a powerful explosion that occurred not far from the Podkamennaya (Lower Stony) Tunguska (Подкаменная Тунгуска) River in what is now Krasnoyarsk Krai (Красноярский Край) in Russia, at 00:13:35 Greenwich Mean Time (around 07:14 local time) on June 30, 1908 (June 17 in the Julian calendar, in use locally at the time).

The explosion is believed to have been caused by the air burst of a large meteoroid or comet fragment at an altitude of 5–10 kilometres (3.1–6.2 mi) above the Earth's surface. Different studies have yielded varying estimates of the object's size, with general agreement that it was a few tens of metres across.

The number of scholarly publications on the problem of the Tunguska explosion since 1908 may be estimated at about 1,000 (mainly in Russian). Many scientists have participated in Tunguska studies, the best-known of them being Leonid Kulik, Yevgeny Krinov, Kirill Florensky, Nikolay Vasiliev, and Wilhelm Fast.

Although the meteoroid or comet burst in the air rather than hitting the surface, this event is still referred to as an impact. Estimates of the energy of the blast range from 5 to as high as 30 megatons of TNT (21–130 PJ), with 10–15 megatons of TNT (42–63 PJ) the most likely—roughly equal to the United States' Castle Bravo thermonuclear bomb tested on March 1, 1954, about 1,000 times as powerful as the atomic bomb dropped on Hiroshima, Japan, and about one-

third the power of the Tsar Bomba, the largest nuclear weapon ever detonated. The explosion knocked over an estimated 80 million trees covering 2,150 square kilometres (830 sq mi). It is estimated that the shock wave from the blast would have measured 5.0 on the Richter scale. An explosion of this magnitude is capable of destroying a large metropolitan area. This possibility has helped to spark discussion of asteroid deflection strategies.

The Tunguska event is the largest impact event over land in Earth's recent history. Impacts of similar size over remote ocean areas would have gone unnoticed before the advent of global satellite monitoring in the 1960s and 1970s.

## Description



Approximate location of the Tunguska event in Siberia

At around 7:17 a.m. local time, Tungus natives and Russian settlers in the hills northwest of Lake Baikal observed a column of bluish light, nearly as bright as the Sun, moving across the sky. About 10 minutes later, there was a flash and a sound similar to artillery fire. Eyewitnesses closer to the explosion reported the sound source moving east to north. The sounds were accompanied by a shock wave that knocked people off their feet and broke windows hundreds of kilometres away. The majority of witnesses reported only the sounds and the tremors, and not the sighting of the explosion. Eyewitness accounts differ as to the sequence of events and their overall duration.

The explosion registered on seismic stations across Eurasia. In some places the shock wave would have been equivalent to an earthquake of 5.0 on the Richter scale. It also produced fluctuations in atmospheric pressure strong enough to be detected in Great Britain. Over the next few days, night skies in Asia and Europe were aglow; it has been theorized that this was due to light passing through high-altitude ice particles formed at extremely cold temperatures, a

phenomenon that occurs when the Space Shuttle re-enters the Earth's atmosphere. In the United States, the Smithsonian Astrophysical Observatory and the Mount Wilson Observatory observed a decrease in atmospheric transparency that lasted for several months, from suspended dust.

### **Selected eyewitness reports**

- Testimony of **S. Semenov** (pronounced SemiONov), as recorded by Leonid Kulik's expedition in 1930.

At breakfast time I was sitting by the house at Vanavara Trading Post (*65 kilometres/40 miles south of the explosion*), facing north. [...] I suddenly saw that directly to the north, over Onkoul's Tunguska Road, the sky split in two and fire appeared high and wide over the forest (*as Semenov showed, about 50 degrees up — expedition note*). The split in the sky grew larger, and the entire northern side was covered with fire. At that moment I became so hot that I couldn't bear it, as if my shirt was on fire; from the northern side, where the fire was, came strong heat. I wanted to tear off my shirt and throw it down, but then the sky shut closed, and a strong thump sounded, and I was thrown a few metres. I lost my senses for a moment, but then my wife ran out and led me to the house. After that such noise came, as if rocks were falling or cannons were firing, the earth shook, and when I was on the ground, I pressed my head down, fearing rocks would smash it. When the sky opened up, hot wind raced between the houses, like from cannons, which left traces in the ground like pathways, and it damaged some crops. Later we saw that many windows were shattered, and in the barn a part of the iron lock snapped.

- Testimony of **Chuchan of Shanyagir tribe**, as recorded by I.M. Suslov in 1926.

We had a hut by the river with my brother Chekaren. We were sleeping. Suddenly we both woke up at the same time. Somebody shoved us. We heard whistling and felt strong wind. Chekaren said, 'Can you hear all those birds flying overhead?' We were both in the hut, couldn't see what was going on outside. Suddenly, I got shoved again, this time so hard I fell into the fire. I got scared. Chekaren got scared too. We started crying out for father, mother, brother, but no one answered. There was noise beyond the hut, we could hear trees falling down. Chekaren and I got out of our sleeping bags and wanted to run out, but then the thunder struck. This was the first thunder. The Earth began to move and rock, wind hit our hut and knocked it over. My body was pushed down by sticks, but my head was in the clear. Then I saw a wonder: trees were falling, the branches were on fire, it became mighty bright, how can I say this, as if there was a second sun, my eyes were hurting, I even closed them. It was like what the Russians call lightning. And immediately there was a loud thunderclap. This was the second thunder. The morning was sunny, there were no clouds, our Sun was shining brightly as usual, and suddenly there came a second one!

Chekaren and I had some difficulty getting out from under the remains of our hut. Then we saw that above, but in a different place, there was another flash, and loud thunder came. This was the third thunder strike. Wind came again, knocked us off our feet, struck against the fallen trees. We looked at the fallen trees, watched the tree tops get snapped off, watched the fires. Suddenly Chekaren yelled 'Look up' and pointed with his hand. I looked there and saw another flash, and it made another thunder. But the noise was less than before. This was the fourth strike, like normal

thunder.

Now I remember well there was also one more thunder strike, but it was small, and somewhere far away, where the Sun goes to sleep.

- **Sibir** newspaper, July 2, 1908

On the 17th of June, around 9am in the morning, we observed an unusual natural occurrence. In the north Karelinski village (200 verst, or about 130 miles, north of Kirensk) the peasants saw to the north west, rather high above the horizon, some strangely bright (impossible to look at) bluish-white heavenly body, which for 10 minutes moved downwards. The body appeared as a "pipe", i.e. a cylinder. The sky was cloudless, only a small dark cloud was observed in the general direction of the bright body. It was hot and dry. As the body neared the ground (forest), the bright body seemed to smudge, and then turned into a giant billow of black smoke, and a loud knocking (not thunder) was heard, as if large stones were falling, or artillery was fired. All buildings shook. At the same time the cloud began emitting flames of uncertain shapes. All villagers were stricken with panic and took to the streets, women cried, thinking it was the end of the world.

The author of these lines was meantime in the forest about 6 verst (about four miles) north of Kirensk, and heard to the north east some kind of artillery barrage, that repeated in intervals of 15 minutes at least 10 times. In Kirensk in a few buildings in the walls facing north east window glass shook.

- **Siberian Life** newspaper, July 27, 1908

"When the meteorite fell, strong tremors in the ground were observed, and near the Lovat village of the Kansk uezd two strong explosions were heard, as if from large-caliber artillery."

- **Krasnoyarets** newspaper, July 13, 1908

Kezhemskoe village. On the 17th an unusual atmospheric event was observed. At 7:43 the noise akin to a strong wind was heard. Immediately afterwards a horrific thump sounded, followed by an earthquake which literally shook the buildings, as if they were hit by a large log or a heavy rock. The first thump was followed by a second, and then a third. Then the interval between the first and the third thumps were accompanied by an unusual underground rattle, similar to a railway upon which dozens of trains are travelling at the same time. Afterwards for 5 to 6 minutes an exact likeness of artillery fire was heard: 50 to 60 salvoes in short, equal intervals, which got progressively weaker. After 1.5 - 2 minutes after one of the "barrages" six more thumps were heard, like cannon firing, but individual, loud and accompanied by tremors.

The sky, at the first sight, appeared to be clear. There was no wind and no clouds. However upon closer inspection to the north, i.e. where most of the thumps were heard, a kind of an ashen cloud was seen near the horizon which kept getting smaller and more transparent and possibly by around 2-3 p.m. completely disappeared.

## History

There was little scientific curiosity about the impact at the time, possibly due to the isolation of the Tunguska region. If there were any early expeditions to the site, the records were likely to have been lost during the subsequent chaotic years — World War I, the Russian Revolution of 1917 and the Russian Civil War.

The first recorded expedition arrived at the scene more than a decade after the event. In 1921, the Russian mineralogist Leonid Kulik, visiting the Podkamennaya Tunguska River basin as part of a survey for the Soviet Academy of Sciences, deduced from local accounts that the explosion had been caused by a giant meteorite impact. He persuaded the Soviet government to fund an expedition to the Tunguska region, based on the prospect of meteoric iron that could be salvaged to aid Soviet industry. Kulik's party eventually undertook an expedition in 1927.



Photograph from Kulik's 1927 expedition

Upon arrival, Kulik made arrangements with the local Evenki hunters to guide his party to the impact site. Reaching the explosion site was an extremely arduous task. Upon reaching an area just south of the site, the superstitious Evenki hunters would go no further, fearing what they

called the Valleysmen. Kulik had to return to the nearby village, and his party was delayed for several days while they sought new guides.

The spectacle that confronted Kulik as he stood on a ridge overlooking the devastated area was overwhelming. To the explorers' surprise, no crater was to be found. There was instead around ground zero a vast zone (8 kilometers across) of trees scorched and devoid of branches, but standing upright. Those farther away had been partly scorched and knocked down in a direction away from the centre. Much later, in the 1960s, it was established that the zone of leveled forest occupied an area of some 2150 square kilometers, its shape resembling a gigantic spread-eagled butterfly with a “wingspan” of 70 kilometers and a “body length” of 55 kilometers.

Upon closer examination, Kulik located holes which he erroneously concluded were meteorite holes; however, he did not have the means at this time to excavate the holes.

During the next ten years there were three more expeditions to the area. Kulik found several dozens of little “pothole” bogs, each some 10 to 50 meters in diameter, that he thought might be meteoric craters. After a laborious exercise in draining one of these bogs (the so-called “Suslov’s crater”, 32 meters in diameter), he found there was an old stump on the bottom, ruling out the possibility that it was a meteoric crater. In 1938, Kulik arranged for an aerial photographic survey of the area covering the central part of the leveled forest (some 250 square kilometers). The negatives of these aerial photographs (1500 negatives, each 18 x 18 cm) were burned in 1975 by order of Yevgeny Krinov, then Chairman of the Committee on Meteorites of the USSR Academy of Sciences. It was done under the pretext that they were a fire hazard, but the truth may have been the active dislike by official meteorite specialists of anything associated with an unyielding enigma. However, positive imprints could be preserved for further studies in the Russian city of Tomsk.

Despite the large amount of devastation, there was no crater to be seen.

Expeditions sent to the area in the 1950s and 1960s found microscopic silicate and magnetite spheres in siftings of the soil. Similar spheres were predicted to exist in the felled trees, although they could not be detected by contemporary means. Later expeditions did identify such spheres in the resin of the trees. Chemical analysis showed that the spheres contained high proportions of nickel relative to iron, which is also found in meteorites, leading to the conclusion they were of extraterrestrial origin. The concentration of the spheres in different regions of the soil was also found to be consistent with the expected distribution of debris from a meteorite airburst. Later studies of the spheres found unusual ratios of numerous other metals relative to the surrounding environment, which was taken as further evidence of their extraterrestrial origin.

Chemical analysis of peat bogs from the area also revealed numerous anomalies considered consistent with an impact event. The isotopic signatures of stable carbon, hydrogen, and nitrogen isotopes at the layer of the bogs corresponding to 1908 were found to be inconsistent with the isotopic ratios measured in the adjacent layers, and this abnormality was not found in bogs located outside the area. The region of the bogs showing these anomalous signatures also contains an unusually high proportion of iridium, similar to the iridium layer found in the K–T boundary. These unusual proportions are believed to result from debris from the impacting body

that deposited in the bogs. The nitrogen is believed to have been deposited as acid rain, a suspected fallout from the explosion.

## **Earth impactor model**

### **Meteoroid airburst**

The leading scientific explanation for the explosion is the airburst of a meteoroid 6–10 kilometres (4–6 miles) above Earth's surface.

Meteoroids enter Earth's atmosphere from outer space every day, usually travelling at a speed of more than 10 kilometres per second (6 miles/sec or 21,600 mph). The heat generated by compression of air in front of the body (ram pressure) as it travels through the atmosphere is immense and most meteoroids burn up or explode before they reach the ground. Since the second half of the 20th century, close monitoring of Earth's atmosphere has led to the discovery that such meteoroid airbursts occur rather frequently. A stony meteoroid of about 10 metres (30 ft) in diameter can produce an explosion of around 20 kilotons, similar to that of the Fat Man bomb dropped on Nagasaki, and data released by the U.S. Air Force's Defense Support Program indicate that such explosions occur high in the upper atmosphere more than once a year. Tunguska-like megaton-range events are much rarer. Eugene Shoemaker estimated that such events occur about once every 300 years.

### **Blast patterns**

The explosion's effect on the trees near ground zero was replicated during atmospheric nuclear tests in the 1950s and 1960s. These effects are caused by the shock wave produced by large explosions. The trees directly below the explosion are stripped as the blast wave moves vertically downward, while trees further away are knocked over because the blast wave is travelling closer to the horizontal when it reaches them.

Soviet experiments performed in the mid-1960s, with model forests (made of matches on wire stakes) and small explosive charges slid downward on wires, produced butterfly-shaped blast patterns strikingly similar to the pattern found at the Tunguska site. The experiments suggested that the object had approached at an angle of roughly 30 degrees from the ground and 115 degrees from north and had exploded in mid-air.

### **Asteroid or comet?**

The composition of the Tunguska body remains a matter of controversy. In 1930, the British astronomer F.J.W. Whipple suggested that the Tunguska body was a small comet. A cometary meteorite, being composed primarily of ice and dust, could have been completely vaporized by the impact with the Earth's atmosphere, leaving no obvious traces. The comet hypothesis was further supported by the glowing skies (or "skyglows" or "bright nights") observed across Europe for several evenings after the impact, possibly explained by dust and ice that had been dispersed

from the comet's tail across the upper atmosphere. The cometary hypothesis gained a general acceptance amongst Soviet Tunguska investigators by the 1960s.

In 1978, astronomer Ľubor Kresák suggested that the body was a fragment of the short-period Comet Encke, which is responsible for the Beta Taurid meteor shower: the Tunguska event coincided with a peak in that shower, and the approximate trajectory of the Tunguska impactor is consistent with what would be expected from such a fragment. It is now known that bodies of this kind explode at frequent intervals tens to hundreds of kilometres above the ground. Military satellites have been observing these explosions for decades.

In 1983, astronomer Zdeněk Sekanina published a paper criticizing the comet hypothesis. He pointed out that a body composed of cometary material, travelling through the atmosphere along such a shallow trajectory, ought to have disintegrated, whereas the Tunguska body apparently remained intact into the lower atmosphere. Sekanina argued that the evidence pointed to a dense, rocky object, probably of asteroidal origin. This hypothesis was further boosted in 2001, when Farinella, Foschini, *et al.* released a study suggesting that the object had arrived from the direction of the asteroid belt.

Proponents of the comet hypothesis have suggested that the object was an extinct comet with a stony mantle that allowed it to penetrate the atmosphere.

The chief difficulty in the asteroid hypothesis is that a stony object should have produced a large crater where it struck the ground, but no such crater has been found. It has been hypothesized that the passage of the asteroid through the atmosphere caused pressures and temperatures to build up to a point where the asteroid abruptly disintegrated in a huge explosion. The destruction would have to have been so complete that no remnants of substantial size survived, and the material scattered into the upper atmosphere during the explosion would have caused the skyglows. Models published in 1993 suggested that the stony body would have been about 60 metres across, with physical properties somewhere between an ordinary chondrite and a carbonaceous chondrite.

Christopher Chyba and others have proposed a process whereby a stony meteorite could have exhibited the behavior of the Tunguska impactor. Their models show that when the forces opposing a body's descent become greater than the cohesive force holding it together, it blows apart, releasing nearly all its energy at once. The result is no crater, and damage distributed over a fairly wide radius, all of the damage being blast and thermal.

Three-dimensional numerical modelling of the Tunguska impact done by Utyuzhnikov and Rudenko in 2008 supports the comet hypothesis. According to their results, the comet matter dispersed in the atmosphere, while the destruction of the forest was caused by the shock wave.

During the 1990s, Italian researchers extracted resin from the core of the trees in the area of impact to examine trapped particles that were present during the 1908 event. They found high levels of material commonly found in rocky asteroids and rarely found in comets.

In research published in the journal *Geophysical Research Letters*, scientists contend that the impact was caused by a comet because of the sightings of noctilucent clouds following the impact, a phenomenon caused by massive amounts of water vapor in the upper atmosphere. They compared the noctilucent cloud phenomenon to the exhaust plume from the NASA space shuttle Endeavour.

## **Lake Cheko**

In June 2007, it was announced that scientists from the University of Bologna had identified a lake in the Tunguska region as a possible impact crater from the event. They do not dispute that the Tunguska body exploded in midair but believe that a one-meter fragment survived the explosion and impacted the ground. Lake Cheko is a small, bowl-shaped lake approximately 8 kilometres north-northwest of the hypocenter. The hypothesis has been disputed by other impact crater specialists. A 1961 investigation had dismissed a modern origin of Lake Cheko, saying that the presence of metres-thick silt deposits at the lake's bed suggests an age of at least 5,000 years; but more recent research suggests that only a meter or so of the sediment layer on the lake bed is "normal lacustrine sedimentation," a depth indicating a much younger lake of about 100 years. Acoustic-echo soundings of the lake floor provide support for the hypothesis that the lake was formed by the Tunguska event. The soundings revealed a conical shape for the lake bed, which is consistent with an impact crater. Magnetic readings indicate a possible meter-sized chunk of rock below the lake's deepest point that may be a fragment of the colliding body. Finally, the lake's long axis points to the hypocenter of the Tunguska explosion, about 7.0 km away. Work is still being done at Lake Cheko to determine its origins.

The conclusions of the Italian scientist were published on the website of the University of Bologna. The main points are that "Cheko, a small lake located in Siberia close to the epicentre of the 1908 Tunguska explosion, might fill a crater left by the impact of a fragment of a Cosmic Body. Sediment cores from the lake's bottom were studied to support or reject this hypothesis. A 175-cm-long core, collected near the center of the lake, consists of an upper cca. 1-m-thick sequence of lacustrine deposits overlaying coarser chaotic material. <sup>210</sup>Pb and <sup>137</sup>Cs indicate that the transition from lower to upper sequence occurred close to the time of the Tunguska Event. Pollen analysis reveals that remains of aquatic plants are abundant in the top post-1908 sequence but are absent in the lower pre-1908 portion of the core. These results, including organic C, N and  $\delta^{13}\text{C}$  data, suggest that Lake Cheko formed at the time of the Tunguska Event."

## **Speculative hypotheses**

The behaviour of meteorites in the Earth's atmosphere was less well understood during the early decades of the 20th century. Due to this, as well as the paucity of relevant data resulting from Soviet secrecy during the Cold War, a great many other hypotheses for the Tunguska event have sprung up, none of which are accepted by the scientific community.

## **Comet 2005NB56**

One study "suggests that a chunk of Comet 2005NB56 caused the 5–10 megaton fireball, bouncing off the atmosphere and back into orbit around the sun." The scientists involved in the study claim that the object that caused the event will pass close to Earth again in 2045.

## **End of the world?**

According to G. K. Kulesh, head of the Kirensk Meteorological Station

The peasants of the village [of Karelino] were so stunned by the crashes that they sent a deputation to town to the local archpriest to ask if the end of the world was beginning, [and] how they were preparing for it in Kirensk.

## **Natural H-bomb**

In 1989, Serge J.D. D'Alessio and Archie A. Harms suggested that some of the deuterium in a comet entering the Earth's atmosphere may have undergone a nuclear fusion reaction, leaving a distinctive signature in the form of carbon-14. They concluded that any release of nuclear energy would have been almost negligible. Independently, in 1990, César Sirvent proposed that a deuterium comet, i.e., a comet with an anomalous high concentration of deuterium in its composition, could have exploded as a natural hydrogen bomb, generating most of the energy released. The sequence would be first a mechanical or kinetic explosion, triggering a thermonuclear reaction. These proposals are inconsistent with our knowledge of the composition of comets and of the temperature and pressure conditions necessary for initiating a nuclear fusion reaction. Studies have found the concentration of radioactive isotopes in the blast region to be inconsistent with those expected following a nuclear explosion, fusion or otherwise.

Edward Drobyshevski, generally considered a fringe scientist, has suggested that the event was caused by the explosion of the hydrogen-saturated part of the nucleus of a comet that struck the Earth's atmosphere, with most of the remaining comet nucleus surviving, and possibly continuing to orbit the sun.

## **Black hole**

In 1973, Albert A. Jackson and Michael P. Ryan, physicists at the University of Texas, proposed that the Tunguska event was caused by a small (around  $10^{17}$  kg to  $10^{19}$  kg) black hole passing through the Earth. This hypothesis is flawed, as there was no so-called exit event — a second explosion occurring as the black hole, having tunneled through the Earth, shot out the other side on its way back into space. Based on the direction of impact, the exit event would have occurred in the North Atlantic, closer than the impact event to the seismic recording stations that collected much of the evidence of the event. The hypothesis also fails to account for evidence that cosmic material was deposited by the impacting body, including dust trails in the atmosphere and the distribution of high-nickel magnetic spherules around the impact area.

## **Antimatter**

In 1941, Lincoln LaPaz, and later in 1965, Clyde Cowan, Chandra R. Atluri, and Willard F. Libby suggested that the Tunguska event was caused by the annihilation of a chunk of antimatter falling from space. As with the other hypotheses described in this section, this does not account for the mineral debris left in the area of the explosion.

## **The Wardencllyffe Tower**

Oliver Nichelson suggested that the Tunguska explosion may have been the result of an experiment by Nikola Tesla using the Wardencllyffe Tower, performed during one of Admiral Robert Peary's North Pole expeditions.

This theory failed to gain many adherents owing to the lack of positive evidence, the presence of meteoroid fragments in soils and trees from the time, and the fact that the Wardencllyffe Tower was largely or entirely inactive at that time.

## **Alien spaceship crash**

A number of theories based on UFOs have claimed that the Tunguska event was the result of the activities of extraterrestrial beings, including an exploding alien spaceship or even an alien weapon going off to "save the Earth from an imminent threat". These claims appear to originate from a science fiction story "The Explosion" written by the Soviet engineer Alexander Kazantsev in 1946, in which a nuclear-powered Martian spaceship, trying to land on the Earth, meets with a disaster and blows up in mid-air. Kazantsev never visited Hiroshima, but his idea of the above-ground explosion of the Tunguska space body was inspired by the news about the nuclear explosion over that Japanese city, as well as by his talks with some leading Soviet nuclear physicists.

Many events in Kazantsev's tale, which was intended as pure fantasy, were subsequently confused with the actual occurrences at Tunguska. The nuclear-powered UFO hypothesis was adopted by the TV critics Thomas Atkins and John Baxter in their book *The Fire Came By* (1976). The television series *The Secret KGB UFO Files (Phenomenon: The Lost Archives)* in 1998, broadcast on Turner Network Television, referred to the Tunguska event as "the Russian Roswell" and claimed that crashed UFO debris had been recovered from the site. In 2004, a group from the Tunguska Spatial Phenomenon Foundation claimed to have found the wreckage of an alien spacecraft at the site. In 2009, Dr. Yuri Labvin, the president of the Tunguska Spatial Phenomenon Foundation repeated these claims, based upon findings of quartz slabs with strange markings on them found at the site, which, he claims, represent the remnants of an alien spaceship's control panel.

## **Geophysical hypothesis**

Astrophysicist Wolfgang Kundt has suggested the Tunguska event was caused by the sudden release and subsequent explosion of 10 million tons of natural gas from within the Earth's crust.

The similar verneshot hypothesis has also been suggested as a possible cause of the Tunguska event.

## Similar events

The Tunguska event is the strongest, but not the only, significant meteorite airburst in recent history. A selection of similar events follows.

| Date               | Place   | Yield of explosion (TNT equivalent)    | Height of explosion | Remarks   |
|--------------------|---|--|---------------------|---|
| June 30, 1908      | Tunguska. This line is to provide comparison data. 60 kilometres (37 mi) West northwest of Vanavara, at  60°53'09"N 101°53'40"E / 60.88583°N 101.89444°E in Krasnoyarsk Krai, Russian Empire | 10–15 megatonnes of TNT (42–63 PJ)     | 8.5 km (5.3 mi)     |   |
| August 13, 1930    | Curuçá River Area, Amazonas, Brazil   | 0.1–1.0 megatonne of TNT (0.42–4.2 PJ) |                     |   |
| May 31, 1965       | Southeastern Canada   | 600 tonnes of TNT (2.5 TJ)             | 13 km (8 mi)        | 1 g (0.035 oz) material from meteorite found  |
| September 17, 1966 | Lake Huron, Michigan, USA - Ontario, Canada   | 600 tonnes of TNT (2.5 TJ)             | 13 km (8 mi)        | No material from meteorite found  |
| February 5, 1967   | Vilna, Alberta, Canada  | 600 tonnes of TNT (2.5 TJ)             | 13 km (8 mi)        | Two very small fragments found - 48 milligrams (0.0017 oz) and 94 milligrams (0.0033 oz).   |
| September 22, 1979 | Southern Indian Ocean   | 2 kilotonnes of TNT (8.4 TJ)           |                     | Stored at University of Alberta, in Edmonton. This controversial and assumed explosion over the Indian Ocean was named the <i>Vela Incident</i> , having been detected by an American Vela Hotel satellite (6911). That high-altitude sentry satellite carried several physics instruments designed |

specifically to detect nuclear explosions.

Three possible causes emerged over the several years following the event: 1) a secret nuclear test, likely by South Africa or Israel; 2) an asteroid or meteorite impact; or 3) spurious instrumentation noise on board the satellite.

Despite numerous sweeps by special U.S.A.F. radiation detection aircraft, no airborne nuclear contaminants were detected.

January 19, 1993 Lugo, Northern Italy >10 kilotonnes of TNT (42 TJ)

January 18, 1994 Cando, Spain

December 9, 1997 150 km South of Nuuk, Greenland, at  62°54'N 50°06'W / 62.9°N 50.1°W >0.064 kilotonnes of TNT (0.27 TJ) >25 km (16 mi)

One airburst at 46 km, three more breakups detected between 25 and 30 km. No remains found so far. Yield only based on luminosity, i.e., the total energy might have been considerably larger.

June 6, 2002 Eastern Mediterranean Event over the Mediterranean Sea between Libya and Greece 26 kilotonnes of TNT (110 TJ)

September 25, 2002 Bodaybo, Russia 0.5–5 kilotonnes of TNT (2.1–21 TJ)

October 7, 2008 Nubian Desert, Sudan 0.9–2.1 kilotonnes of TNT (3.8–8.8 TJ)

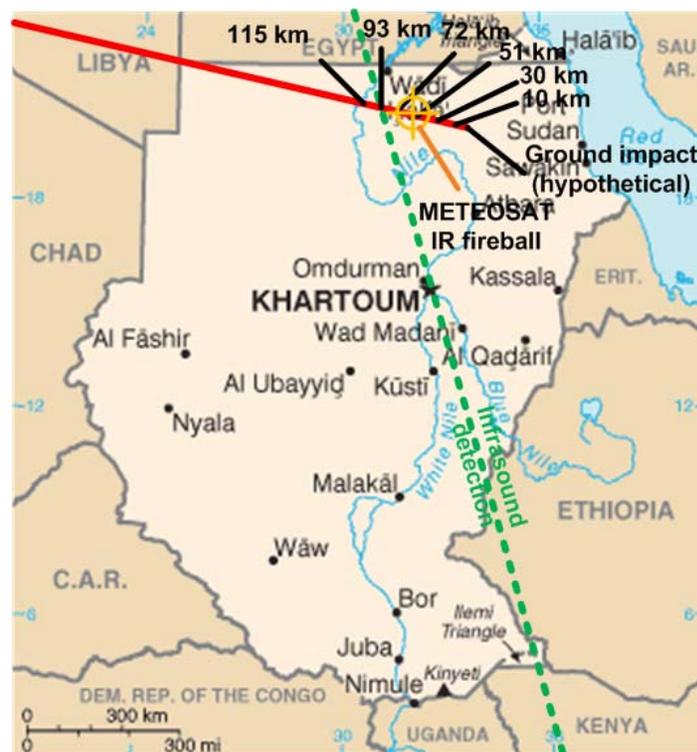
Object identified before impact as 2008 TC3. Systematic search for fragments found a total of 280 fragments, with a mass of 3.9 kilograms.

## Eastern Mediterranean event

The **Eastern Mediterranean Event** was a high-energy aerial explosion over the Mediterranean Sea, around 34°N 21°E (between Libya and Crete, Greece) on June 6, 2002. This explosion, similar in power to a small atomic bomb, has been related to an asteroid undetected while approaching the Earth. The object disintegrated and no part was recovered. Since it did not reach the surface and it exploded over the sea, no crater was formed.

The event occurred during the 2001–2002 India–Pakistan standoff, and there were concerns by General Simon Worden that a similar explosion could have sparked a nuclear war between the two countries, had the timing been different, which would have devastated both regions, causing deaths numbering over 10 million.

## 2008 TC<sub>3</sub>



Ground path of the meteoroid; red line is the path, terminating where it would have hit the ground; green line is the infrasound detection of the explosion; orange crosshairs show METEOSAT IR fireball location; predicted altitudes are listed; exact path and fireball altitude not confirmed

**2008 TC<sub>3</sub>** (Catalina Sky Survey temporary designation **8TA9D69**) was a meteoroid 2 to 5 meters (7 to 16 ft) in diameter that entered Earth's atmosphere on October 7, 2008, at 02:46 UTC (05:46 local time). It exploded an estimated 37 kilometers (23 mi) above the Nubian Desert in Sudan. A search of the impact zone that began on December 2008 turned up 10.5 kilograms (23 lb) of meteorites in 600 fragments, which are surviving pieces of the meteoroid. The meteorites are of a rare type known as ureilites, which contain, among other minerals, nanodiamonds.

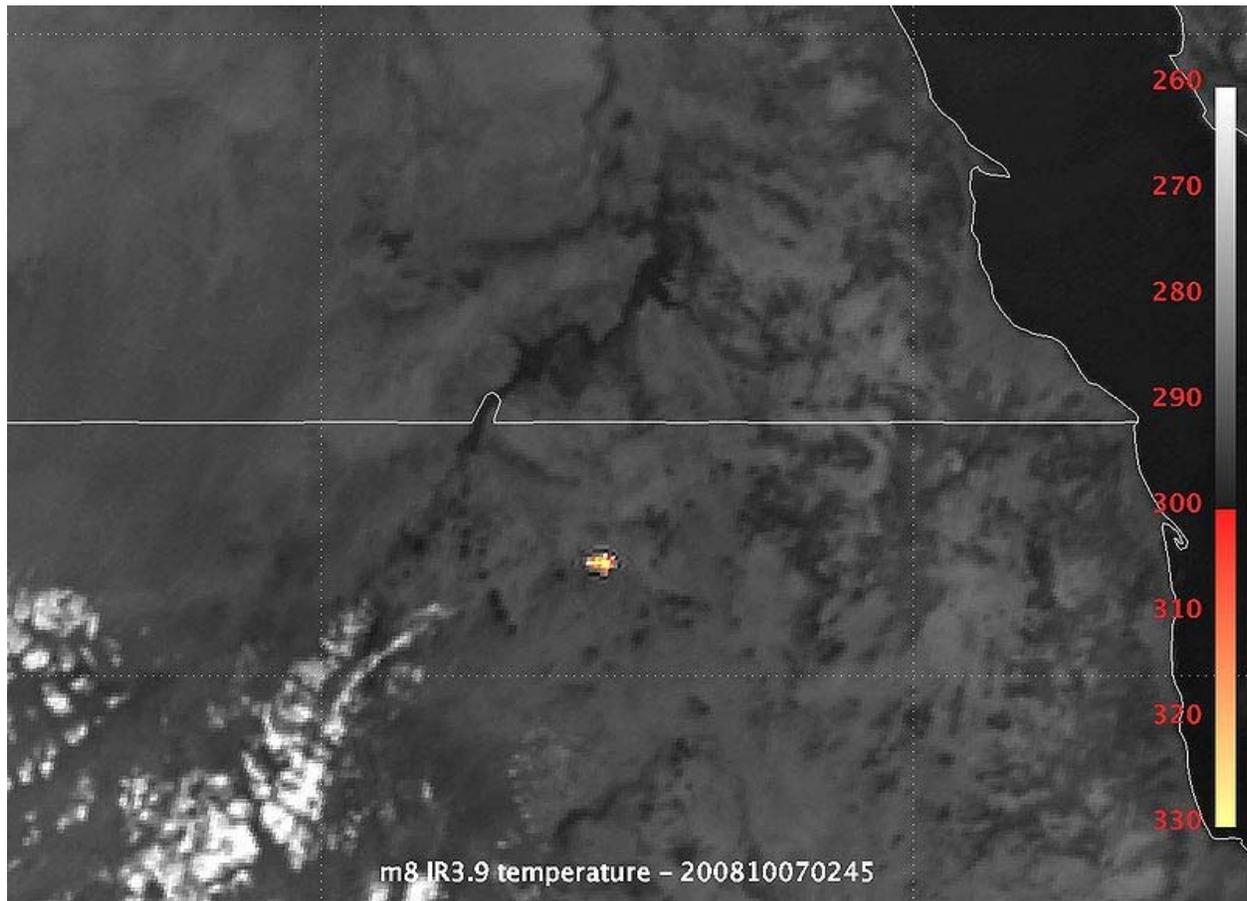
## Discovery

The meteoroid was discovered by Richard A. Kowalski at the Catalina Sky Survey (CSS) 1.5-meter telescope at Mount Lemmon, north of Tucson, Arizona, USA, on October 6, 06:39 UTC, about 20 hours before the impact.

The meteoroid was notable as the first such body to be observed and tracked prior to reaching Earth. The process of detecting and tracking a near-Earth object, an effort sometimes referred to as Spaceguard, was put to the test. In total, 586 astrometric and almost as many photometric observations were performed by 27 amateur and professional observers in less than 19 hours and reported to the Minor Planet Center, which issued 25 Minor Planet Electronic Circulars with new orbit solutions in eleven hours as observations poured in. On October 7, 01:49 UTC, the meteoroid entered the shadow of the Earth which made further observations impossible.

Impact predictions were performed by University of Pisa's CLOMON 2 semi-automatic monitoring system as well as Jet Propulsion Laboratory's Sentry system. Spectral observations that were performed by astronomers at the 4.2-meter William Herschel Telescope at La Palma, Canary Islands are consistent with either a C-type or M-type asteroid.

## Explosion



Meteosat 8/EUMETSAT infrared image of the explosion

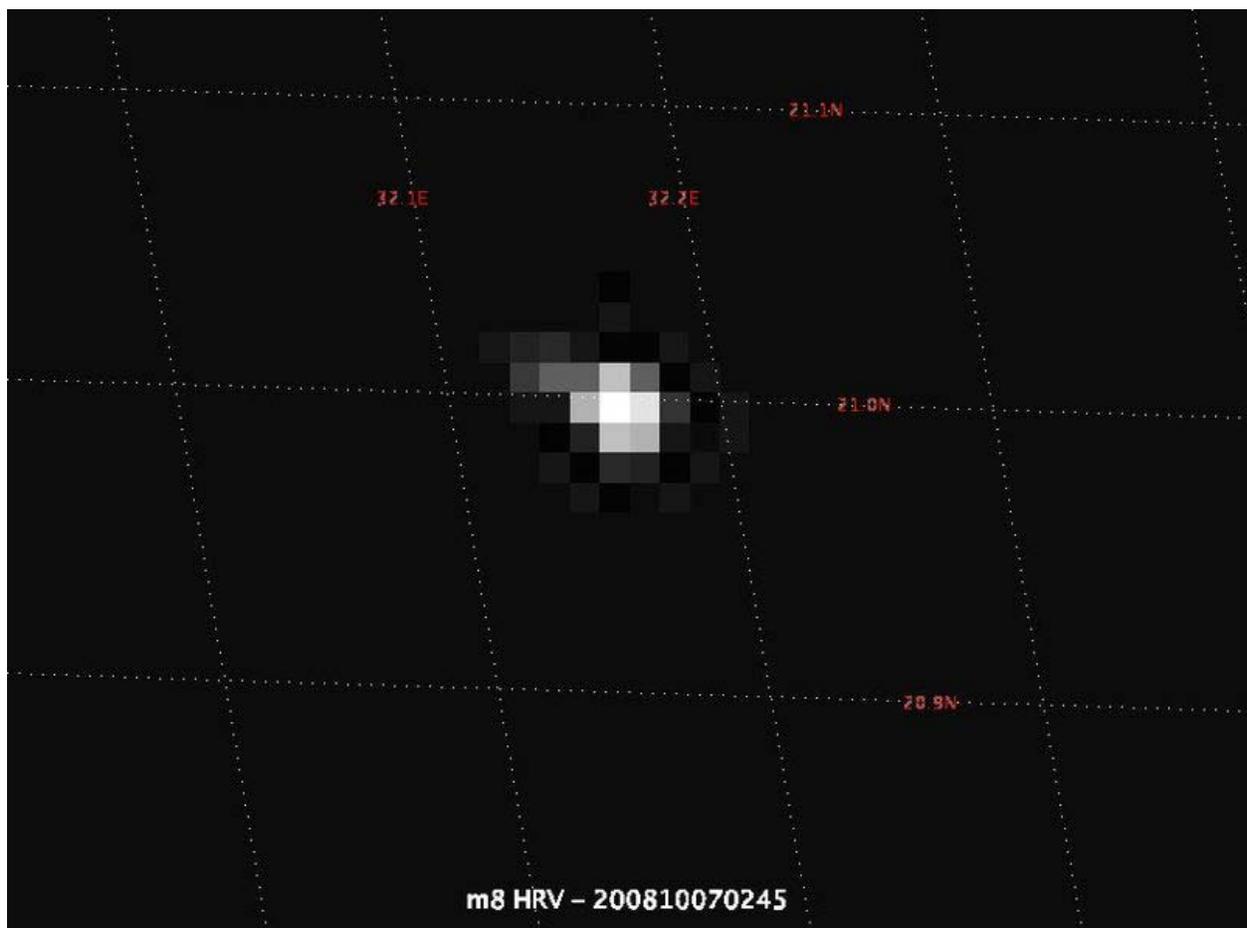
The object is confirmed to have entered Earth's atmosphere as a meteor above northern Sudan at a velocity of 12.8 kilometres per second (29,000 mph). Estimated trajectory has the object coming out of the western sky at an azimuth of 281 degrees, and an altitude angle of 19 degrees to the local horizon.

It exploded tens of kilometers above the ground with the energy of 0.9 to 2.1 kilotons of TNT, causing a large fireball or bolide in the early morning sky. Very few people inhabit the remote area of the Nubian Desert where the explosion took place; *The Times*, however, reported that the meteoroid's "light was so intense that it lit up the sky like a full moon and an airliner 1,400 km (870 miles) away reported seeing the bright flash." A webcam captured the flash lighting up El-Gouna beach 725 kilometres north. A low-resolution image of the explosion was captured by the weather satellite Meteosat 8. The Meteosat images place the fireball at [🌐21°00'N 32°09'E / 21.00°N 32.15°E](#). Infrasound detector arrays in Kenya also detected a sound wave from the direction of the expected impact corresponding to energy of 1.1 to 2.1 kilotons of TNT. Meteoroids of this size hit Earth about two or three times a year.

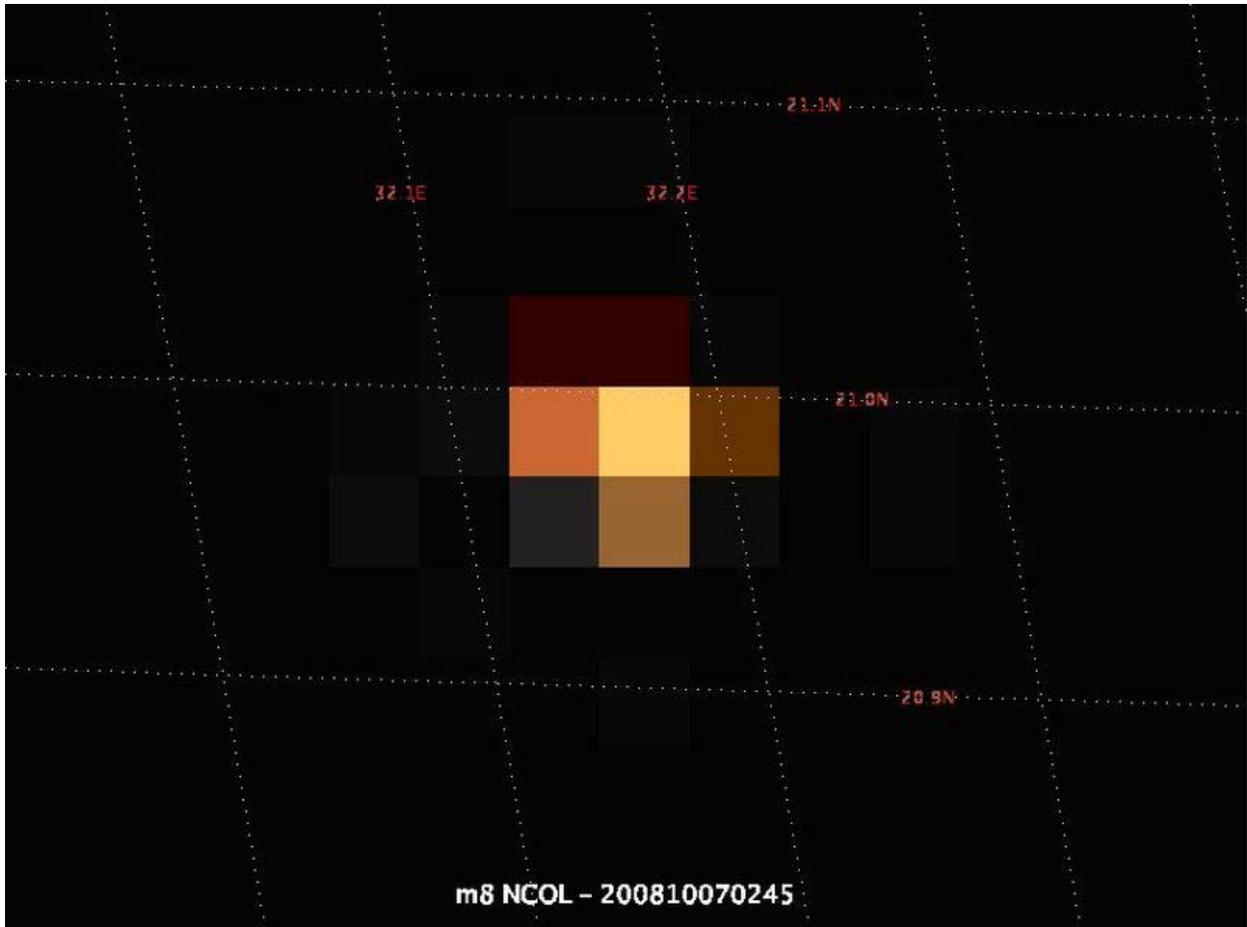
The trajectory showed intersection with Earth's surface at roughly  $20^{\circ}18'N$   $33^{\circ}30'E$  /  $20.3^{\circ}N$   $33.5^{\circ}E$  though the object was expected to break up perhaps 100–200 kilometers (62–120 mi) west as it descended, somewhat east of the Nile River, and about 100 kilometers (62 mi) south of the Egypt–Sudan border.

According to U.S. government sources U.S. satellites detected the impact at 02:45:40 UT, with the initial detection at  $20^{\circ}54'N$   $31^{\circ}24'E$  /  $20.9^{\circ}N$   $31.4^{\circ}E$  at 65.4 kilometers (40.6 mi; 35.3 nmi) altitude and final explosion at  $20^{\circ}48'N$   $32^{\circ}12'E$  /  $20.8^{\circ}N$   $32.2^{\circ}E$  at 37 kilometers (23 mi; 20 nmi) altitude. These images have not been publicly released.

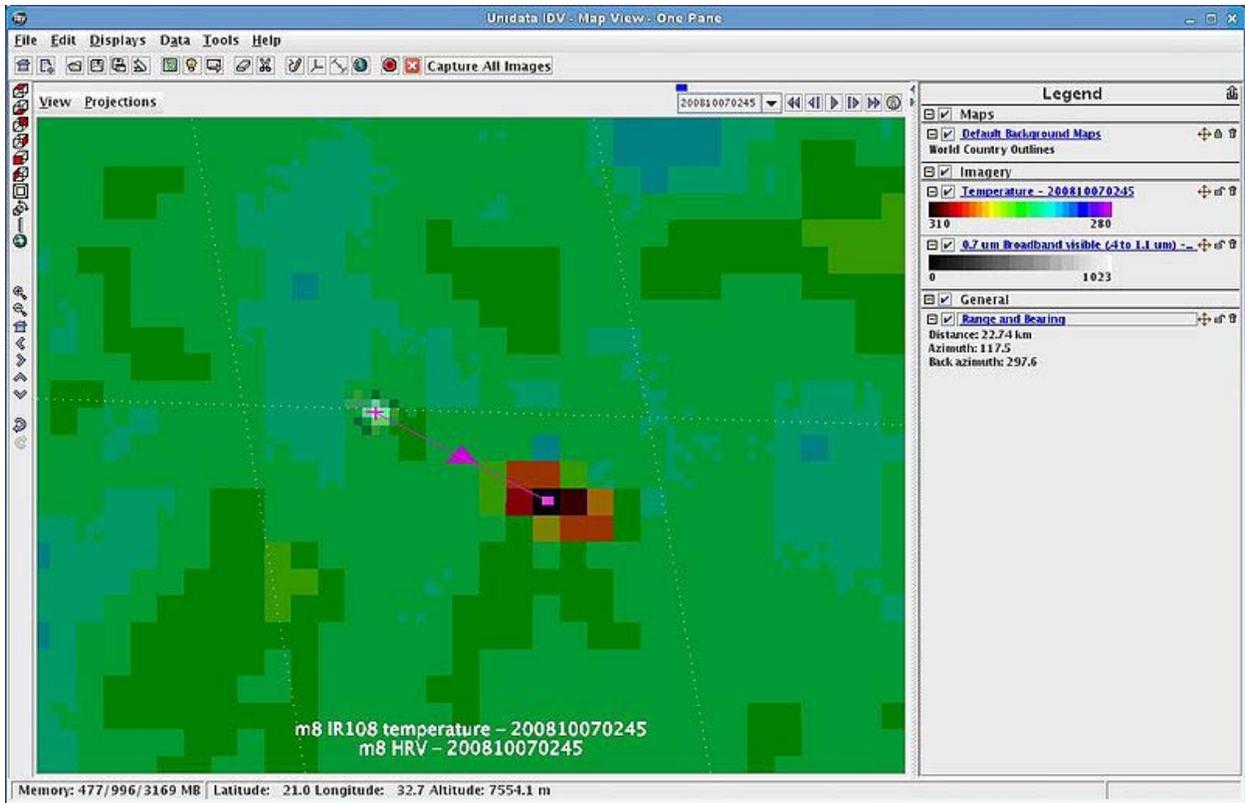
## EUMETSAT fireball images



Meteosat 8 / EUMETSAT visual image of first light flare from 2008 TC3 with lat/long reference



Meteosat 8 / EUMETSAT IR image of main fireball from 2008 TC3



Meteosat images combined, showing offset from first light flare to main IR flare

## Recovered fragments (Almahata Sitta meteorite)



2008 TC3 fragment found on Feb. 28, 2009 by Peter Jenniskens, with help from students and staff of the University of Khartoum. Nubian Desert, Sudan.

### Search

A search of the impact zone that began on December 6, 2008, turned up 10.5 kilograms (23 lb) of rock in some 600 fragments. These meteorites are collectively named Almahata Sitta, which means "Station Six" in Arabic and is a train station between Wadi Halfa and Khartoum, Sudan. This search was led by Peter Jenniskens from the SETI Institute, California and Muawia Shaddad of the University of Khartoum in Sudan and carried out with collaboration of students and staff of the University of Khartoum. The first 15 meteorites were found in the first three days of the search. Numerous witness were interviewed, and the search was guided with a search grid and specific target area produced by NASA's Jet Propulsion Laboratory in Pasadena, California. While fragments have been found before from fireballs seen in the sky, this was the first time fragments had been found from an object that was previously tracked in outer space before hitting Earth.

## **Analysis**

Samples of the Almahata Sitta meteorite were sent for analysis to a consortium of researchers led by Jenniskens, the Almahata Sitta consortium, including NASA Ames in California, the Johnson Space Center in Houston, the Carnegie Institution of Washington, and Fordham University in New York City. The first sample measured was an anomalous ultra-fine-grained porous polymict ureilite achondrite, with large carbonaceous grains. Reflectance spectra of the meteorite, combined with the astronomical observations, identified asteroid 2008 TC3 as an F-type asteroid class. These fragile anomalous dark carbon-rich ureilites are now firmly linked to the group of F-class asteroids.

## **Full circle**

Richard Kowalski received a tiny fragment of Almahatta Sitta, a gift from friends and well-wishers on the Minor Planet Mailing List, which Kowalski founded in order to help connect professional and amateur astronomers.

## Chapter- 4

# Asteroid Impact Avoidance and Lowell Observatory Near-Earth-Object Search

## Asteroid impact avoidance



Artist's impression of a major impact event. The collision between Earth and an asteroid a few kilometres in diameter releases as much energy as the simultaneous detonation of several million nuclear bombs.

**Asteroid mitigation strategies** are "planetary defense" methods by which near-Earth objects could be diverted, preventing potentially catastrophic impact events. A sufficiently large impact would cause massive tsunamis and/or, by placing large quantities of dust into the stratosphere blocking sunlight, an impact winter. A collision between the earth and a ~10 km object 65

million years ago is believed to have produced the Chicxulub Crater and the Cretaceous–Tertiary extinction event.

While in theory the chances of such an event are no greater now than at any other time in history, recent astronomical events (such as Shoemaker-Levy 9) have drawn attention to such a threat, and advances in technology have opened up new options.

## **Detection efforts**

### **What do we need to know?**

Almost any deflection effort requires years of warning, allowing time to build a slow-pusher or explosive device to deflect the object.

An impact by a 10 km asteroid on the Earth is widely viewed as an extinction-level event, likely to cause catastrophic damage to the biosphere. Depending on speed, objects as small as 100 m in diameter are historically extremely destructive. There is also the threat from comets coming into the inner Solar System. The impact speed of a long-period comet would likely be several times greater than that of a near-Earth asteroid, making its impact much more destructive; in addition, the warning time is unlikely to be more than a few months.

Finding out the material composition of the object is also necessary before deciding which strategy is appropriate. Missions like the 2005 Deep Impact probe have provided valuable information on what to expect.

### **History of government mandates**

In a 1992 report to NASA, a coordinated Spaceguard Survey was recommended to discover, verify and provide follow-up observations for Earth-crossing asteroids. This survey was expected to discover 90% of these objects larger than one kilometer within 25 years. Three years later, another NASA report recommended search surveys that would discover 60-70% of short-period, near-Earth objects larger than one kilometer within ten years and obtain 90% completeness within five more years.

In 1998, NASA formally embraced the goal of finding and cataloging, by 2008, 90% of all near-Earth objects (NEOs) with diameters of 1 km or larger than could represent a collision risk to Earth. The 1 km diameter metric was chosen after considerable study indicated that an impact of an object smaller than 1 km could cause significant local or regional damage but is unlikely to cause a worldwide catastrophe. The impact of an object much larger than 1 km diameter could well result in worldwide damage up to, and potentially including, extinction of the human race. The NASA commitment has resulted in the funding of a number of NEO search efforts that are making considerable progress toward the 90% goal by 2008.

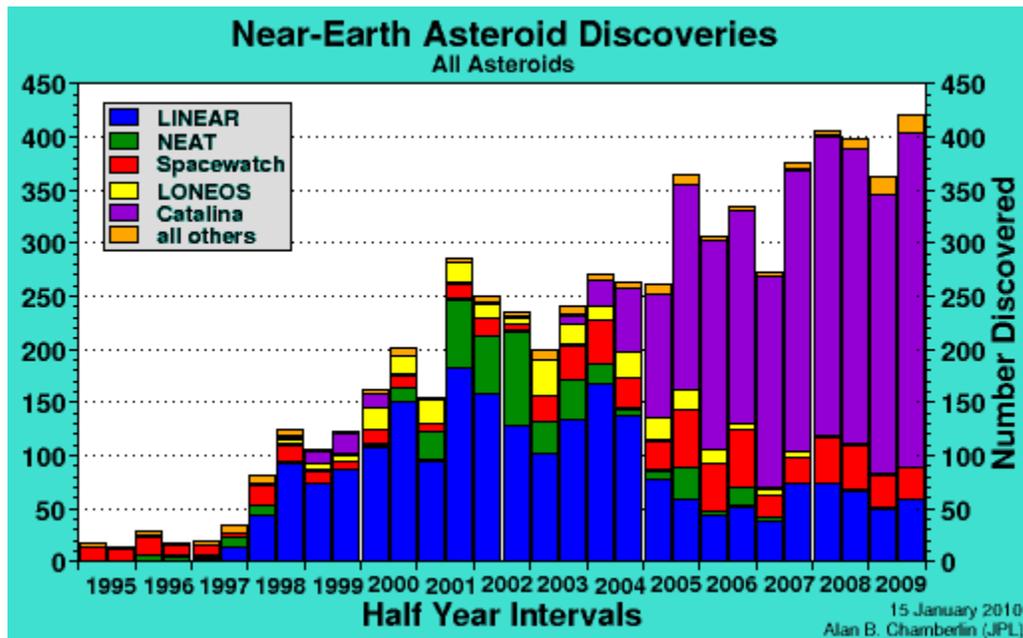
NASA is close to achieving this goal, and should achieve it within a few years. However, as the 2009 discovery of an NEO approximately 2 to 3 kilometers in diameter demonstrates, there are still large objects to be detected.

U.S. Representative George E. Brown, Jr. (D-CA) was quoted as voicing his support for planetary defense projects in *Air & Space Power Chronicles*, saying "If some day in the future we discover well in advance that an asteroid that is big enough to cause a mass extinction is going to hit the Earth, and then we alter the course of that asteroid so that it does not hit us, it will be one of the most important accomplishments in all of human history."

Because of Congressman Brown's long-standing commitment to planetary defense, a U.S. House of Representatives' bill, H.R. 1022, was named in his honor: The George E. Brown, Jr. Near-Earth Object Survey Act. This bill "to provide for a Near-Earth Object Survey program to detect, track, catalogue, and characterize certain near-earth asteroids and comets" was introduced in March 2005 by Rep. Dana Rohrabacher (R-CA). It was eventually rolled into S.1281, the NASA Authorization Act of 2005, passed by Congress on December 22, 2005, subsequently signed by the President, and stating in part:

The U.S. Congress has declared that the general welfare and security of the United States require that the unique competence of NASA be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth. The NASA Administrator shall plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90% completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act. The NASA Administrator shall transmit to Congress not later than 1 year after the date of enactment of this Act an initial report that provides the following: (A) An analysis of possible alternatives that NASA may employ to carry out the Survey program, including ground-based and space-based alternatives with technical descriptions. (B) A recommended option and proposed budget to carry out the Survey program pursuant to the recommended option. (C) Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth. The result of this directive was a report presented to Congress in early March 2007. This was an Analysis of Alternatives (AoA) study led by NASA's Program Analysis and Evaluation (PA&E) office with support from outside consultants, the Aerospace Corporation, NASA Langley Research Center (LaRC), and SAIC (amongst others).

## Ongoing projects



Number of NEOs detected by various projects

Astronomers have been conducting surveys to locate the NEOs, many (as of early 2007) funded by NASA's Near Earth Object (NEO) program office as part of their Spaceguard program. One of the best-known is LINEAR that began in 1996. By 2004 LINEAR was discovering tens of thousands of objects each year and accounting for 65% of all new asteroid detections. LINEAR uses two one-meter telescopes and one half-meter telescope based in New Mexico.

Spacewatch, which uses a 90 centimeter telescope sited at the Kitt Peak Observatory in Arizona, updated with automatic pointing, imaging, and analysis equipment to search the skies for intruders, was set up in 1980 by Tom Gehrels and Dr. Robert S. McMillan of the Lunar and Planetary Laboratory of the University of Arizona in Tucson, and is now being operated by Dr. McMillan. The Spacewatch project has acquired a 1.8 meter telescope, also at Kitt Peak, to hunt for NEOs, and has provided the old 90 centimeter telescope with an improved electronic imaging system with much greater resolution, improving its search capability.

Other near-earth object tracking programs include Near-Earth Asteroid Tracking (NEAT), Lowell Observatory Near-Earth-Object Search (LONEOS), Catalina Sky Survey, Campo Imperatore Near-Earth Objects Survey (CINEOS), Japanese Spaceguard Association, and Asiago-DLR Asteroid Survey. Pan-STARRS is expected to complete telescope construction by 2012.

"Spaceguard" is the name for these loosely affiliated programs, some of which receive NASA funding to meet a U.S. Congressional requirement to detect 90% of near-earth asteroids over 1 km diameter by 2008. A 2003 NASA study of a follow-on program suggests spending US\$250–450 million to detect 90% of all near-earth asteroids 140 meters and larger by 2028.

Orbit@home provides distributed computing resources to optimize search strategy, and NEODyS is an online database of known NEOs.

## **Detection from space**

On November 8, 2007, the House Committee on Science and Technology's Subcommittee on Space and Aeronautics held a hearing to examine the status of NASA's Near-Earth Object survey program. The prospect of using the Wide-field Infrared Survey Explorer was proposed by NASA officials.

WISE will survey the sky in the infrared band at a very high sensitivity. Asteroids that absorb solar radiation can be observed through the infrared band. NASA officials told Committee staff that NASA plans to use WISE to detect NEOs, in addition to performing its science goals. It is projected that WISE could detect 400 NEOs (roughly two percent of the estimated NEO population of interest) within the one-year mission.

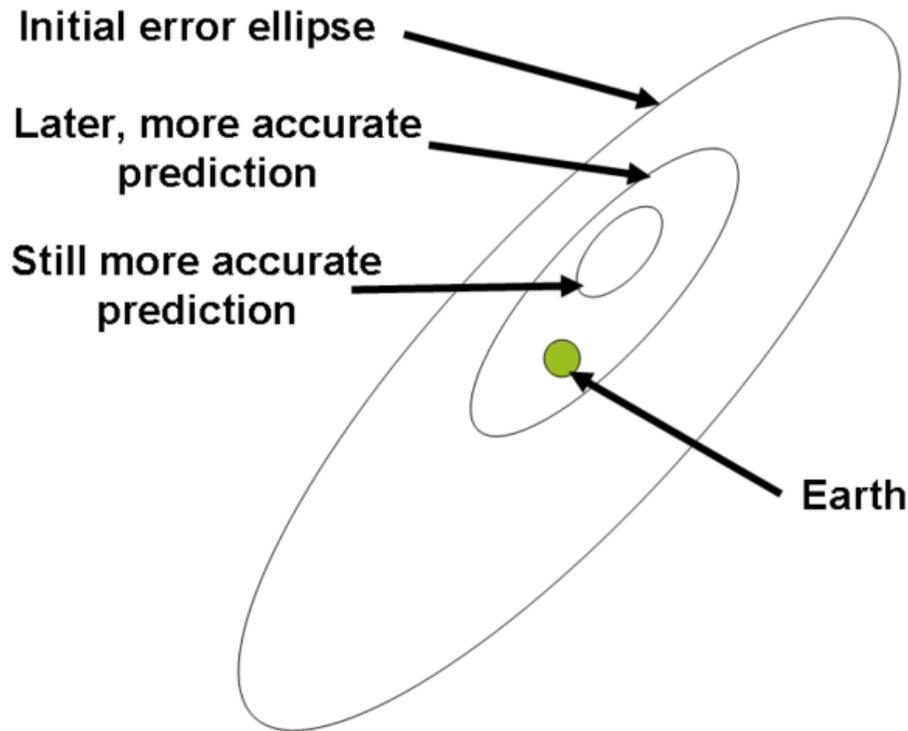
NEOSSat is a micro satellite by Canada's CSA that will hunt for NEOs from space.

## **Results**

Research published in the March 26, 2009 issue of the journal Nature, describes how scientists were able to identify an asteroid in space before it entered Earth's atmosphere, enabling computers to determine its area of origin in the solar system as well as predict the arrival time and location on Earth of its shattered surviving parts. The four-meter-diameter asteroid, called 2008 TC3, was initially sighted by the automated Catalina Sky Survey telescope, on October 6, 2008. Computations correctly predicted impact would occur 19 hours after discovery in the Nubian Desert of northern Sudan.

A number of potential threats have been identified, such as 99942 Apophis (previously known by its provisional designation 2004 MN<sub>4</sub>), which had been given an impact probability of ~3% for the year 2029. This probability has been revised to zero on the basis of new observations.

## Impact probability calculation pattern



Why asteroid impact probability goes up, then down

The ellipses in the diagram at right show the likely asteroid position at closest earth approach. At first, with only a few asteroid observations, the error ellipse is very large and includes the Earth. Further observations shrink the error ellipse, but it still includes the Earth. This raises the impact probability, since the Earth now covers a larger fraction of the error region. Finally, yet more observations (often radar observations, or discovery of a previous sighting of the same asteroid on archival images) shrink the ellipse until the Earth is outside the error region, and the impact probability returns to near zero.

## Collision avoidance strategies

Various collision avoidance techniques have different trade-offs with respect to metrics such as overall performance, cost, operations, and technology readiness. There are various methods for changing the course of an asteroid/comet. These can be differentiated by various types of attributes such as the type of mitigation (deflection or fragmentation), energy source (kinetic,

electromagnetic, gravitational, solar/thermal, or nuclear), and approach strategy (interception, rendezvous, or remote station). Strategies fall into two basic sets: destruction and delay.

Destruction concentrates on rendering the impactor harmless by fragmenting it and scattering the fragments so that they miss the Earth or burn up in the atmosphere. This does not always solve the problem, as sufficient amounts of material hitting the Earth at high speed can be devastating even if they are not collected together in a single body. The amount of energy released by a single large collision or many small collisions is essentially the same, given the physics of kinetic and potential energy. If a large amount of energy is transmitted, it could heat the surface of the planet to an uninhabitable temperature.

Collision avoidance strategies can also be seen as either direct, or indirect. The direct methods, such as nuclear devices or kinetic impactors, violently intercept the bolide's path. Direct methods are preferred because they are generally less costly in time and money. Their effects may be immediate, thus saving precious time. These methods might work for short-notice, or even long-notice threats, from solid objects that can be directly pushed, but probably not effective against loosely aggregated rubble piles. The indirect methods, such as gravity tractors, attaching rockets or mass drivers, laser canons, etc., will travel to the object then take more time to change course up to 180 degrees to fly along side, and then will also take much more time to change the asteroids path just enough so it will miss Earth.

Many NEOs are "flying rubble piles" only loosely held together by gravity, and a deflection attempt might just break up the object without sufficiently adjusting its course. If an asteroid breaks into fragments, any fragment larger than 35 m across would not burn up in the atmosphere and itself could impact Earth. Tracking the thousands of fragments that could result from such an explosion would be a very daunting task. Many small impacts could cause greater devastation than one large impact.

Against some rubble piles, a nuclear device may be delivered to it and dock with it, then it could penetrate to its center, and explode sending fragments in all directions, thus reducing the amount of material reaching the Earth. The explosion can also increase the surface area of the threat enough so that more pieces will burn up harmlessly high in the atmosphere.

Delay exploits the fact that both the Earth and the impactor are in orbit. An impact occurs when both reach the same point in space at the same time, or more correctly when some point on Earth's surface intersects the impactor's orbit when the impactor arrives. Since the Earth is approximately 12,750 km in diameter and moves at approx. 30 km per second in its orbit, it travels a distance of one planetary diameter in about 425 seconds, or slightly over seven minutes. Delaying, or advancing the impactor's arrival by times of this magnitude can, depending on the exact geometry of the impact, cause it to miss the Earth. By the same token, the arrival time of the impactor must be known to this accuracy in order to forecast the impact at all, and to determine how to affect its velocity.

## **Nuclear weapons**

Detonating an explosive nuclear device above the surface (or on the surface or beneath it) of an NEO would be one option, with the blast vaporizing part of the surface of the object and nudging it off course with the reaction. This is a form of nuclear pulse propulsion. Even if not completely vaporized, the resulting reduction of mass from the blast combined with the radiation blast and rocket exhaust effect from ejecta could produce positive results.

Another proposed solution is to detonate a series of smaller nuclear devices alongside the asteroid, far enough away as not to fracture the object. Providing this was done far enough in advance, the relatively small forces from any number of nuclear blasts could be enough to alter the object's trajectory enough to avoid an impact. The 1964 book *Islands in Space*, calculates that a nuclear megatonnage necessary for several deflection scenarios exists. In 1967, graduate students under Professor Paul Sandorff at the Massachusetts Institute of Technology designed a system using rockets and nuclear explosions to prevent a hypothetical impact on Earth by the asteroid 1566 Icarus. This design study was later published as Project Icarus which served as the inspiration for the 1979 film *Meteor*.

## **Kinetic impact**

The hurling of a massive object at the NEO, such as a spacecraft or another near-earth object, is another violent possibility. A small asteroid or large mass in a stable high-Earth orbit would have tremendous kinetic energy stored up. With the addition of some thrust from mounted rockets (plasma or otherwise), it could be used like a stone from a slingshot to deflect the incoming threat.

An alternative means of deflecting an asteroid is to attempt to directly alter its momentum by sending a spacecraft to collide with the asteroid.

The European Space Agency is already studying the preliminary design of a space mission able to demonstrate this futuristic technology. The mission, named Don Quijote, is the first real asteroid deflection mission ever designed.

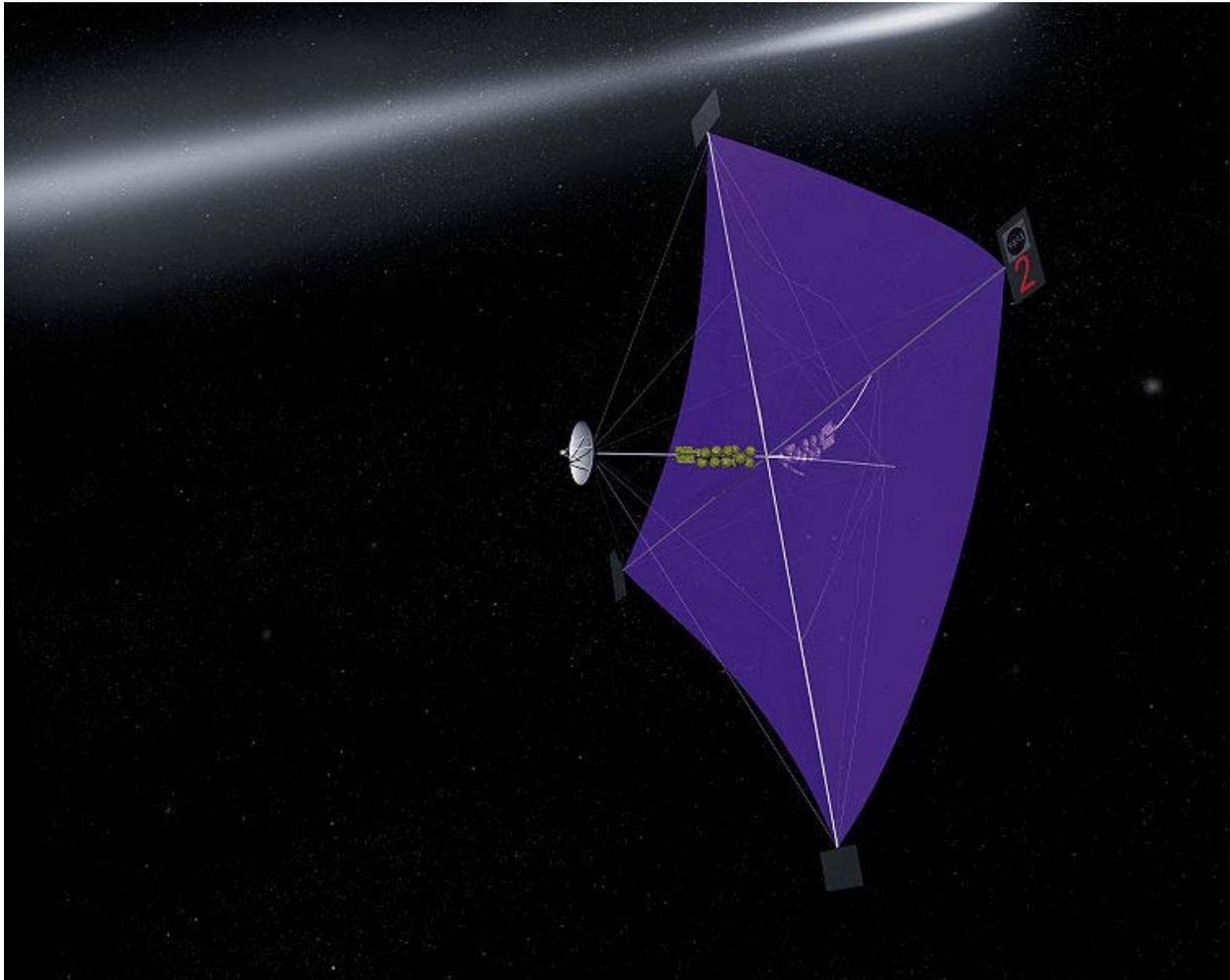
In the case of 99942 Apophis it has been demonstrated by ESA's Advanced Concepts Team that deflection could be achieved by sending a simple spacecraft weighing less than one ton to impact against the asteroid. During a trade-off study one of the leading researchers argued that a strategy called 'kinetic impactor deflection' was more efficient than others.

## **Asteroid gravitational tractor**

One more alternative to explosive deflection is to move the asteroid slowly over a time. Tiny constant thrust accumulates to deviate an object sufficiently from its predicted course. Edward T. Lu and Stanley G. Love have proposed using a large heavy unmanned spacecraft hovering over an asteroid to gravitationally pull the latter into a non-threatening orbit. The spacecraft and the asteroid mutually attract one another. If the spacecraft counters the force towards the asteroid by, e.g., an ion thruster, the net effect is that the asteroid is accelerated towards the spacecraft and

thus slightly deflected from its orbit. While slow, this method has the advantage of working irrespective of the asteroid composition or spin rate — rubble pile asteroids would be difficult or impossible to deflect by means of nuclear detonations while a pushing device would be hard or inefficient to mount on a fast rotating asteroid. A gravity tractor would likely have to spend several years beside the asteroid to be effective.

### Use of focused solar energy



NASA study of a solar sail. The sail would be 0.5 km wide

H. Jay Melosh proposed to deflect an asteroid or comet by focusing solar energy onto its surface to create thrust from the resulting vaporization of material, or to amplify the Yarkovsky effect. Over a span of months or years enough solar radiation can be directed onto the object to deflect it.

This method would first require the construction of a space station with a system of gigantic lens and magnifying glasses near earth. Then the station would be transported toward the Sun.

## Mass driver

A mass driver is an (automated) system on the asteroid to eject material into space thus giving the object a slow steady push and decreasing its mass. A mass driver is designed to work as a very low Specific Impulse system, which in general uses a lot of propellant, but very little power.

The idea is that when using local material as propellant, the amount of propellant is not as important as the amount of power, which is likely to be limited.

Another possibility is to use a mass driver on the moon aimed at the NEO to take advantage of the moon's orbital velocity and inexhaustible supply of "rock bullets".

## Conventional rocket motor

Attaching any spacecraft propulsion device would have a similar effect of giving a steady push, possibly forcing the asteroid onto a trajectory that takes it away from Earth. An in-space rocket engine that is capable of imparting an impulse of  $10^6$  N·s (E.g. adding 1 km/s to a 1000 kg vehicle), will have a relatively small effect on a relatively small asteroid that has a mass of roughly a million times more. Chapman, Durda, and Gold's white paper calculates deflections using existing chemical rockets delivered to the asteroid.

## Other proposals

- Non-conventional engines, such as VASIMR
- Wrapping the asteroid in a sheet of reflective plastic such as aluminized PET film as a solar sail
- "Painting" or dusting the object with titanium dioxide (white) or soot (black) to alter its trajectory via the Yarkovsky effect.
- Planetary scientist Eugene Shoemaker in 1996 proposed deflecting a potential impactor by releasing a cloud of steam in the path of the object, hopefully gently slowing it. Nick Szabo in 1990 sketched a similar idea, "cometary aerobraking", the targeting of a comet or ice construct at an asteroid, then vaporizing the ice with nuclear explosives to form a temporary atmosphere in the path of the asteroid.
- Attaching a tether and ballast mass to the asteroid to alter its trajectory by changing its center of mass.
- Laser ablation
- Magnetic Flux Compression
- NEONet

## Deflection technology concerns

Carl Sagan, in his book *Pale Blue Dot*, expressed concerns about deflection technology: that any method capable of deflecting impactors *away* from Earth could also be abused to divert non-threatening bodies *toward* the planet. Considering the history of genocidal political leaders and the possibility of the bureaucratic obscuring of any such project's true goals to most of its

scientific participants, he judged the Earth at greater risk from a man-made impact than a natural one. Sagan instead suggested that deflection technology should only be developed in an actual emergency situation.

Analysis of the uncertainty involved in nuclear deflection shows that the ability to protect the planet does not imply the ability to target the planet. A nuclear bomb which changed an asteroid's velocity by 10 meters/second (plus or minus 20%) would be adequate to push it out of an earth-impacting orbit. However, if the uncertainty of the velocity change was more than a few percent, there would be no chance of directing the asteroid to a particular target.

According to Rusty Schweickart, the gravitational tractor method is also controversial because during the process of changing an asteroid's trajectory the point on Earth where it could most likely hit would be slowly shifted across different countries. It means that the threat for the entire planet would be minimized at the cost of some specific states' security. In Schweickart's opinion, choosing the way the asteroid should be "dragged" would be a tough diplomatic decision.

## Planetary defense timeline

- In their 1964 book, *Islands in Space*, Dandridge M. Cole and Donald W. Cox noted the dangers of planetoid impacts, both those occurring naturally and those that might be brought about with hostile intent. They argued for cataloging the minor planets and developing the technologies to land on, deflect, or even capture planetoids.
- In the 1980s NASA studied evidence of past strikes on planet Earth, and the risk of this happening at our current level of civilization. This led to a program that maps which objects in our solar system both cross Earth's orbit and are large enough to cause serious damage if they ever hit.
- In the 1990s, US Congress held hearings to consider the risks and what needed to be done about them. This led to a US\$3 million annual budget for programs like Spaceguard and the near-earth object program, as managed by NASA and USAF.
- In 2005 the world's astronauts published an open letter through the Association of Space Explorers calling for a united push to develop strategies to protect Earth from the risk of a cosmic collision.
- It is currently (as of late 2007) believed that there are approximately 20,000 objects capable of crossing Earth's orbit and large enough (140 meters or larger) to warrant concern. On the average, one of these will collide with Earth each 5,000 years, unless preventative measures are undertaken. It is now anticipated that by year 2008, 90% of such objects that are 1 km or more in diameter will have been identified and will be monitored. The further task of identifying and monitoring all such objects of 140m or greater is expected to be complete around 2020.
- The Catalina Sky Survey (CSS) is one of NASA's four funded surveys to carry out a 1998 U.S. Congress mandate to find and catalog by the end of 2008, at least 90 percent of all near-Earth objects (NEOs) larger than 1 kilometer across. CSS discovered 310 NEOs in 2005, 400 in 2006 and the record will be broken with 450 NEOs found in 2007. In doing this survey they discovered on November 20, 2007, an asteroid, designated 2007 WD<sub>5</sub>, which initially was estimated to have a chance of hitting Mars on January 30, 2008,

but further observations during the following weeks allowed NASA to rule out an impact. NASA estimated a near miss by 26,000 km.

## **Lowell Observatory Near-Earth-Object Search**

**Lowell Observatory Near-Earth-Object Search (LONEOS)** was a project designed to discover asteroids and comets that orbit near the Earth. The project, funded by NASA, was directed by Dr. Ted Bowell of Lowell Observatory in Flagstaff, Arizona. The LONEOS project began in 1993 and ran until the end of February 2008.

### **Hardware**

LONEOS, in its final configuration, used a 0.6-meter f/1.8 Schmidt telescope, acquired from Ohio Wesleyan University in 1990, and a Lowell-built 16 megapixel CCD detector. This combination of instruments provided a field of view of 2.88 by 2.88 degrees (8.3 square degrees). It had a maximum nightly scan area of about 1,000 square degrees (covered four times). The instrument could cover the entire accessible dark sky in about a month. The CCD has detected asteroids as faint as visual magnitude 19.8 but its typical limiting visual magnitude was 19.3. The instrument is located at Lowell Observatory's dark sky site, Anderson Mesa Station, near Flagstaff, Arizona, USA.

Four computers were used. Two were used for frame reductions, one for telescope pointing control and one for camera control. The camera control software had scripting capability and could control all the other computers.

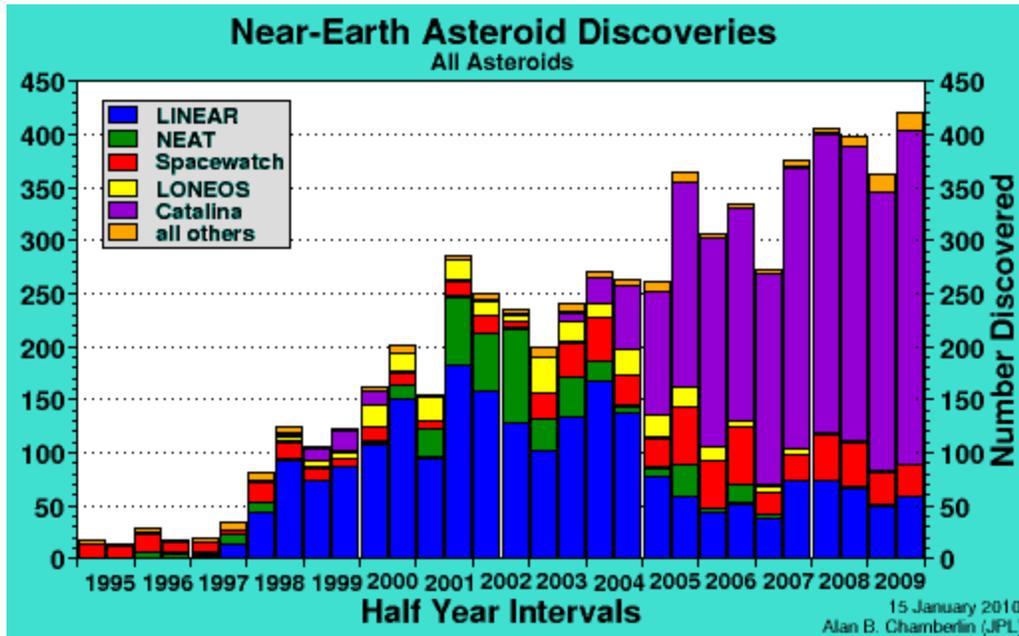
### **Technique**

Asteroids were found by obtaining four pictures (frames) of the same region of sky, each frame temporally separated by 15 to 30 minutes. The set of four frames were then submitted to reduction software which located all star-like sources on the frame and identified sources that moved with asteroid-like motion. The observer visually examined all asteroid detections that had motion different from a typical main-belt asteroid. Human examination was required because most putative NEO detections were not real but some kind of imaging artifact.

All asteroid positions were converted to equatorial coordinates. Various USNO star catalogs were used for this conversion until 2007. Then the Sloan Digital Sky Survey catalog was used, along with supplemental information from the Carlsberg Catalog and the 2MASS catalog. Asteroid brightness was converted to standard visual magnitude. These data, along with the time of the observations, were sent to the Minor Planet Center (MPC) from which they were distributed to the scientific community. Potential near-Earth objects were handled expeditiously so that other observers could locate the asteroid on the same night and make further observations.

Telescope operation was automated to the extent that the survey could be run all night without observer intervention. However, the telescope was seldom operated in the automatic mode because an observer was required to reduce data promptly and to correct any malfunctions that might have occurred.

## Other surveys



Number of NEOs detected by various projects

During the period of LONEOS operation, several other NASA funded NEO searches were underway. These projects include LINEAR, Catalina, Spacewatch, and NEAT. Amateur observers made a significant contribution during this time with independent NEO discoveries and by performing follow-up observations of recent discoveries made by the NASA sponsored surveys.

## LONEOS discovery and performance statistics

The table below lists the number of discoveries made by LONEOS each year of operation. Asteroids thought to be larger than one kilometer in diameter were used as benchmarks in assessing survey completeness. Hence, some table elements have two numbers separated by a slash. The second number represents the number of discoveries larger than one kilometer. The column labeled "Asteroid Observations" is the number of observations sent to the MPC. Each asteroid was typically observed four times (once per frame) each night.

| Year  | Asteroid Observations | NEAs   | PHAs | Atens | Apollos | Amors  | Comets |
|-------|-----------------------|--------|------|-------|---------|--------|--------|
| 1998  | 122550                | 7/4    | 0    | 0/0   | 3/2     | 4/2    | 1      |
| 1999  | 128220                | 14/7   | 5    | 2/2   | 6/3     | 6/2    | 6      |
| 2000  | 271237                | 38/10  | 4    | 3/0   | 18/5    | 17/5   | 6      |
| 2001  | 626976                | 42/11  | 9    | 4/0   | 17/4    | 21/7   | 7      |
| 2002  | 407064                | 21/4   | 3    | 3/1   | 9/0     | 9/3    | 3      |
| 2003  | 720528                | 54/10  | 17   | 5/1   | 26/3    | 23/6   | 2      |
| 2004  | 716152                | 39/4   | 9    | 5/0   | 22/4    | 12/0   | 4      |
| 2005  | 820609                | 42/4   | 8    | 6/0   | 15/1    | 21/3   | 8      |
| 2006  | 679927                | 19/1   | 2    | 0/0   | 11/1    | 8/0    | 2      |
| 2007  | 630469                | 12/0   | 2    | 2/0   | 4/0     | 6/0    | 3      |
| 2008  | 88953                 | 1/0    | 0    | 0/0   | 1/0     | 0/0    | 0      |
| Total | 5212685               | 289/55 | 59   | 30/4  | 131/23  | 127/28 | 42     |

## Other Science

The LONEOS frame archive provides a data set with wide spatial and temporal sky coverage. Other investigators have used these characteristics to produce the following research papers and presentations.

- Investigating the Distinct Components of the Galactic Stellar Halo RR Lyrae from the LONEOS-I Survey, American Astronomical Society, AAS Meeting #211, #163.02, Huber, Mark; Miceli, A.; Cook, K. H.; Rest, A.; Narayan, G.; Stubbs, C. W.
- Evidence for Distinct Components of the Galactic Stellar Halo from 838 RR Lyrae Stars Discovered in the LONEOS-I Survey, eprint arXiv:0706.1583, Miceli, A.; Rest, A.; Stubbs, C. W.; Hawley, S. L.; Cook, K. H.; Magnier, J. Johal, E. A.; Krisciunas, K.; Howell, E.; Koehn, B.
- Detecting variable objects with the LONEOS photometric database: 15000 square degrees of variability measurements down to 19th magnitude in R, American Astronomical Society, 199th AAS Meeting, #101.10; Bulletin of the American Astronomical Society, Vol. 33, p.1463, Rest, A.; Miceli, A.; Miknaitis, G.; Covarrubias, R.; Stubbs, C.; Magnier, E.; Koehn, B.; Howell, T.; Cook, K.; Krisciunas, K.

## Highlights

- 1999 April 12, Shawn Hermann discovers an Aten, 1999 HF1, more than three kilometers in diameter.
- 1999 December 2, Bruce Koehn discovers the first Earth-crossing Damaclod, 1999 XS35, (later identified as a comet).
- 2001 August 14, Mike Van Ness discovers the second Earth-crossing Damaclod, 2001 OG108.

- 2003 September 27, Bob Cash finds the (then) closest Earth-crossing asteroid, 2003 SQ222.
- 2003 October 15, Brian A. Skiff recovers 1937 UB (Hermes), a lost asteroid for 66 years.
- 2004 May 20, Brian Skiff finds an asteroid, 2004 JG6, with the (then) smallest orbit. It is the second asteroid found that has an orbit entirely within Earth's orbit.

## **LONEOS staff**

Lowell staff:

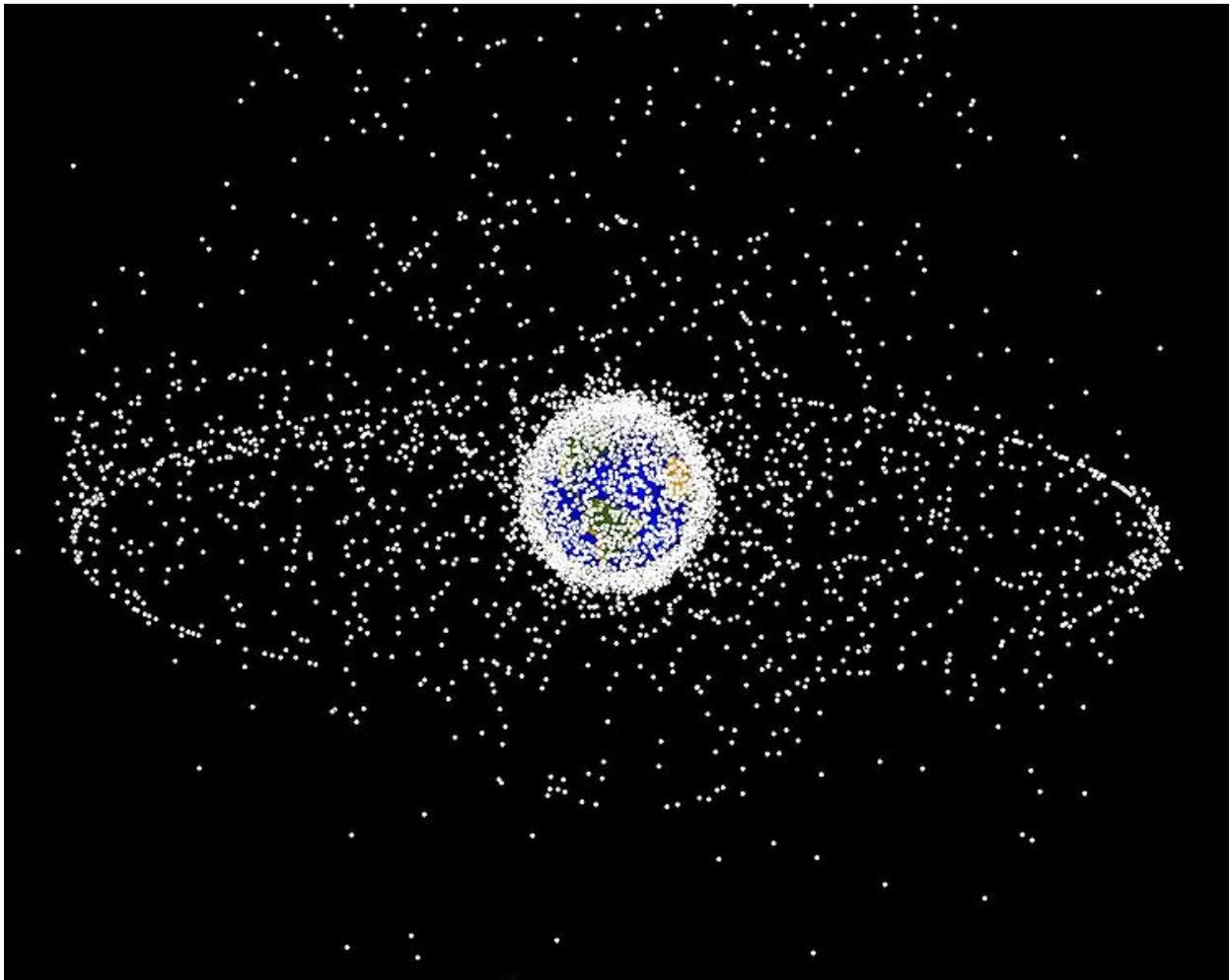
- Dr. Edward Bowell: Principal investigator
- Dr. Bruce Koehn: Computer programming
- Brian Skiff, Bill Ferris, Mike Van Ness, Shawn Hermann: Professional observers
- Christopher Onken, Jennifer Palguta, Wendy Kelly, Jason Sanborn, Thomas Grimstad, Lori Levy, Robert Cash, George Bliss, James Ashley: Volunteer observers

Collaborators:

- Dr. Steve Howell, WIYN/NOAO: CCD performance modeling
- Dr. Karri Muinonen, University of Helsinki: Asteroid detection modeling

## Chapter- 5

# Space Debris



Space debris populations seen from outside geosynchronous orbit (GEO). Note the two primary debris fields, the ring of objects in GEO, and the cloud of objects in low earth orbit (LEO).

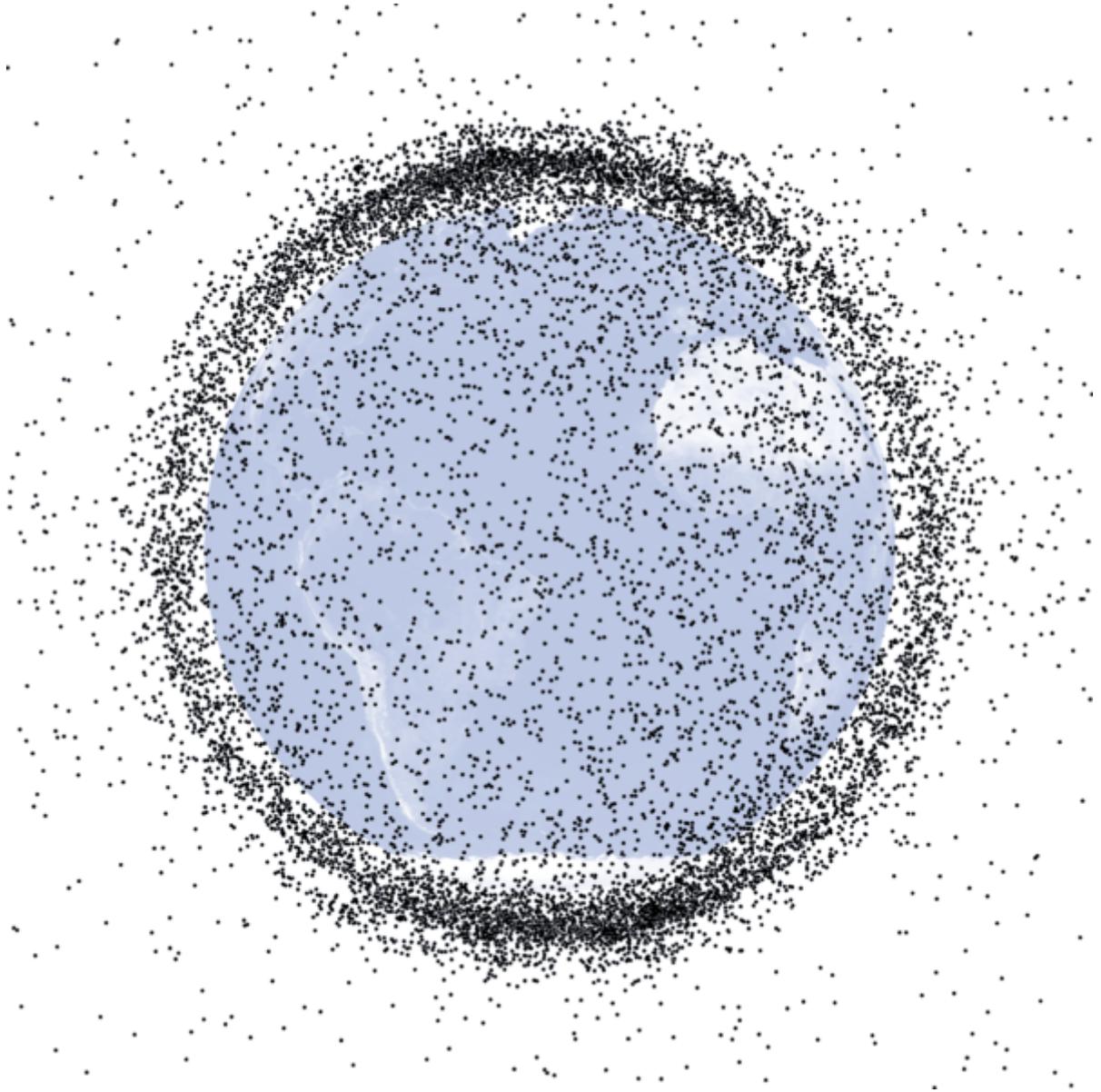


Image made from models used to track debris in Earth orbit

**Space debris** (also known as **orbital debris**, **space junk**, and **space waste**) is the collection of objects in orbit around Earth that were created by humans but no longer serve any useful purpose. These objects consist of everything from spent rocket stages and defunct satellites to explosion and collision fragments. The debris can include slag and dust from solid rocket motors, surface degradation products such as paint flakes, coolant released by RORSAT nuclear powered satellites, clusters of small needles, and objects released due to the impact of micrometeoroids or fairly small debris onto spacecraft. As the orbits of these objects often overlap the trajectories of spacecraft, debris is a potential collision risk.

The vast majority of the estimated tens of millions of pieces of space debris are small particles, like paint flakes and solid rocket fuel slag. Impacts of these particles cause erosive damage,

similar to sandblasting. The majority of this damage can be mitigated through the use of a technique originally developed to protect spacecraft from micrometeorites, by adding a thin layer of metal foil outside of the main spacecraft body. Impacts take place at such high velocities that the debris is vaporized when it collides with the foil, and the resulting plasma spreads out quickly enough that it does not cause serious damage to the inner wall. However, not all parts of a spacecraft may be protected in this manner, i.e. solar panels and optical devices (such as telescopes, or star trackers), and these components are subject to constant wear by debris and micrometeorites.

The present means for spacecraft shielding, such as those used for the manned modules of the International Space Station, are only capable of protecting against debris with diameters below about 1 centimetre (0.39 in). The only remaining means of protection would be to maneuver the spacecraft in order to avoid a collision. This, however, requires that the orbit of the respective object be precisely known. The current equipment used to gather such information is only capable of tracking objects down to about 5 centimetres (2.0 in) diameter in low Earth orbit, and about 50 centimetres (20 in) in geosynchronous orbit. Out of the estimated 600,000 objects above 1 centimetre (0.39 in) diameter, only 19,000 can be tracked as of today. This leads to wide uncertainties in the estimated quantities of debris, and the predicted path of their orbits.

If a collision with larger debris does occur, many of the resulting fragments from the damaged spacecraft will also be in the 1 kilogram (2.2 lb) mass range, and these objects become an additional collision risk. As the chance of collision is a function of the number of objects in space, there is a critical density where the creation of new debris occurs faster than the various natural forces that remove these objects from orbit. Beyond this point a runaway chain reaction can occur that quickly reduces all objects in orbit to debris in a period of years or months. This possibility is known as the "Kessler Syndrome", and there is debate as to whether or not this critical density has already been reached in certain orbital bands.

## History

### Micrometeorites

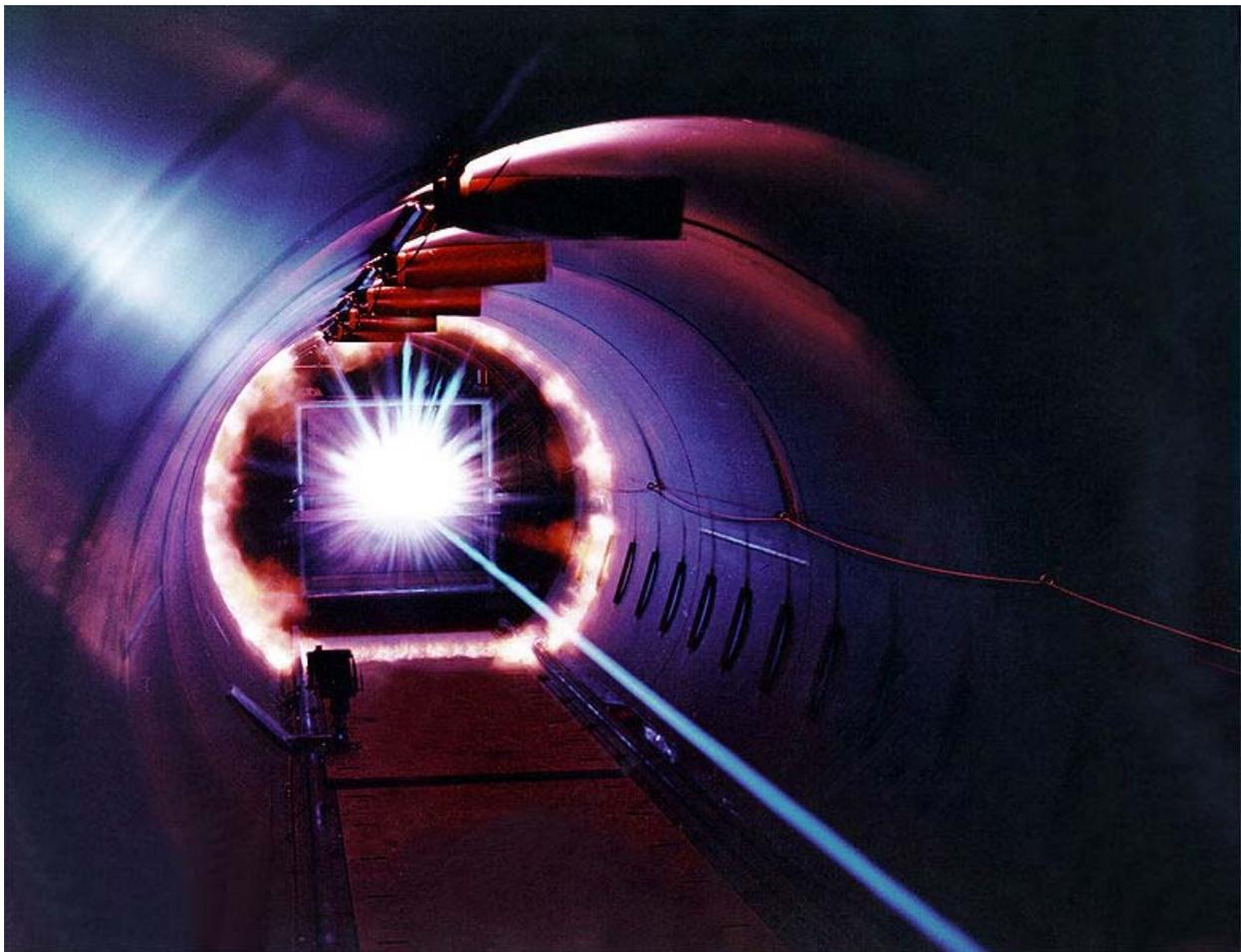
In 1946, during the Giacobinid meteor shower, Helmut Landsberg collected several small magnetic particles that apparently were associated with the shower. Fred Whipple was intrigued by this and wrote a paper that demonstrated that particles of this size were too small to maintain their velocity when they encountered the upper atmosphere. Instead, they would quickly decelerate and then fall to Earth unmelted. In order to classify these sorts of objects, he coined the term "micro-meteorites".

This early work, in collaboration with Fletcher Watson, led the Harvard Observatory to build a station observatory to directly measure the velocity of the meteors that could be seen. At the time some argued that meteors were extra-solar in origin, while others claimed they were leftovers from the formation of the solar system. These direct measurements were able to locate the source of the meteors, demonstrating that the bulk of material was leftover from comet tails, and that none of it could be demonstrated to have an extra-solar origin. Today it is understood that

meteors of all sorts are leftover material from the formation of the solar system, part of the interplanetary dust cloud or the various other objects made up from this material, like comets.

These studies were based on optical measures only. In 1957 Hans Pettersson conducted one of the first direct measurements of the fall of space dust on the Earth, estimating it to be 14,300,000 tons per year. If this were true, then the meteor flux in space was much higher than what the telescopes were seeing. If true, meteors would present a very serious risk to missions deeper in space, specifically the high-orbiting Apollo capsules. To determine which measure was more accurate, a number of additional studies followed, including the Pegasus satellite program. These showed that the flux in line with the optical measures, around 10,000 to 20,000 tons per year.

### **Micrometeorite shielding**



The "energy flash" of a hypervelocity impact during a simulation of what happens when a piece of orbital debris hits a spacecraft in orbit.

Although Whipple's work pre-dated the space race, it proved useful when space exploration started only a few years later. This work had demonstrated that the chance of being hit by a larger meteor, large enough to destroy a spacecraft, was extremely remote. However, it also

demonstrated that a spacecraft would be hit by micrometeorites, about the size of dust grains, almost constantly. Early attempts to protect spacecraft against these micrometeorites generally employed a brute-force approach, which used an outer wall that was thick enough to protect the spacecraft from these sorts of impacts. This was generally far thicker than what was needed for the spacecraft's mechanical structure. Since spacecraft launch costs are a direct relation to their mass, this was an expensive solution.

A better solution had already been developed by Whipple in 1946. Originally known as a "meteor bumper", what is today known as the Whipple shield consisted of a thin foil film held a short distance away from the spacecraft's body. When a micrometeorite hit the foil it would be vaporized into a plasma that would quickly spread out. By the time the plasma crossed the short distance between the shield and the spacecraft, it would be so diffuse that it would not be able to penetrate the structural material below. This allowed the spacecraft body to be built to whatever thickness was needed just for its own structural needs, while the foil would add little additional weight. For spacecraft that spend the majority of their time in orbit, some variety of the Whipple shield has been almost universal for decades.

### **Kessler's asteroid study**

As space missions moved out from the Earth and into deep space, the question arose about the environment of the asteroid belt, which probes would have to pass through on voyages to the outer solar system. Although Whipple had demonstrated that the near-Earth environment was not a problem for space travel, the same depth of analysis had not been applied to the belt. Into this void stepped Donald Kessler, who published a series of papers, starting in late 1968, estimating the density of asteroids.

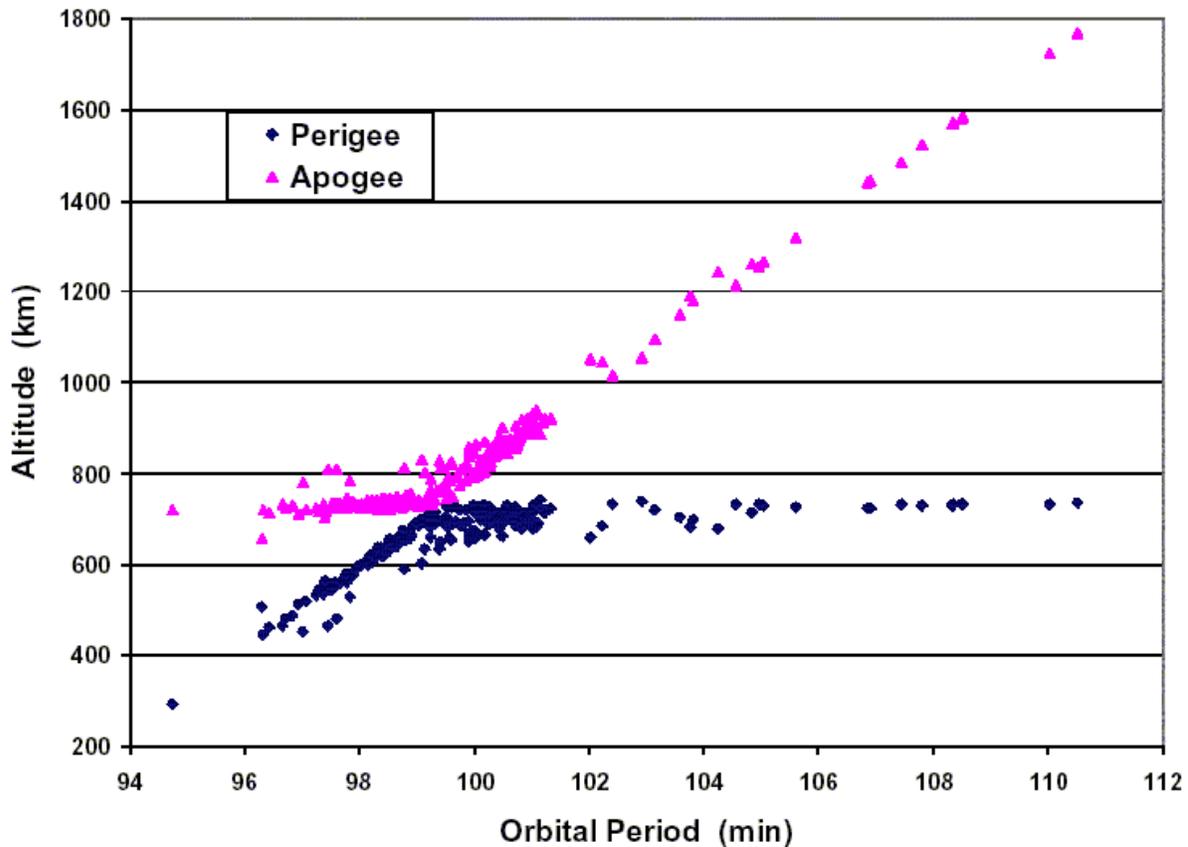
This work led to a 1971 paper on the dynamics of the asteroid system and its evolution over time. Kessler started with the observation that large objects in the belt would eventually be pulled onto collision courses by the actions of the other planets, notably Jupiter. When they collided, a spray of material would be ejected that would lie in a range of new orbital paths similar to the original pre-impact orbit. Since these new orbits overlapped, the objects would then be subject to collisions between each other, and since there were more of them, subsequent impacts would increase in frequency. This ablation cascade process would continue, reducing the size of the objects over time. Based on the measured sizes of known asteroids, Kessler was able to demonstrate that this time scale was in the order of billions of years. This being the case, the density of small debris would be fairly low.

The main outcome of the study was the demonstration that transiting the asteroid belt was not particularly dangerous. The Pioneer and Voyager missions successfully transited this region only a few years later.

### **NORAD, Gabbard and Kessler**

Since the earliest days of the space race, the North American Aerospace Defense Command (NORAD) had maintained a database of all known rocket launches and the various objects that reach orbit as a result – not just the satellites themselves, but the aerodynamic shields that

protected them during launch, upper stage booster rockets that placed them in orbit, and in some cases, the lower stages as well. Known as the Space Object Catalog when it was created with the launch of Sputnik in 1957, NASA later started publishing data-massaged versions of the database in the now common two-line element set format.



Gabbard diagram of almost 300 pieces of debris from the disintegration of the five month old third stage of the Chinese Long March 4 booster on 11 March 2000.

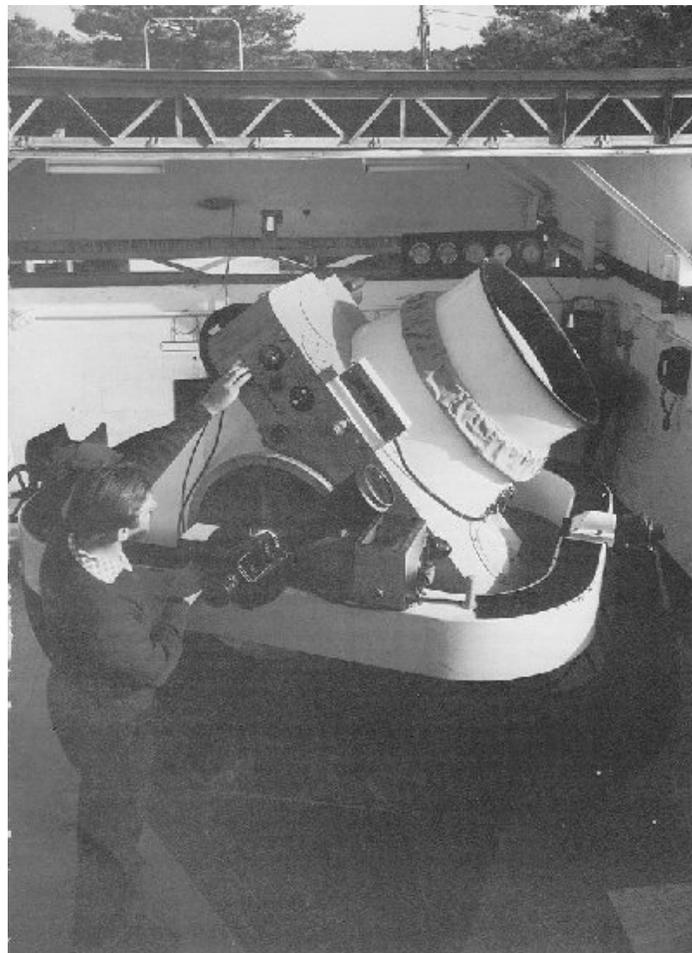
The trackers that fed the database were also aware of a number of other objects in orbit, many of which were the results of on-orbit explosions. Some of these were deliberately caused as a part of 1960's anti-satellite weapon (ASAT) testing, while others were the result of rocket boosters that had "blown up" in orbit as leftover fuel expanded into a gas and ruptured their tanks. Since these objects were only being tracked in a haphazard way, a NORAD employee, John Gabbard, took it upon himself to keep a separate database of as many of these objects as he could. Studying the results of these explosions, Gabbard developed a new technique for predicting the orbital paths of their products. "Gabbard diagrams" (or plots) are widely used today. Along with Preston Landry, these studies were used to dramatically improve the modelling of orbital evolution and decay.

When NORAD's database first became publicly available in the 1970s, Kessler applied the same basic technique developed for the asteroid belt study to the database of known objects. In 1978, Kessler and Burton Cour-Palais co-authored the seminal "Collision Frequency of Artificial

Satellites: The Creation of a Debris Belt", which showed that the same process that controlled the evolution of the asteroids would cause a similar collisional process in Low Earth Orbit (LEO), but instead of billions of years, the process would take just decades. The paper concluded that by about the year 2000, the collisions from debris formed by this process would outnumber micrometeorites as the primary ablative risk to spacecraft.

At the time this did not seem like cause for major concern, as it was widely held that drag with the upper atmosphere would de-orbit the debris faster than it was being created. However, Gabbard was aware that the number of objects in space was under-represented in the NORAD data, and was familiar with the sorts of debris and their behaviour. Shortly after Kessler's paper was published, Gabbard was interviewed on the topic, and coined the term "Kessler syndrome" to refer to the regime where the debris had become a significant issue. The reporter used the term verbatim, and when it was picked up in a *Popular Science* article in 1982, the term became widely used. The article won the Aviation and Space Writers Association's 1982 National Journalism Award.

### Follow-up studies



Baker-Nunn cameras were widely used in the study of the space debris problem

A lack of good data about the debris problem prompted a series of studies to better characterize the LEO environment. In October 1979 NASA provided Kessler with additional funding for further studies of the problem.

Several approaches were used by these studies. Some used optical telescopes or short-wavelength radars to more accurately measure the number and size of objects in space. The optical measurements alone demonstrated that the published population count was too low by at least 50%. Before this it was believed that the NORAD database was essentially complete and accounted for at least the majority of large objects in orbit. These measurements demonstrated that the NORAD list deliberately eliminated some objects (typically U.S. military spacecraft), could not easily account for objects under 20 centimetres (7.9 in) in size, and didn't bother to track many others because they were considered unimportant. In particular, the debris left over from exploding rocket boosters and several 1960s anti-satellite tests were only tracked in a haphazard way in the main database.

Other studies used microscopes to study spacecraft that had returned to Earth, looking for impacts that had already taken place and had gone unnoticed. Sections of Skylab and the Apollo CSMs that had been recovered in the 1960s and '70s were shown to be heavily pitted by debris. To everyone's surprise, every study demonstrated that the debris flux was much higher than expected, and that debris was already the primary source of collisions in space. LEO was already suffering from the Kessler Syndrome, as originally defined. Later refinements were added as the result of the return of Solar Max, the Long Duration Exposure Facility, numerous Space Shuttle missions, and similar spacecraft studies. Similar studies continue to this day.

One discovery that was particularly disconcerting was that 42% of all cataloged debris was the result of only 19 events, explosions of spent rocket stages, mostly from U.S. Deltas. Kessler made this discovery after using Gabbard's methods against known debris fields, overturning the previously held belief that most unknown debris was from formerly unknown ASAT tests. The Delta was a workhorse of the U.S. space program, and there were already numerous other Delta components in orbit that had not yet exploded.

### **A new Kessler Syndrome**

During the same period, the US Air Force ran an experimental program to determine what would happen if debris collided with satellites or other debris. The study demonstrated that the process was entirely unlike the micrometeor case, and that many large chunks of debris would be created that would themselves be a collisional threat. This leads to a worrying possibility – instead of the density of debris being a measure of the number of items launched into orbit, it was that number plus any new debris caused when they collided. If the new debris did not decay from orbit before impacting another object, the number of debris items would continue to grow even if there were no new launches.

In 1991 Kessler published a new work using the best data then available. In "Collisional cascading: The limits of population growth in low earth orbit" he mentioned the USAF's conclusions about the creation of debris. Although the vast majority of debris objects by number was lightweight, like paint flecks, the majority of the *mass* was in heavier debris, about

1 kilogram (2.2 lb) or heavier. This sort of mass would be enough to destroy any spacecraft on impact, creating more objects in the critical mass area. As the National Academy of Sciences put it:

A 1-kg object impacting at 10 km/s, for example, is probably capable of catastrophically breaking up a 1,000-kg spacecraft if it strikes a high-density element in the spacecraft. In such a breakup, numerous fragments larger than 1 kg would be created.

Kessler's analysis led to the conclusion that the problem could be categorized into three regimes. With a low enough density the addition of debris through impacts is lower than their rate of decay, and the problem does not become significant. Beyond that is a critical density where additional debris can quickly upset the system and lead to additional collisions. At a high enough density the rate of production is greater than decay rates, leading to a "cascade", or chain reaction, that quickly reduces the on-orbit population to small objects on the order of a few cm in size, making any sort of space activity very hazardous. This worrying possibility became the new use of the term "Kessler Syndrome".

In a historical overview written in early 2009, Kessler summed up the situation bluntly:

Aggressive space activities without adequate safeguards could significantly shorten the time between collisions and produce an intolerable hazard to future spacecraft. Some of the most environmentally dangerous activities in space include large constellations such as those initially proposed by the Strategic Defense Initiative in the mid-1980s, large structures such as those considered in the late-1970s for building solar power stations in Earth orbit, and anti-satellite warfare using systems tested by the USSR, the U.S., and China over the past 30 years. Such aggressive activities could set up a situation where a single satellite failure could lead to cascading failures of many satellites in a period of time much shorter than years.

### **Debris growth**

Faced with this potentially worrying scenario, as early as the 1980s NASA and other groups within the U.S. attempted to limit the growth of debris. One particularly effective solution was implemented by McDonnell Douglas on the Delta booster, by moving the boosters away from their payload and then venting any remaining fuel in the tanks. This eliminated the pressure build-up in the tanks that had caused them to explode in the past. Other countries, however, were not as quick to adopt this sort of measure, and the problem continued to grow throughout the 1980s, especially due to a large number of launches in the Soviet Union.

A new battery of studies followed as NASA, NORAD and others attempted to better understand exactly what the environment was like. Every one of these studies adjusted the number of pieces of debris in this critical mass zone upward. In 1981 when Scheffter's article was published it was placed at 5,000 objects, but a new battery of detectors in the Ground-based Electro-Optical Deep Space Surveillance system quickly found new objects within its resolution. By the late 1990s it was thought that the majority of 28,000 launched objects had already decayed and about 8,500 remained in orbit. By 2005 this had been adjusted upward to 13,000 objects, and a 2006 study raised this to 19,000 as a result of an ASAT test and a satellite collision.

The population growth has led to intense debate within the community on the nature of the problem and earlier dire warnings. Following Kessler's 1991 derivation, and updates from 2001, the LEO environment within the 1,000 kilometres (620 mi) altitude range should now be within the cascading region. However, only one major incident has occurred: the 2009 satellite collision between Iridium 33 and Cosmos 2251. The lack of any obvious cascading in the short term has led to a number of complaints that the original estimates overestimated the issue. Others have pointed out that the start of a cascade would not be obvious until the situation was well advanced, which might take years.

A 2006 NASA model suggested that even if no new launches took place, the environment would continue to contain the then-known population until about 2055, at which point it would increase on its own. Richard Crowther of Britain's Defence Evaluation and Research Agency stated that he believes the cascade will begin some time around 2015. The National Academy of Sciences, summarizing the view among professionals, noted that there was widespread agreement that two bands of LEO space, 900 to 1,000 kilometres (620 mi) and 1,500 kilometres (930 mi) altitudes, were already past the critical density.

## Characterization

### Large vs. small

Any discussion of space debris generally categorizes large and small debris. "Large" is defined not by its size so much as the current ability to detect objects of some lower size limit. Generally, large is taken to be 10 centimetres (3.9 in) across or larger, with typical masses on the order of 1 kilogram (2.2 lb). Logically it would follow that small debris would be anything smaller than that, but in fact the cutoff is normally 1 centimetre (0.39 in) or smaller. Debris between these two limits would normally be considered "large" as well, but goes unmeasured due to our inability to track them.

In terms of numbers, the vast bulk of debris consists of smaller objects, 1 centimetre (0.39 in) or less. The mid-2009 update to the NASA debris FAQ places the number of large debris items over 10 centimetres (3.9 in) at 19,000, between 1 and 10 centimetres (3.9 in) approximately 500,000, and estimates that debris items smaller than 1 centimetre (0.39 in) probably exceeds tens of millions. In terms of mass, the vast majority of the overall weight of the debris is concentrated in larger objects, using numbers from 2000, about 1,500 objects weighing more than 100 kilograms (220 lb) each account for over 98% of the 1,900 tons of debris then known in low earth orbit.

Since space debris comes from man-made objects, the total *possible* mass of debris is easy to calculate: it is the total mass of all spacecraft and rocket bodies that have reached orbit. The actual mass of debris is much lower than that, as a considerable proportion of these objects have since decayed. As debris mass tends to be dominated by larger objects, most of which have long ago been detected, the total mass has remained relatively constant in spite of the addition of many smaller objects. Using the older figure of 8,500 known debris items, the total mass is estimated at 5,500 tonnes.

## **Debris in LEO**

Every satellite, space probe and manned mission has the potential to create space debris. Any impact between two objects of sizeable mass spalls off shrapnel debris from the force of collision. Each piece of shrapnel has the potential to cause further damage, creating even more space debris. With a large enough collision (such as one between a space station and a defunct satellite), the amount of cascading debris could be enough to render Low Earth Orbit essentially unusable.

The problem in LEO is compounded by the fact that there are few "universal orbits" that keep spacecraft in particular rings, as opposed to GEO, a single widely-used orbit. The closest would be the sun-synchronous orbits that maintain a constant angle between the sun and orbital plane. But LEO satellites are in many different orbital planes providing global coverage, and the 15 orbits per day typical of LEO satellites results in frequent approaches between object pairs. Since sun-synchronous orbits are polar, the polar regions are common crossing points.

After space debris is created, orbital perturbations mean that the orbital plane's direction will change over time, and thus collisions can occur from virtually any direction. Collisions thus usually occur at very high relative velocities, typically several kilometres per second. Such a collision will normally create large numbers of objects in the critical size range, as was the case in the 2009 collision. It is for this reason that the Kessler Syndrome is most commonly applied only to the LEO region. In this region a collision will create debris that will cross other orbits and this population increase that leads to the cascade effect.

At the most commonly-used low earth orbits for manned missions, 400 kilometres (250 mi) and below, residual air drag helps keep the zones clear. Collisions that occur under this altitude are also less of an issue, since they result in fragment orbits having perigee at or below this altitude. The critical altitude also changes as a result of the space weather environment, which causes the upper atmosphere to expand and contract. An expansion of the atmosphere leads to an increased drag to the fragments, resulting in a shorter orbit life time. An expanded atmosphere for some period of time in the 1990s is one reason the orbital debris density remained lower for some time. Another is the rapid reduction in launches by Russia, which conducted the vast majority of launches during the 1970s and 80s.

## **Debris at higher altitudes**

At higher altitudes, where atmospheric drag is less significant, orbital decay takes much longer. Slight atmospheric drag, lunar perturbations, and solar radiation pressure can gradually bring debris down to lower altitudes where it decays, but at very high altitudes this can take millennia. Thus while these orbits are generally less used than LEO, and the problem onset is slower as a result, the numbers progress toward the critical threshold much more quickly.

The problem is especially problematic in the valuable geostationary orbits (GEO), where satellites are often clustered over their primary ground "targets" and share the same orbital path. Orbital perturbations are significant in GEO. Active satellites maintain their station via thrusters,

but if they become inoperable they become a collision concern (as in the case of Telstar 401). There has been estimated to be one close (within 50 meters) approach per year.

On the upside, relative velocities in GEO are low, compared with those between objects in largely random low earth orbits. The impact velocities peak at about 100 metres per second (330 ft/s). This means that the debris field from such a collision is not the same as a LEO collision and does not pose the same sort of risks, at least over the short term. It would, however, almost certainly knock the satellite out of operation. Large-scale structures, like solar power satellites, would be almost certain to suffer major collisions over short periods of time.

In response, the ITU has placed increasingly strict requirements on the station-keeping ability of new satellites and demands that the owners guarantee their ability to safely move the satellites out of their orbital slots at the end of their lifetime. However, studies have suggested that even the existing ITU requirements are not enough to have a major effect on collision frequency. Additionally, GEO orbit is too distant to make accurate measurements of the existing debris field for objects under 1 metre (3 ft 3 in), so the precise nature of the existing problem is not well known. Others have suggested that these satellites be moved to empty spots within GEO, which would require less maneuvering and make it easier to predict future motions. An additional risk is presented by satellites in other orbits, especially those satellites or boosters left stranded in geostationary transfer orbit, which are a concern due to the typically large crossing velocities.

In spite of these efforts at risk reduction, spacecraft collisions have taken place. *Olympus* was hit by a meteor on 11 August 1993 and left adrift. On 24 July 1996, *Cerise*, a French microsatellite in a sun-synchronous LEO, was hit by fragments of an Ariane-1 H-10 upper-stage booster that had exploded in November 1986. On 29 March 2006, the Russian *Express-AM11* communications satellite was struck by an unknown object which rendered it inoperable. Luckily, the engineers had enough time in contact with the spacecraft to send it to a parking orbit out of GEO.

## Sources of debris

Spent rocket upper stages and abandoned satellites are only the tip of the iceberg as far as the space debris population is concerned. There are a number of processes and events that generate new debris objects. Events that lead to the generation of space debris are on-orbit explosions or collisions, firings of solid rocket motors, releases of RORSAT reactor coolant, the release of mission-related objects (such as covers for optical instruments, or yo-yo de-spin weights), and impacts of micrometeoroids or small space debris onto spacecraft. Processes that lead to the generation of new debris are the degradation of spacecraft surfaces and the delamination of objects due to the influence of the radiation environment in space.

## Dead spacecraft



Vanguard 1 remains in orbit over 50 years after launch. Communications were lost in 1964, but it will remain in orbit for 240 years.

In 1958 the United States launched *Vanguard I* into a Medium Earth orbit (MEO). It became one of the longest surviving pieces of space junk and as of October 2009 remains the oldest piece still in orbit.

In a catalog listing known launches up to July 2009, the Union of Concerned Scientists listed 902 operational satellites. This is out of a known population of 19,000 large objects and about 30,000 objects ever launched. Thus, operational satellites represent a small minority of the population of man-made objects in space. The rest are, by definition, debris.

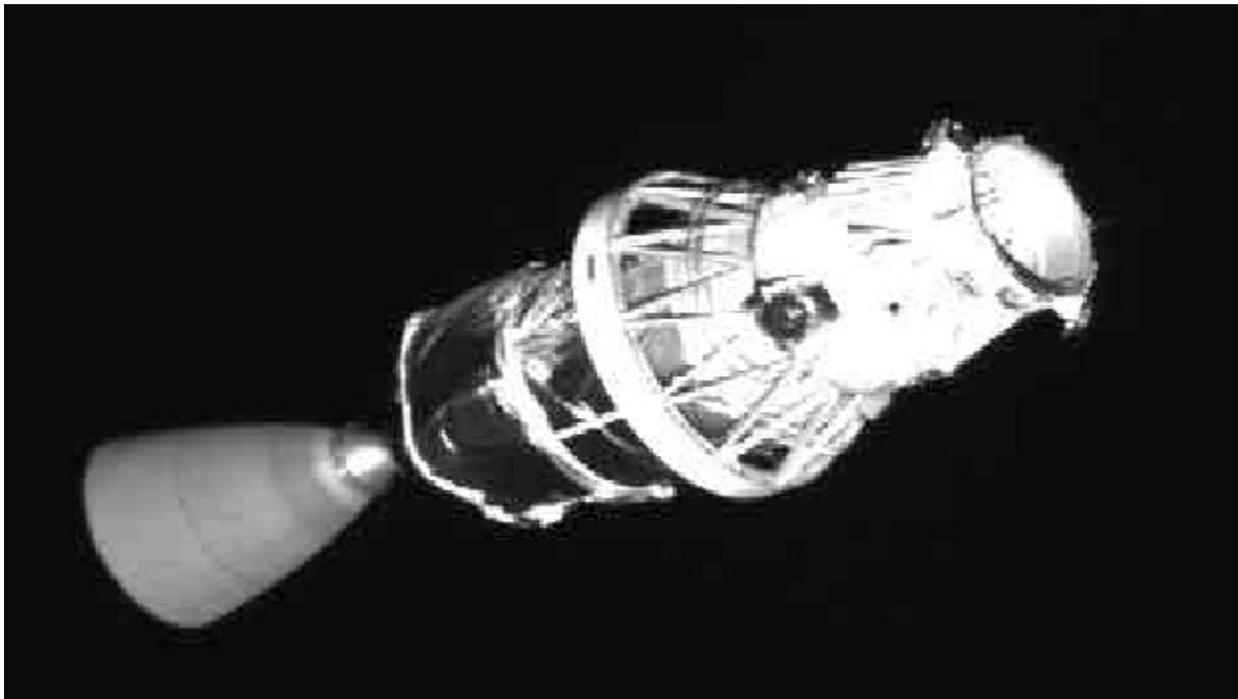
One particular series of satellites presents an additional concern. During the 1970s and 80s the Soviet Union launched a number of naval surveillance satellites as part of their RORSAT program. As radar returns fall off with the fourth power, in order to obtain useful returns the satellites were powered with a BES-5 nuclear reactor in order to provide enough energy to the broadcaster. The satellites were normally boosted into a medium altitude graveyard orbit, but there were several failures that resulted in radioactive material reaching the ground. Even those successfully disposed of now face a debris issue of their own, with a calculated probability of 8% that one will be punctured and release its coolant over any 50 year period. The coolant self-forms into droplets up to around some centimeters in size and these represent a significant debris source of their own.

In February 2009, a US satellite collided with a defunct Russian satellite over Siberia.

## Lost equipment

Debris is also commonly caused during space-walks. According to Edward Tufte's book *Envisioning Information*, space debris objects have included a glove lost by astronaut Ed White on the first American space-walk (EVA); a camera Michael Collins lost near the spacecraft Gemini 10; garbage bags jettisoned by the Soviet cosmonauts throughout the *Mir* space station's 15-year life; a wrench and a toothbrush. Sunita Williams of STS-116 also lost a camera during EVA. In an EVA to reinforce a torn solar panel during STS-120, a pair of pliers was lost and during STS-126, Heidemarie Stefanyshyn-Piper lost a briefcase-sized tool bag in one of the mission's EVAs.

## Boosters



Spent upper stage of a Delta II rocket (photographed by the XSS 10 satellite)

Lower stages, like the solid rocket boosters of the Space Shuttle, or the Saturn IB stage of the Apollo program era, do not reach orbital velocities and do not add to the mass load in orbit. Upper stages, like the Inertial Upper Stage, start and end their productive lives in orbit. Boosters remain a serious debris problem and one of the major known impact events was due to an Ariane booster.

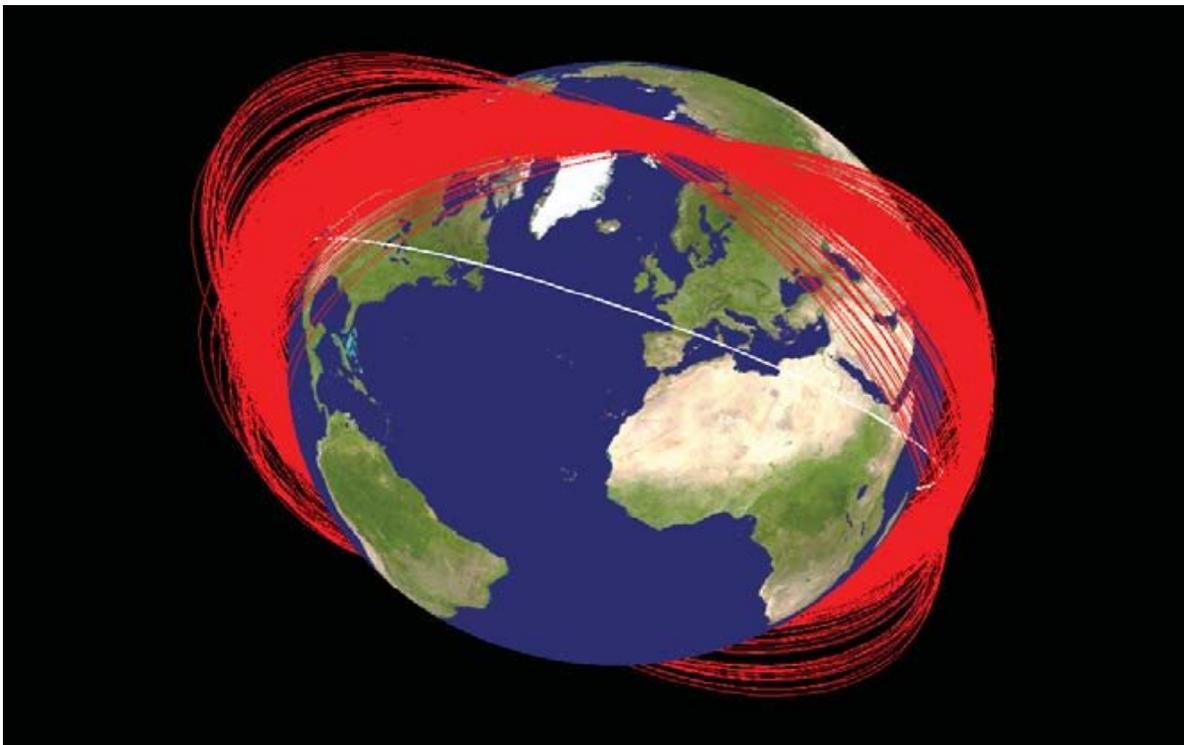
During the initial attempts to characterize the space debris problem, it became evident that a good proportion of all debris was due to the breaking up of rocket boosters. Although NASA quickly made efforts to improve the survivability of their boosters, other countries did not follow suit for some time. On 11 March 2000, a Chinese Long March 4's CBERS-1/SACI-1 upper stage exploded in orbit and created a debris cloud.

An event of similar magnitude occurred on 19 February 2007, when a Russian Briz-M booster stage exploded in orbit over South Australia. The booster had been launched on 28 February 2006, carrying an Arabsat-4A communication satellite but malfunctioned before it could use all of its fuel. The explosion was captured on film by several astronomers, but due to the path of the orbit the debris cloud has been hard to quantify using radar. As of 21 February 2007, over 1,000 fragments had been identified. A third break-up event also occurred on 14 February 2007 as recorded by Celes Trak. Eight break-ups occurred in 2006, the most break-ups since 1993.

### **Debris from and as a weapon**

One major source of debris in the past was the testing of anti-satellite weapons carried out by both the U.S. and Soviet Union in the 1960s and '70s. The NORAD element files only contained data for Soviet tests, and it was not until much later that debris from U.S. tests was identified. By the time the problem with debris was understood, widespread ASAT testing had ended. The U.S.'s only active weapon, Program 437, was shut down in 1975.

The U.S. re-started their ASAT programs in the 1980s with the Vought ASM-135 ASAT. A 1985 test destroyed a 1 tonne (2,200 lb) satellite orbiting at 525 kilometres (326 mi) altitude, creating thousands of pieces of space debris larger than 1 centimetre (0.39 in). Because it took place at relatively low altitude, atmospheric drag caused the vast majority of the large debris to decay from orbit within a decade. Following the U.S. test in 1985, there was a de-facto moratorium on such tests.



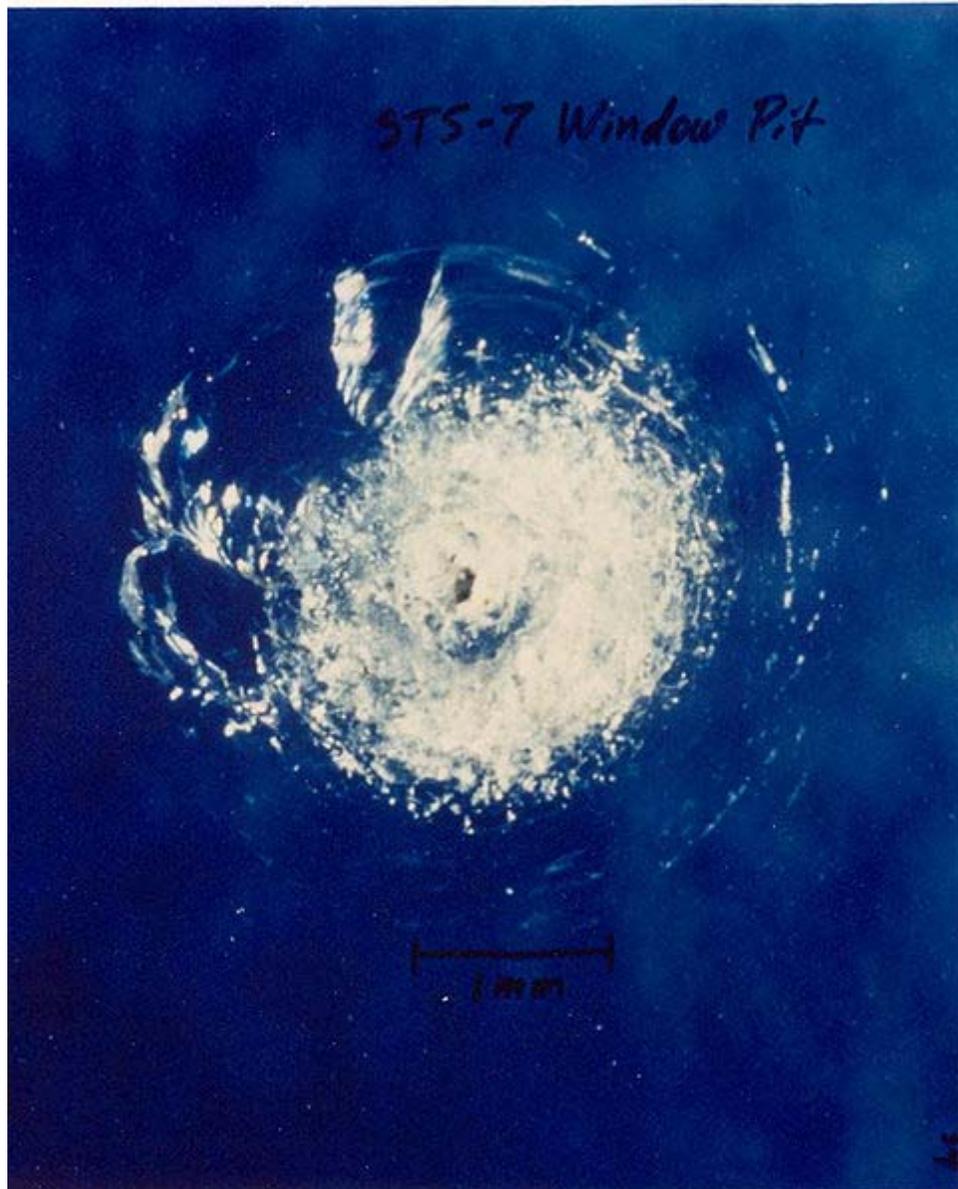
Known orbit planes of Fengyun-1C debris one month after its disintegration by the Chinese ASAT.

China suffered widespread condemnation after their 2007 anti-satellite missile test, both for the military implications as well as the huge amount of debris it created. This is the largest single space debris incident in history, estimated to have created more than 2,300 pieces (updated 13 December 2007) of trackable debris (approximately golf ball size or larger), over 35,000 pieces 1 cm (0.4 in) or larger, and 1 million pieces 1 mm (0.04 in) or larger. Particularly worrying is the fact that the test took place in the most densely populated part of space, as the target satellite orbited between 850 kilometres (530 mi) and 882 kilometres (548 mi). Since the atmospheric drag is quite low at that altitude, the debris will persist for decades. In June 2007, NASA's Terra environmental spacecraft was the first to perform a maneuver in order to prevent impacts from this debris.

On 20 February 2008, the U.S. launched an SM-3 Missile from the USS Lake Erie specially to destroy a defective U.S. spy satellite feared to be carrying 1,000 pounds of toxic hydrazine fuel. Since this event occurred at about 250 km (155 mi) altitude, all of the resulting debris have a perigee of 250 km (155 mi) or lower. The missile was aimed to deliberately reduce the amount of debris as much as possible, and they had decayed by early 2008.

The vulnerability of satellites to a collision with larger debris and the ease of launching such an attack against a low-flying satellite, has led some to speculate that such an attack would be within the capabilities of countries unable to make a precision attack like former U.S. or Soviet systems. Such an attack against a large satellite of 10 tonnes or more would cause enormous damage to the LEO environment.

## Operational aspects



A fleck of paint left this crater on the surface of Space Shuttle Challenger's front window on STS-7.

The vast majority of space debris consists of small particles, from microns up to 1 centimetre (0.39 in). Although there are an estimated 100 million such particles in orbit, they represent a tiny fraction of the total mass of human-made objects in space: perhaps 1%. On impact, these particles cause damage similar to that from a micrometeorite and the widespread use of Whipple shields is effective against the damage they would otherwise cause. Many parts of spacecraft, however, cannot be protected with Whipple shields and are subject to constant wear and tear.

As these sorts of smaller debris represent the minority of the mass, and cause little damage, much of the focus on space debris risks centres on larger debris. The exact definition of "larger" generally means "the size that can be tracked using current technology" and thus changes as tracking technologies improve. In general, these objects are on the order of 10 centimetres (3.9 in) or larger and mass from about 1 kilogram (2.2 lb) and up. Collision with a fragment of this size at the average speed of 10 kilometres per second (6.2 mi/s) would be catastrophic. As a result, space missions have to consider a number of operational factors and risk mitigation strategies.

### **Threat to unmanned spacecraft**

Spacecraft in a debris field are subject to constant wear as a result of impacts with small debris. Critical areas of a spacecraft are normally protected by Whipple shields, eliminating most damage. However, low-mass impacts have a direct impact on the lifetime of a space mission, if the spacecraft is powered by solar panels. These panels are difficult to protect because their front face has to be directly exposed to the sun. As a result, they are often punctured by debris. When hit, panels tend not to produce new debris as much as a cloud of gas-sized particles that does not present as much of a risk to other spacecraft. This gas is generally a plasma when created and consequently presents an electrical risk to the panels themselves. *Olympus* was rendered effectively dead after such a collision, although this was from a Perseid meteor, not spacecraft debris.



Debris impacts on Mir's solar panels degraded their performance. The damage is most noticeable on the panel on the right, which is facing the camera and has high contrast. The more extensive damage to the smaller panel below is due to impact with a Progress spacecraft.

The effect of the many impacts with smaller debris was particularly notable on Mir, the Soviet space station, as it remained in space for long periods of time with the panels originally launched on its various modules.

Impacts with larger debris normally destroy the spacecraft. To date there have been several known and suspected impact events. The earliest on record was the loss of Kosmos 1275, which disappeared on 24 July 1981 only a month after launch. Tracking showed it had suffered some sort of breakup with the creation of 300 new objects. Kosmos did not contain any volatiles and is widely assumed to have suffered a collision with a small object. However, proof is lacking, and

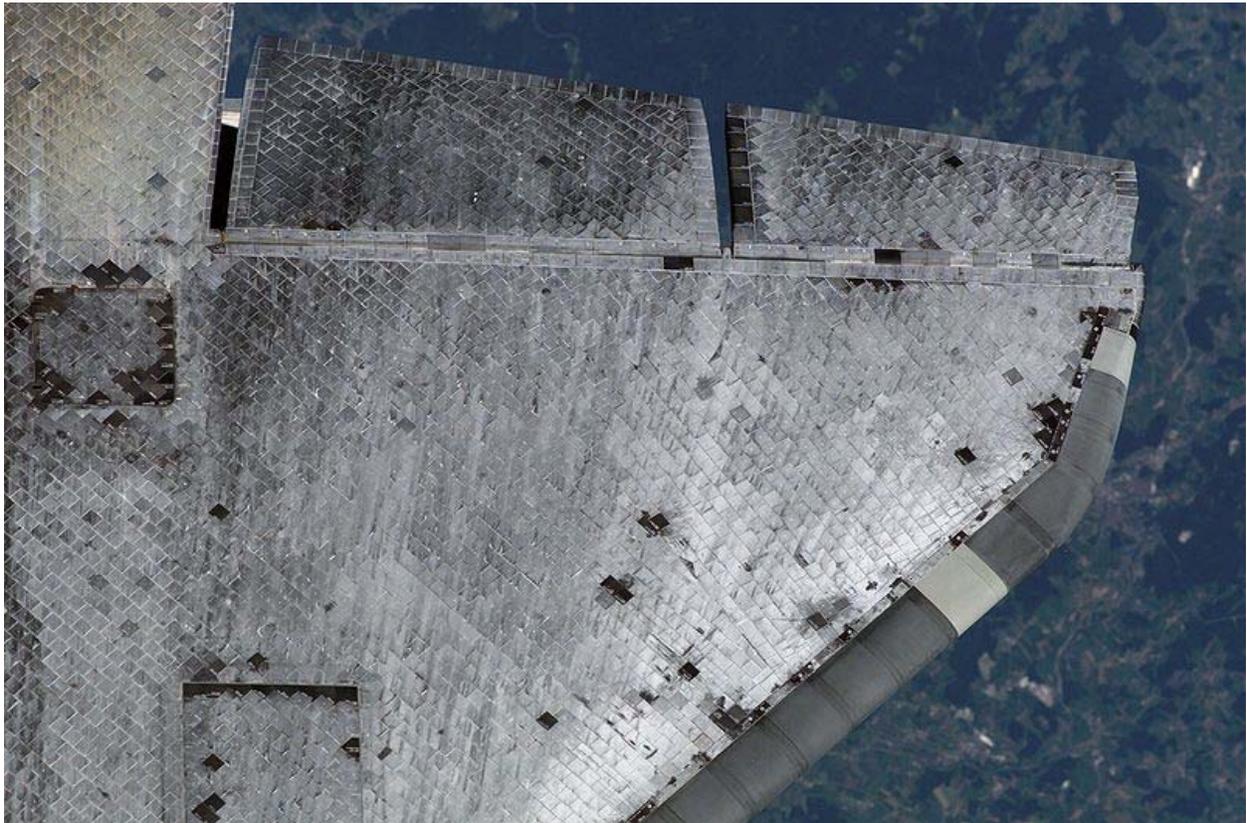
an electrical battery explosion has been offered as a possible alternative. Kosmos 1484 suffered a similar mysterious breakup on 18 October 1993.

Several confirmed impact events have taken place since then. *Olympus* was hit by a meteor on 11 August 1993 and left adrift. On 24 July 1996, the French microsatellite *Cerise* was hit by fragments of an Ariane-1 H-10 upper-stage booster that had exploded in November 1986. On 29 March 2006 the Russian *Express-AM11* communications satellite was struck by an unknown object which rendered it inoperable. Luckily, the engineers had enough time in contact with the spacecraft to send it to a parking orbit out of GEO.

The first major space debris collision was on 10 February 2009 at 16:56 UTC. The deactivated 950 kilograms (2,100 lb) Kosmos 2251 and an operational 560 kilograms (1,200 lb) Iridium 33 collided 500 miles (800 km) over northern Siberia. The relative speed of impact was about 11.7 kilometres per second (7.3 mi/s), or approximately 42,120 kilometres per hour (26,170 mph). Both satellites were destroyed and the collision scattered considerable debris, which poses an elevated risk to spacecraft. The collision created a debris cloud, although accurate estimates of the number of pieces of debris is not yet available.

In a Kessler Syndrome cascade, satellite lifetimes would be measured on the order of years or months. New satellites could be launched through the debris field into higher orbits or placed in lower ones where natural decay processes remove the debris, but it is precisely because of the utility of the orbits between 800 and 1,500 kilometres (930 mi) that this region is so filled with debris.

## Threat to manned spacecraft



Discovery's underside displays a number of new tiles, which are darker. These have replaced tiles that were damaged on earlier missions. This image was taken on STS-114 during the now common "R-Bar Pitch Maneuver" that allows astronauts on the ISS to examine the TPS for damage caused during ascent.

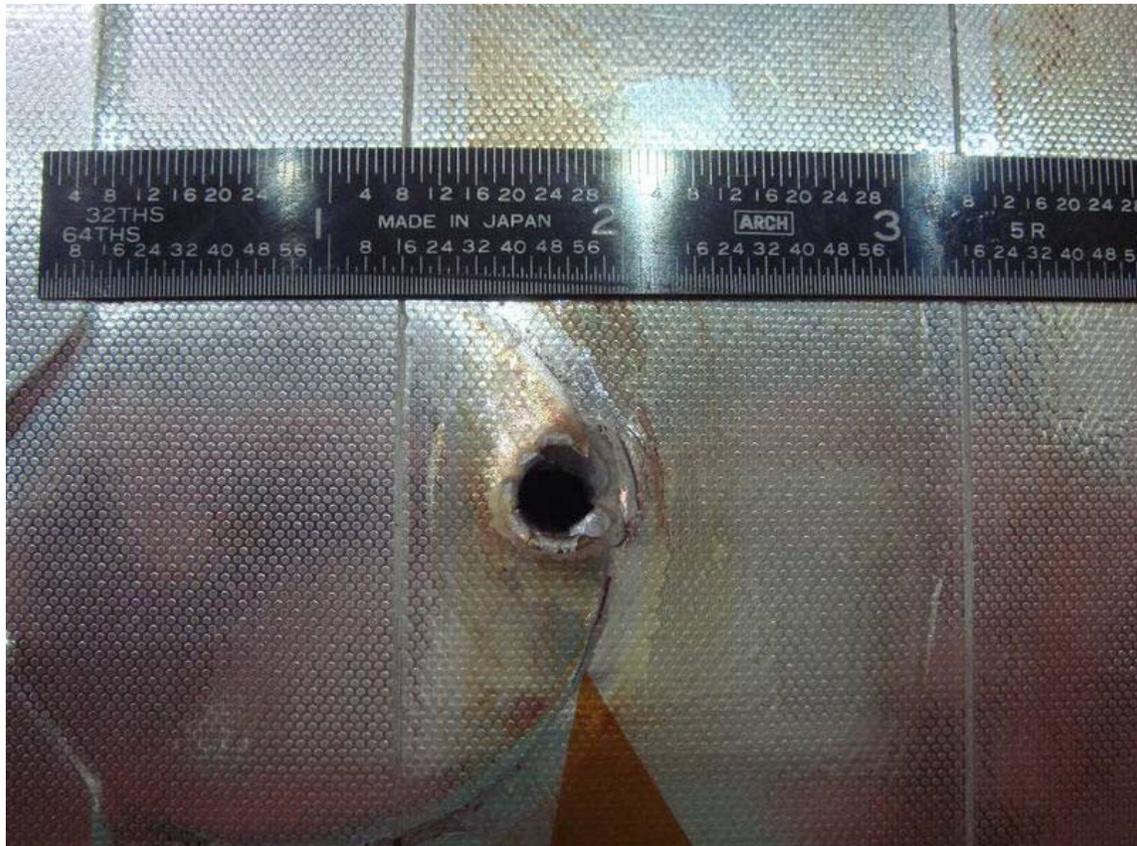
From the earliest days of the Space Shuttle missions, NASA has turned to NORAD's database to constantly monitor the orbital path in front of the Shuttle to find and avoid any known debris. At one point these simulations used up a considerable amount of the NORAD tracking system's capacity. The first official Space Shuttle collision avoidance maneuver was during STS-48 in September 1991. A 7-second reaction control system burn was performed to avoid debris from the Cosmos satellite 955. Similar maneuvers followed on missions 53, 72 and 82.

One of the first events to widely publicize the debris problem was Space Shuttle Challenger's first flight on STS-7. A small fleck of paint impacted Challenger's front window and created a pit over 1 millimetre (0.04 in) wide. Endeavour suffered a similar impact on STS-59 in 1994, but this one pitted the window for about half its depth: a cause for much greater concern. Post-flight examinations have noted a marked increase in the number of minor debris impacts since 1998.

The damage due to smaller debris has now grown to become a significant threat in its own right. Chipping of the windows became common, along with minor damage to the thermal protection system tiles (TPS). To mitigate the impact of these events, once the Shuttle reaches orbit it is

deliberately flown tail first in an attempt to intercept as much of the debris load as possible on the engines and rear cargo bay. These are not used on orbit or during descent and thus are less critical to operations after launch. When flown to the ISS, the Shuttle is moved to a location where the station itself provides as much protection as possible.

The sudden increase in debris load led to a re-evaluation of the debris issue and today a catastrophic impact with large debris is considered to be the #1 threat to Shuttle operations on every mission. Mission planning now requires a thorough discussion of debris risk, requiring an executive level decision to proceed if the risk is greater than 1 in 200 of destroying the Shuttle. On a normal low-orbit mission to the ISS the risks are estimated to be 1 in 300, but the STS-125 mission to repair the Hubble Space Telescope at 350 miles was initially calculated at 1 in 185 due to the 2009 satellite collision, and threatened to cancel the mission. However, a re-analysis as better debris numbers became available reduced this to 1 in 221, and the mission was allowed to proceed.



Endeavour suffered a major hit on the radiator during STS-118. The entry hole is just less than 1/2 inch, the exit hole on the rear of the panel is much larger.

In spite of their best efforts, however, there have been two serious debris incidents on more recent Shuttle missions. In 2006, Atlantis was hit by a small fragment of a circuit board during STS-115, which bored a small hole through the radiator panels in the cargo bay (the large gold colored objects visible when the doors are open). A similar incident followed on STS-118 in

2007, when Endeavour was hit in a similar location by unknown debris which blew a hole several centimetres in diameter through the panel.

The International Space Station (ISS) uses extensive Whipple shielding to protect itself from minor debris threats. However, large portions of the ISS cannot be protected, notably its large solar panels. In 1989 it was predicted that the International Space Station's panels would suffer about 0.23% degradation over four years, which was dealt with by overdesigning the panel by 1%. New figures based on the increase in collisions since 1998 are not available.

Like the Shuttle, the only protection against larger debris is avoidance. On one occasion the crew was forced to abandon work and take refuge in the Soyuz capsule while the threat passed. This close call is a good example of the potential Kessler Syndrome; the debris is believed to be a small 10 centimetres (3.9 in) portion of the former Cosmos 1275, which is the satellite that is considered to be the first example of an on-orbit impact with debris.

If the Kessler Syndrome comes to pass, the threat to manned missions may be too great to contemplate operations in LEO. Although the majority of manned space activities take place at altitudes below the critical 800 to 1,500 kilometres (310 mi) regions, a cascade within these areas would result in a constant rain down into the lower altitudes as well. The time scale of their decay is such that "the resulting debris environment is likely to be too hostile for future space use."

### **Hazard on Earth**



Saudi officials inspect a crashed PAM-D module, January 2001

Although most debris will burn up in the atmosphere, larger objects can reach the ground intact and present a risk.

The original re-entry plan for Skylab called for the station to remain in space for 8 to 10 years after its final mission in February 1974. Unexpectedly high solar activity pushed the space station's orbit closer to Earth than planned. On 11 July 1979, Skylab re-entered the Earth's atmosphere and disintegrated, raining debris harmlessly along a path extending over the southern Indian Ocean and sparsely populated areas of Western Australia.

On 12 January 2001, a Star 48 Payload Assist Module (PAM-D) rocket upper stage re-entered the atmosphere after a "catastrophic orbital decay". The PAM-D stage crashed in the sparsely populated Saudi Arabian desert. It was positively identified as the upper-stage rocket booster for NAVSTAR 32, a GPS satellite launched in 1993.

The Columbia disaster in 2003 demonstrated this risk, as large portions of the spacecraft reached the ground. In some cases entire equipment systems were left intact. NASA continues to warn people to avoid contact with the debris due to the possible presence of hazardous chemicals.

On 27 March 2007, wreckage from a Russian spy satellite was spotted by Lan Chile (LAN Airlines) Airbus A340, which was travelling between Santiago, Chile, and Auckland, New Zealand carrying 270 passengers. The pilot estimated the debris was within 8 km of the aircraft, and he reported hearing the sonic boom as it passed. The aircraft was flying over the Pacific Ocean, which is considered one of the safest places in the world for a satellite to come down because of its large areas of uninhabited water.

There has only been one recorded incident of a person being hit by human-made space debris. In 1997 an Oklahoma woman named Lottie Williams was hit in the shoulder by a 10 x 13 centimetres (5.1 in) piece of blackened, woven metallic material that was later confirmed to be part of the fuel tank of a Delta II rocket which had launched a U.S. Air Force satellite in 1996. She was not injured.

## **Tracking and measurement**

### **Tracking from the ground**

Radar and optical detectors such as lasers are the main tools used for tracking space debris. However, determining orbits to allow reliable re-acquisition is problematic. Tracking objects smaller than 10 cm (4 in) is difficult due to their small cross-section and reduced orbital stability, though debris as small as 1 cm (0.4 in) can be tracked. NASA Orbital Debris Observatory tracked space debris using a 3 m (10 ft) liquid mirror transit telescope.

The U.S. Strategic Command maintains a catalogue containing about 19,000 objects in the version compiled in 2009, in part to prevent misinterpretation as hostile missiles. Observation data gathered by a number of ground-based radar facilities and telescopes as well as by a space-based telescope is used to maintain this catalogue. Nevertheless, the majority of debris objects remain unobserved. There are more than 600,000 objects larger than 1 cm (0.4 in) in orbit

(according to the ESA Meteoroid and Space Debris Terrestrial Environment Reference, the MASTER-2005 model).

Other sources of knowledge on the actual space debris environment include measurement campaigns by the ESA Space Debris Telescope, TIRA (System), Goldstone radar, Haystack radar, and the Cobra Dane phased array radar. The data gathered during these campaigns is used to validate models of the debris environment like ESA-MASTER. Such models are the only means of assessing the impact risk caused by space debris, as only larger objects can be regularly tracked.

### **Measurement in space**



The Long Duration Exposure Facility (LDEF) is an important source of information on the small particle space debris environment.

Returned space debris hardware is also a valuable source of information on the (sub-millimetre) space debris environment. The LDEF satellite deployed by STS-41-C *Challenger* and retrieved by STS-32 *Columbia* spent 68 months in orbit. The close examination of its surfaces allowed the analysis of the directional distribution and the composition of debris flux. The EURECA satellite deployed by STS-46 *Atlantis* in 1992 and retrieved by STS-57 *Endeavour* in 1993 could provide additional insight.

The solar arrays of the Hubble Space Telescope returned during missions STS-61 *Endeavour* and STS-109 *Columbia* are an important source of information on the debris environment. The impact craters found on the surface were counted and classified by ESA to provide another means for validating debris environment models. Similar materials returned from Mir were also extensively studied.

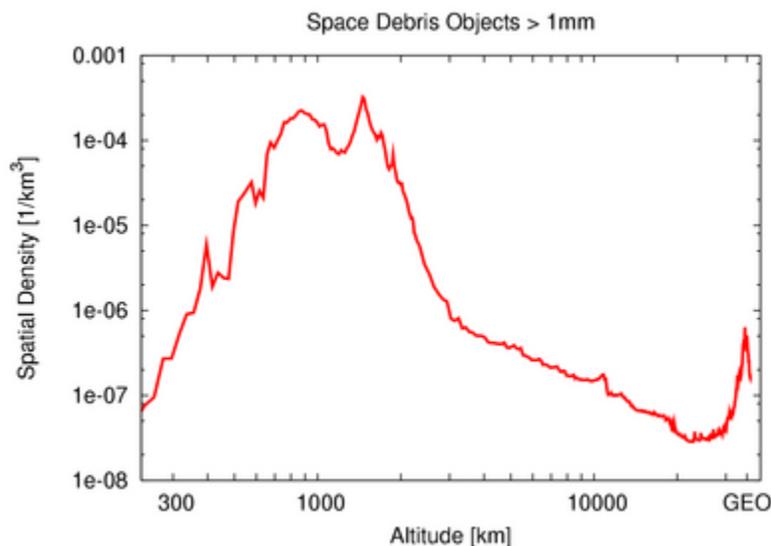
### Gabbard diagrams

Space debris groups resulting from satellite breakups are often studied using scatter plots known as Gabbard diagrams. In a Gabbard diagram, the perigee and apogee altitudes of the individual debris fragments resulting from a collision are plotted with respect to the orbital period of each fragment. The distribution of the resulting diagram can be used to infer information such as direction and point of impact.

## Dealing with debris

In the 2009 European Air and Space Conference, University of Southampton, UK researcher, Hugh Lewis predicted that the threat from space debris would rise 50 percent in the coming decade and quadruple in the next 50 years. Currently more than 13,000 close calls are tracked weekly.

### Growth mitigation



Spatial density of space debris by altitude according to ESA MASTER-2001. This graphic does not include the large amounts of debris from the Chinese ASAT and 2009 collision events.

In order to mitigate the generation of additional space debris, a number of measures have been proposed. The passivation of spent upper stages by the release of residual fuels is aimed at reducing the risk of on-orbit explosions that could generate thousands of additional debris

objects. The previously mentioned change to the Delta boosters in the early days of the debris characterization essentially eliminated their future contribution.

There is no international treaty mandating behavior to minimize space debris, but the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) did publish voluntary guidelines in 2007. As of 2008, the committee is discussing international "rules of the road" to prevent collisions between satellites. NASA has implemented its own procedures for limiting debris production as have some other space agencies, such as the European Space Agency. The ISO is also in the process of preparing a new standard, dealing with space debris mitigation.

### **Self-removal**

It is already an ITU requirement that geostationary satellites be able to remove themselves to a "graveyard orbit" at the end of their lives. It has been demonstrated that the selected orbital areas do not sufficiently protect GEO lanes from debris, although a response has not yet been formulated.

Rocket boosters and some satellites retain enough fuel to allow them to power themselves into a decaying orbit. In cases when a direct (and controlled) de-orbit would require too much fuel, a satellite can also be brought to an orbit where atmospheric drag would cause it to de-orbit after some years. Such a maneuver was successfully performed with the French Spot-1 satellite, bringing its time to atmospheric re-entry down from a projected 200 years to about 15 years by lowering its perigee from 830 km (516 mi) to about 550 km (342 mi).

Another proposed solution is to attach an electrodynamic tether to the spacecraft on launch. At the end of their lifetime it is rolled out and slows down the spacecraft. Although tethers of up to 30 km have been successfully deployed in orbit the technology has not yet reached maturity. It has also been proposed that booster stages include a sail-like attachment to the same end.

### **External removal**

The vast majority of space debris, especially smaller debris, cannot be removed under its own power. A variety of proposals have been made to directly remove such material from orbit. One of the most widely discussed solutions is the laser broom, which uses a powerful ground-based laser to ablate the front surface off known debris and thereby produce a working mass that slows the debris in orbit. With a continued application of such thrust, the debris will eventually spiral down into a low orbit and become subject to atmospheric drag.

The US Air Force worked on a ground-based design under the name "Project Orion". Although a test-bed device was scheduled to launch on a 2003 Space Shuttle, numerous international agreements, forbidding the testing of powerful lasers in orbit, caused the program to be limited to using the laser as a measurement device. In the end, the Space Shuttle Columbia disaster led to the project being postponed and, as Nicholas Johnson, Chief Scientist and Program Manager for NASA's Orbital Debris Program Office, later noted, "There are lots of little gotchas in the Orion final report. There's a reason why it's been sitting on the shelf for more than a decade."

Another well-studied solution is to use a remotely controlled vehicle to rendezvous with debris, capture it, and return to a central station. A number of other proposals intercept the debris in a foamy ball of aerogel or even a spray of water. These would impact with the debris and slow it down. Some propose inflating balloons around the objects in order to increase their atmospheric drag. However, it was pointed out that a balloon could be punctured by other debris, thereby failing in its mission and actually increasing the amount of mass in orbit.

In any event, the cost of launching any of these solutions is about the same as launching any spacecraft. Johnson has stated that none of the existing solutions are currently cost-effective.

Star Inc. has proposed an ElectroDynamic Debris Eliminator (EDDE) vehicle which using an electrodynamic tether for propulsion and orbit transfers, can clean up LEO space debris using lightweight nets. Each vehicle is 100 kg, and packs into 24"x24"x12". They claim that 12 EDDEs can remove all 2465 cataloged LEO objects >2 kg in 7 years. On January 7, 2010 Star Inc. announced that it has won a contract from Navy/SPAWAR for a feasibility study of the application of the ElectroDynamic Debris Eliminator (EDDE).