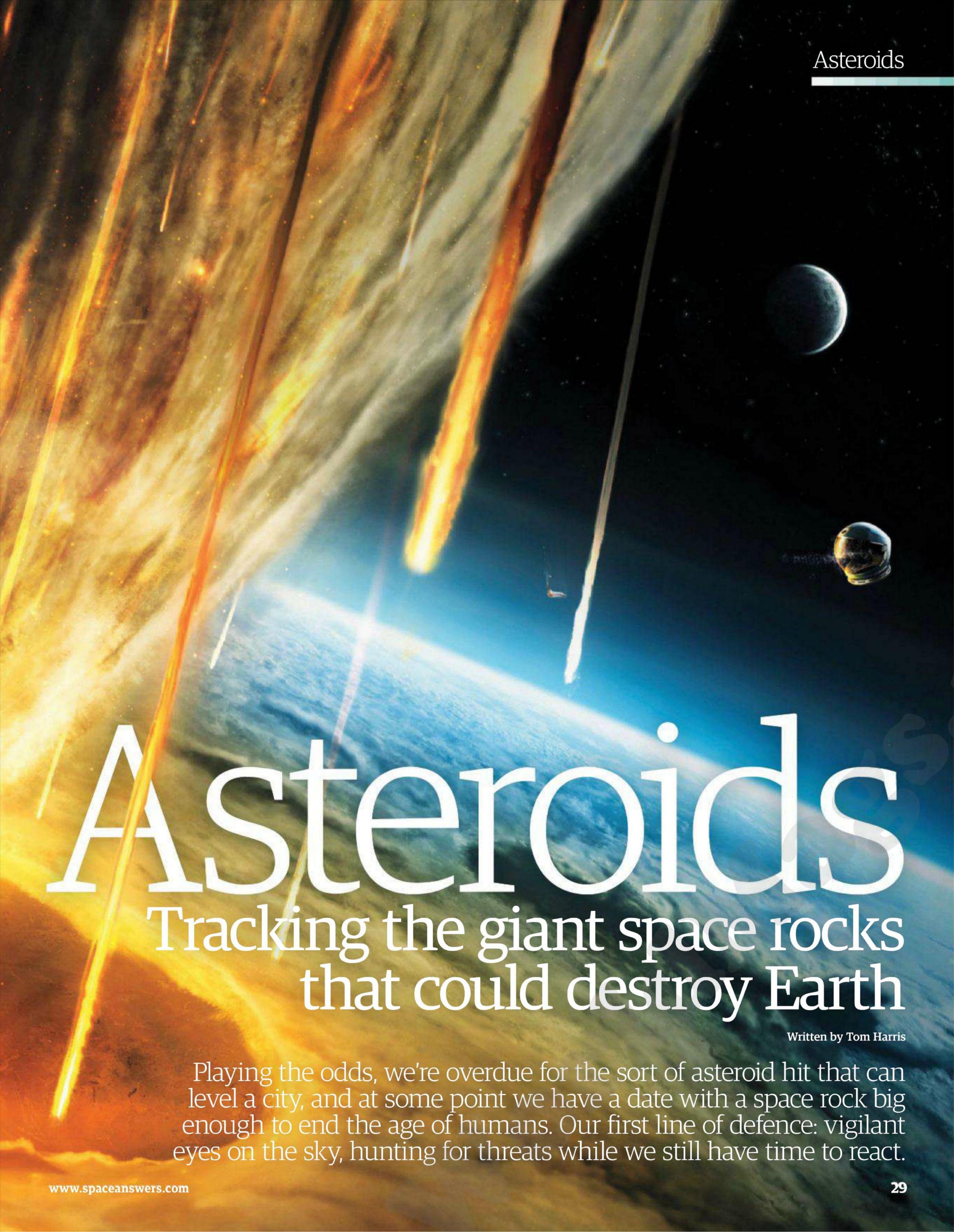


Asteroids

Tracking the giant space rocks that could destroy Earth

Written by Tom Harris

Playing the odds, we're overdue for the sort of asteroid hit that can level a city, and at some point we have a date with a space rock big enough to end the age of humans. Our first line of defence: vigilant eyes on the sky, hunting for threats while we still have time to react.

Dr Don Yeomans and his Near-Earth Object (NEO) Program are responsible for tracking the asteroids that could potentially threaten the Earth

The unsung heroes are a small team of astronomers who scour the night sky for near-Earth objects (NEOs), asteroids and comets that are headed for our neighbourhood. "There are probably a couple dozen folks who are doing this more or less on a full-time basis," explains the manager of NASA's Near-Earth Object Program Office, Dr Don Yeomans. "The vast majority of discoveries are made in the US Southwest and Hawaii, by NASA-supported telescope facilities."

The searchers have been enormously successful, cataloguing more than 9,000 NEOs - objects projected to travel within 1.3 astronomical units of the Sun (195 million kilometres, or 121 million miles). Smaller ones do still sneak up on us, though.

"That happens all the time," Yeomans says. "We had an object about the size of a small or fairly good-sized automobile that actually hit in October 2008. It was discovered about 24 hours in advance. We predicted it would impact over northern Sudan, and it did. It was observed by a KLM airline pilot and somebody with a cell phone camera on the ground. Astronomers actually went over there and looked for fragments of the asteroid and they found several."

Far from a catastrophe, the impact turned out to be an exceptional stroke of luck. "That was a scientific bonanza," Yeomans says. "They can examine these fragments in Earth-based laboratories to find out exactly what the chemical composition is, and they also had observations of this object in space, so they know its spectral characteristics. They could say, all right, this particular type of asteroid is made up of this chemical composition."

On top of identifying planetary threats ahead of time, this is a key benefit of tracking NEOs. "That's sort of the holy grail of asteroid science: to try and take the meteorites that we have in museums and have been studied to death in terms of the composition - chemical and elemental composition - and say, 'All right, this meteorite is an example of that type of asteroid in the sky.'"

There's no shortage of errant debris in the Solar System, left over from its earliest days as a massive cloud of gas and dust. Beginning about 4.6 billion years ago, much of this dust clumped together, forming larger chunks of matter. Many of these chunks, in turn, steadily formed planets and moons. But a lot never joined the big leagues. In fact, about 100 tons of the stuff shows up at Earth's door every day. Fortunately, almost all of it is sand-sized particles that burn up on contact with our atmosphere. There are plenty of bigger pieces out there, though. Most are found in a belt between Mars and Jupiter. It's home to millions of asteroids - chunks of rocky, metallic or carbon-based material. There are even more of their smaller counterparts, meteoroids. Some think Jupiter's gravitational pull has kept the debris in place, preventing it from coalescing into a planet.

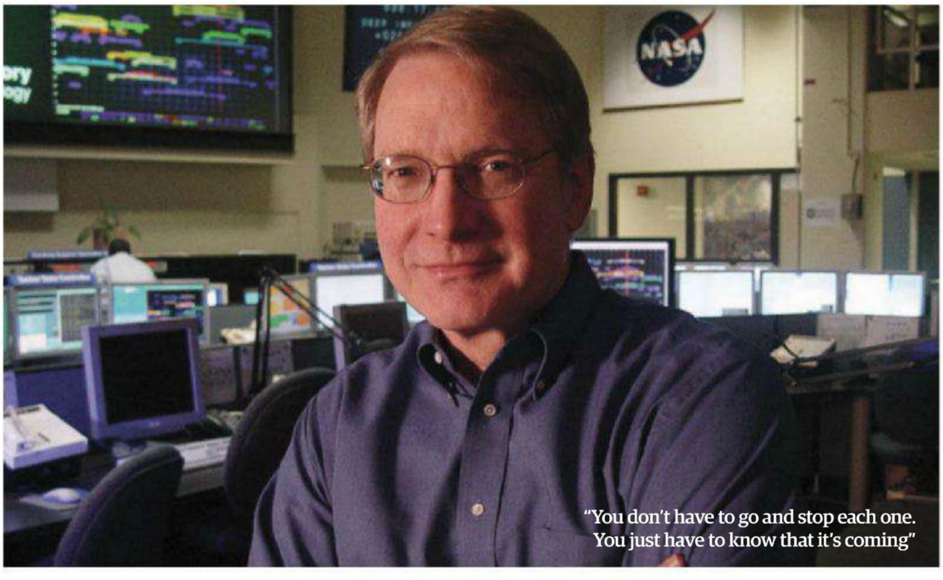
For the most part, these asteroids stay within the belt, revolving around the Sun in an orderly fashion. But now and then, a collision or a gravitational tug knocks an asteroid out of its orbit, into a path that takes it closer to the centre of the Solar System. A fraction of those end up heading our way.

Most of the asteroids that reach Earth come from the inner part of the belt, which is primarily made up of S-type asteroids, composed of silicate rock. We also encounter a good number of C-type asteroids, composed of carbon-rich material. The third variety, metallic M-type asteroids, are rare.

It's a similar story with comets, mixtures of dusty ice and rock that typically travel in the outer regions of the Solar System. The distinction between comets and asteroids is blurry, as some asteroids may contain ice, and comets may be fairly rocky. One of the chief distinctions is where you find them. Comets are concentrated in a region beyond Neptune and in a more distant comet concentration, called the Oort Cloud, about a light year from the Sun.

All told, there are potentially trillions of comets in the Solar System, though nearly all will never get anywhere near us. They stick to their wide orbits, the most distant potentially taking 30 million years for a single trip around the Sun. But, just as with asteroids, chance collisions and gravitational tugs occasionally set a comet into an orbit that takes it through the centre of the Solar System. Fortunately, comets' tails - streams of icy gaseous material vaporised by the Sun's heat - make them easier to spot. For instance, when the Hale-Bopp comet gets close to the Sun, it grows a tail spanning millions of kilometres. Comets and asteroids have played a critical role in our history

"If we detect a larger threat - the sort that could devastate a wide area or wipe out humanity - we'll need to alter its path"



"You don't have to go and stop each one. You just have to know that it's coming" as a species. In fact, we most likely owe our very existence to them, a few times over.

First, of course, our planet formed from asteroids colliding and clumping together. But beyond that, many scientists believe that comets delivered much of the water and carbon-based molecules that set the stage for the beginning of terrestrial life, 3.8 billion years ago. Flash forward to 65 million years ago, and a foreign object intervened again. A massive asteroid or comet collision brought about a rapid shift in our atmosphere that caused the extinction of about 75 per cent of life on Earth, including the dinosaurs. While it was surely no picnic for our mammalian ancestors either, the elimination of so many predators ultimately gave them a chance to thrive and evolve.

Asteroids and comets may play a critical role in our future, too, but the next hit isn't likely to be so beneficial to us. Scientists estimate the sort of impact that took out the dinosaurs – a collision with a comet or asteroid measuring ten kilometres (6.2 miles) or greater – comes along on average every 50-100 million years, but any day could be the day.

Objects measuring 30-100 metres (165-328 feet), big enough to cause substantial local damage or kick up tidal waves, hit every few hundred years or so. The last one was the Tunguska event, a massive explosion caused by an estimated 40-metre (132-foot), 80,000-ton asteroid fragment bursting over Siberia in 1908. It claimed no human casualties, but only because it happened to strike an uninhabited region. With an explosive energy about 500 times more powerful than the Hiroshima bomb, it cleared millions of trees across a 40-kilometre (25-mile) area and generated a shockwave powerful enough to shatter windows and knock people down many miles away. If it had hit a major city, the impact would have been the most devastating disaster in human history.

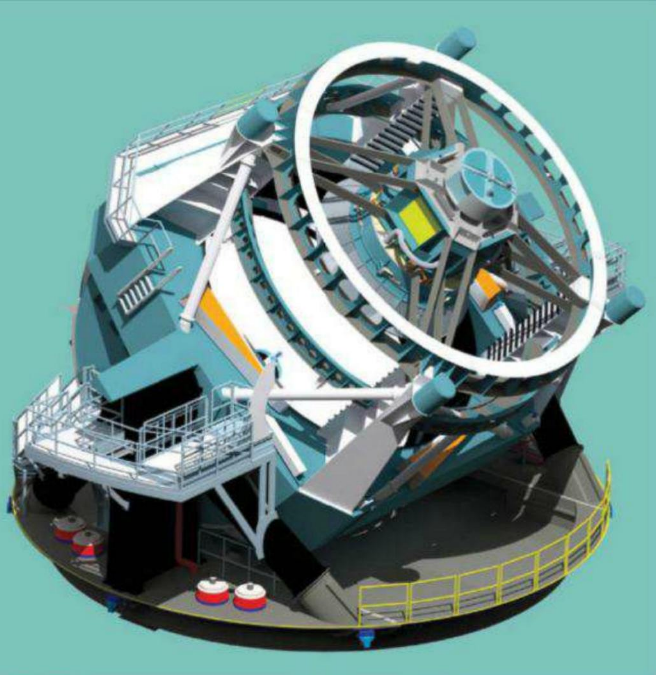
Fortunately, the odds are against such a hit. About 71 per cent of the Earth's surface is ocean, making the sea the most likely destination for an impact. On top of that, huge, uninhabited areas of land, such as Antarctica, increase our odds. Because of this, we've been blissfully unaware of most hits throughout human history. In this sense, the Tunguska event was a stroke of luck. It woke us up to the risks, spurring us to search the sky for potential dangers.

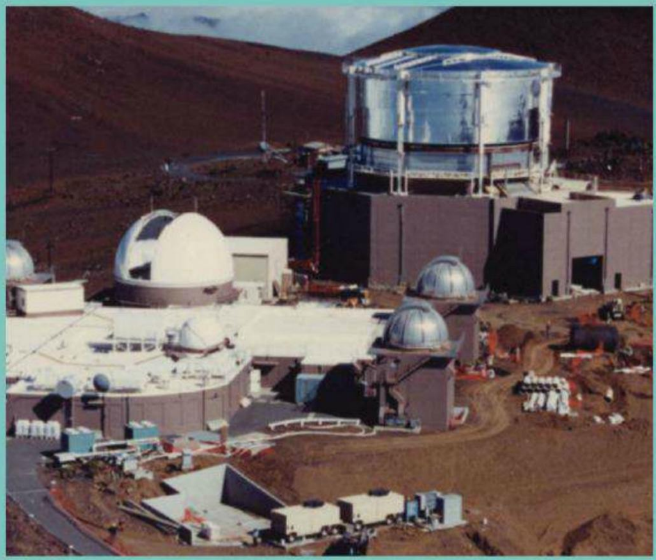
We've had other reminders since, including the first observation of a spectacular impact with a fellow planet. In 1994, the comet Shoemaker-Levy 9 collided with Jupiter, breaking up in its atmosphere into 21 fragments, some as large as two kilometres (1.25 miles) in diameter. On Earth, an impact of this calibre would have brought about global destruction.

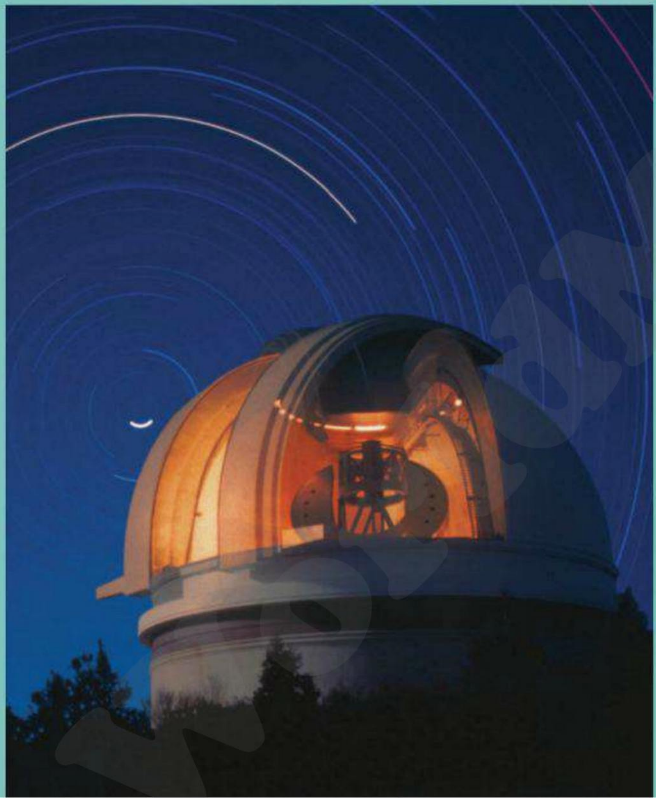
NASA's main objective is identifying and tracking potentially hazardous asteroids (PHAs), defined as objects measuring at least 100 metres (328 feet) that have the potential to get within 0.05 astronomical units (about 4.7 million miles) of Earth.

The key equipment is a powerful telescope that captures detailed images of the night sky with a charge-coupled device (CCD), the same array of light-sensitive cells at the heart of a digital camera. But, Yeomans explains, successful asteroid and comet-hunting ultimately depends on something a little more low-tech: "Persistence."

He describes a simple but painstaking process: "Basically, what they do is point their telescopes







Our eyes on the sky

The Large Synoptic Survey Telescope (LSST)

When it comes online, the 8.4-metre (27.5-foot) LSST in Chile will mark a substantial leap forward. It will combine a large aperture, a wide field of view, a 3-billion-pixel camera, and advanced data processing to monitor the night sky. It will be able to capture 800 panoramic images every night, covering the visible sky twice in a week.

Maui Space Surveillance Site (MSSS)

The MSSS is part of a US Air Force satellite-tracking and research facility on Maui, Hawaii. It sits on the crest of Haleakala, an extinct volcano. The combination of minimal light pollution and a stable climate of dry, clean air gives the location exceptional year-round visibility.

In 2000, the Jet Propulsion Laboratory began using one of the two 1.2-metre (3.9-foot) telescopes to hunt for NEOs. To optimise the telescope for this, the US Air Force and JPL configured it for a larger field of view and installed a specialised camera.

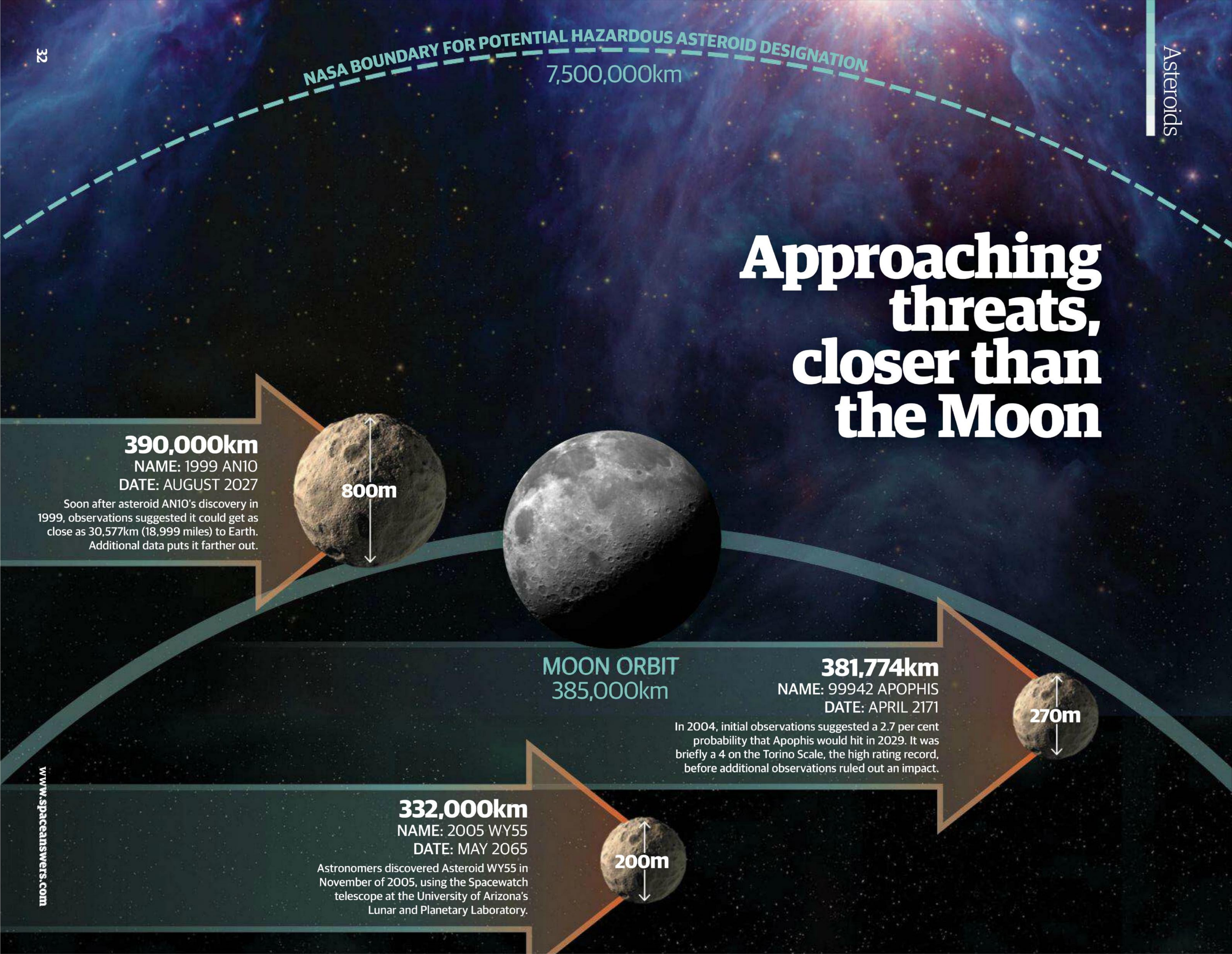
In June, the MSSS team completed a modernisation of a range of equipment.

The Palomar Observatory

As a key observatory in the NASA Jet Propulsion Laboratory's NEO search programme going back to 1973, Palomar has been the site for thousands of discoveries, including hundreds of NEOs. The observatory is located in north San Diego county, California, and is owned and operated by the California Institute of Technology, which partners with JPL, Cornell, and many other institutions on a wide range of projects.

The observatory is home to five telescopes, including the 508-centimetre (200-inch) Hale, which was the world's largest telescope when it went into operation in 1947. The telescopes have seen regular upgrades, including a camera for NEO observations, the Near-Earth Asteroid Tracker, installed in 2001.

Approaching threats, closer than the Moon



390,000km
NAME: 1999 AN10
DATE: AUGUST 2027

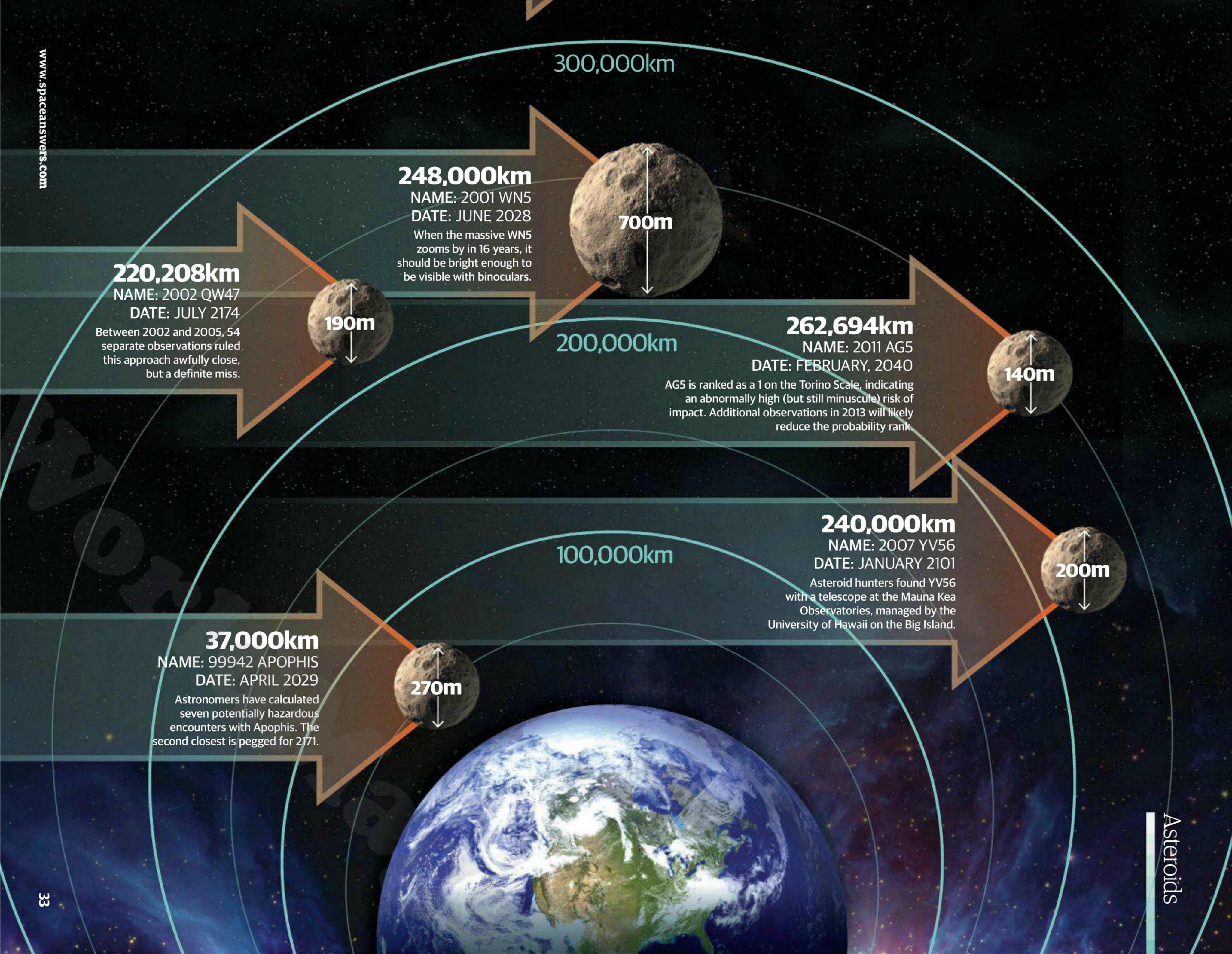
Soon after asteroid AN10's discovery in 1999, observations suggested it could get as close as 30,577km (18,999 miles) to Earth. Additional data puts it farther out.

381,774km
NAME: 99942 APOPHIS
DATE: APRIL 2171

In 2004, initial observations suggested a 2.7 per cent probability that Apophis would hit in 2029. It was briefly a 4 on the Torino Scale, the high rating record, before additional observations ruled out an impact.

332,000km
NAME: 2005 WY55
DATE: MAY 2065

Astronomers discovered Asteroid WY55 in November of 2005, using the Spacewatch telescope at the University of Arizona's Lunar and Planetary Laboratory.


300,000km
200,000km
100,000km
248,000km
NAME: 2001 WN5
DATE: JUNE 2028
When the massive WN5 zooms by in 16 years, it should be bright enough to be visible with binoculars.
700m
220,208km
NAME: 2002 QW47
DATE: JULY 2174
Between 2002 and 2005, 54 separate observations ruled this approach awfully close, but a definite miss.
190m
262,694km
NAME: 2011 AG5
DATE: FEBRUARY, 2040
AG5 is ranked as a 1 on the Torino Scale, indicating an abnormally high (but still minuscule) risk of impact. Additional observations in 2013 will likely reduce the probability rank.
140m
240,000km
NAME: 2007 YV56
DATE: JANUARY 2101
Asteroid hunters found YV56 with a telescope at the Mauna Kea Observatories, managed by the University of Hawaii on the Big Island.
200m
37,000km
NAME: 99942 APOPHIS
DATE: APRIL 2029
Astronomers have calculated seven potentially hazardous encounters with Apophis. The second closest is pegged for 2171.
270m

at a region of the dark sky and take a CCD image, come back to that same region 15 minutes later and take another image, come back to that same region 15 minutes later and take a third, or a fourth image. Then you can compare those three or four images to see if anything in the field has moved during the times that you took those images. The stars, of course, will remain stationary and will not have appeared to have moved, but any near-Earth asteroids will have appeared to move from one image to another, and the computers are good at picking up motions like that."

While it can be monotonous, computer technology has expedited the process immensely. Astronomers used to do it the hard way, examining two photographic plates under a microscope. "You would compare the images taken a few minutes apart one after the other, back and forth," Yeomans says. "The stars hadn't moved between when the two images were taken but the asteroid would have, so its image would appear to be hopping back and forth."

Today, computers make some of the discoveries themselves. Yeomans says the most successful search observatory today, the Catalina Sky Survey near Tuscon, Arizona, depends on close human-computer collaboration. "They routinely have the computer find candidates, and then a human observer looks at them to confirm that, in fact, the object that the computer picked was a near-Earth asteroid. So these computer programs, at least in this one case with the Catalina Sky Survey, don't actually completely replace humans. They simply make it easier for the humans to consider only the likely suspects."

Yeomans says the key is getting high-fidelity images of large sections of the night sky: "Ideally, you would like to have a telescope with a large aperture, so you could collect a lot of light, and you'd have a wide field of view that covers a lot of sky. I think the perfect telescope would be one that went very deep to find faint objects and then at the same time covered a lot of sky so that you could cover a fair bit of the accessible sky every night."

Asteroid hunters have had to make do with less than perfect equipment, Yeomans says. "In fact, most of the telescopes that are currently being used were not built for the express purpose of finding near-Earth objects. So, they're one-metre class aperture – that is, their mirrors are usually one metre. There are a couple that are one and a half metres, 1.8 metres. But they weren't built with near-Earth object discovery in mind, so they're not all that wide field."

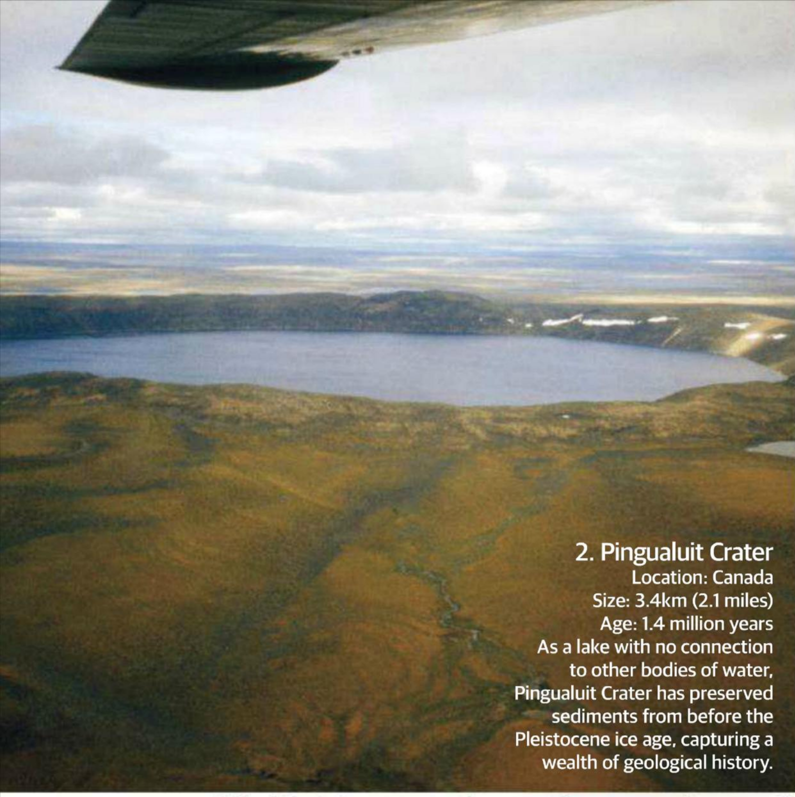
The NEO watch is getting a major upgrade with the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), a new telescope facility on top of the volcano Haleakala on the island of Maui. Designed with near-Earth object observation in mind, the system will boast 3-16 times the collecting power of other telescopes. A larger field of view will allow the system to scan the sky much more quickly, while massive CCD arrays will be able to pick up far fainter objects than other NEO survey telescopes. With 1.4 billion pixels apiece, the system's four cameras will be the largest in existence. Its prototype telescope, PS1, began regular survey operations in 2010. The finished four-telescope array will follow.

In the future, Yeomans is looking forward to the Large Synoptic Survey Telescope (LSST), a facility

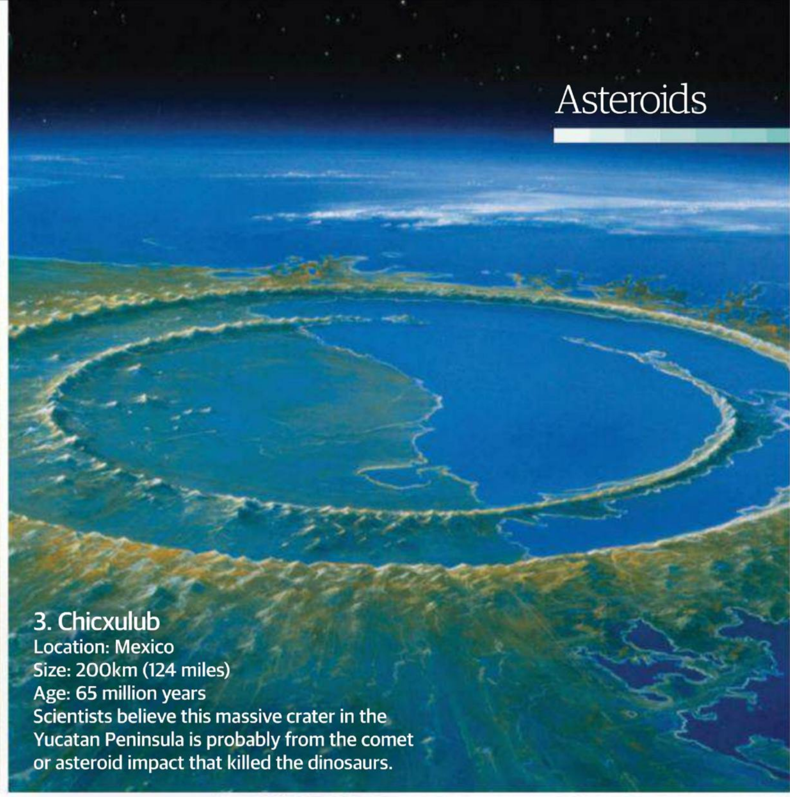
Massive Earth impacts

1. Wolfe Creek Crater
Location: Australia
Size: 1.2km (0.7 miles)
Age: 300,000 years
While the crater was long-known to the Aboriginal people, Europeans didn't discover it until 1947, while conducting an aerial survey.

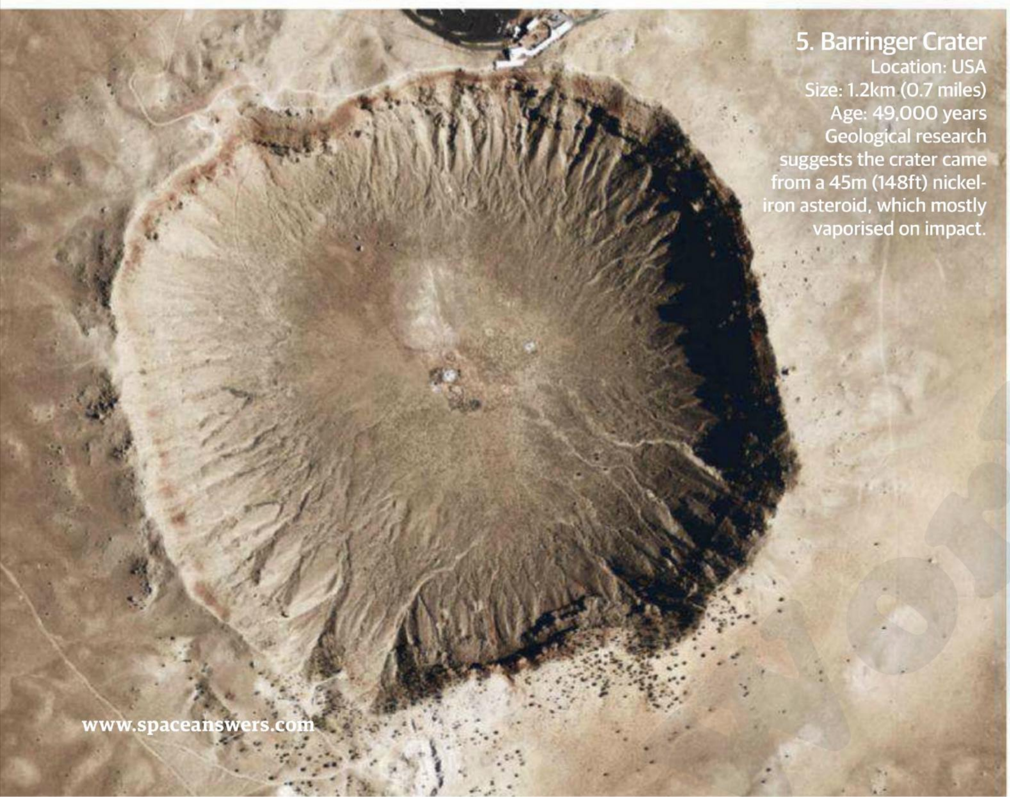
6. Aorounga Crater
Location: Chad
Size: 13km (8 miles)
Age: 350 million years
Additional circular features near the larger crater indicate a multiple impact event.



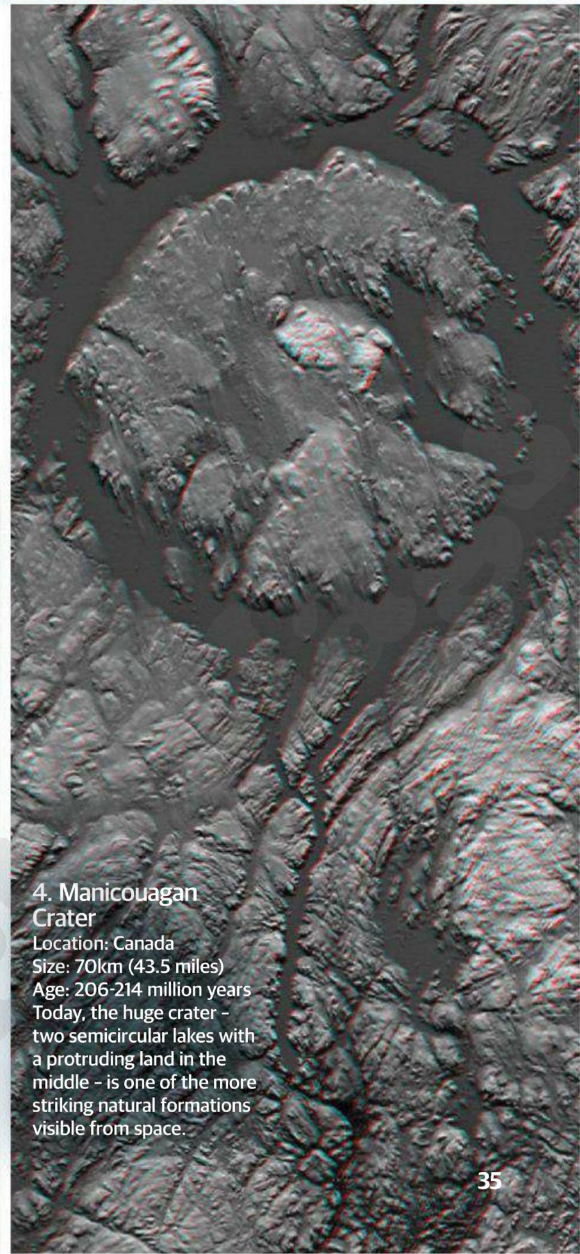
2. Pingualuit Crater
Location: Canada
Size: 3.4km (2.1 miles)
Age: 1.4 million years
As a lake with no connection to other bodies of water, Pingualuit Crater has preserved sediments from before the Pleistocene ice age, capturing a wealth of geological history.



3. Chicxulub
Location: Mexico
Size: 200km (124 miles)
Age: 65 million years
Scientists believe this massive crater in the Yucatan Peninsula is probably from the comet or asteroid impact that killed the dinosaurs.



5. Barringer Crater
Location: USA
Size: 1.2km (0.7 miles)
Age: 49,000 years
Geological research suggests the crater came from a 45m (148ft) nickel-iron asteroid, which mostly vaporised on impact.



4. Manicouagan Crater
Location: Canada
Size: 70km (43.5 miles)
Age: 206-214 million years
Today, the huge crater – two semicircular lakes with a protruding land in the middle – is one of the more striking natural formations visible from space.

in Chile that will deliver unprecedented detail when it comes online around 2020. "It's an 8.4-metre (27.5-foot) aperture, and it's extremely wide-field. So although it's not being built expressly for near-Earth objects, they simply can't avoid them."

In the effort to catalogue potential hazards, discovering a new comet or asteroid is only the beginning. To assess the possibility of Earth impact, astronomers need to figure out where each is going, which means pinpointing its position and trajectory.

Yeomans says stars provide the starting point: "Say you've got four stars in the background and you've got an asteroid in the foreground. You can measure the distance between asteroid and star 1, the distance between asteroid and star 2, the distance between asteroid and star 3 and so on. Since you know the positions of the stars you can determine the position of the asteroid when you took that image. If you have a bunch of these observations, then you know where the asteroid was – its angular position in the sky."

The key to improving accuracy, he explains, is multiple observations: "As the asteroid is observed more and more, day after day, we get more of these observations, and so the orbit gets better and better. What we do is we start with a preliminary orbit and then we project that orbit forward in time through all of the observations we have in hand, and we ask the question, 'Well, how well did that preliminary orbit match where that asteroid was observed to have been?' Then we say, 'Oh well, it wasn't a perfect fit, but we can use the differences between the observed and the predicted position of the asteroid to refine the orbit and the next time we observe it we'll know better where it is.' We can predict its motion much better in the future as we get more and more observations on which to base the orbit."

The necessary follow-up observations have a surprising source. "The majority I would say are done by amateurs, actually," Yeomans says. "They're really amateurs in name only because they're extremely sophisticated observers, most of them."

Yeomans says the hub is the Minor Planet Center in Cambridge, Massachusetts, which acts as clearing house for all data on the Solar System: "The amateurs, or the professionals for that matter, will take their data, report the time at which they observed, and the so-called right ascension and declination, which are two measurements of where that asteroid was at that given time. They will send those observations to the Minor Planet Center, and the Minor Planet Center will do a preliminary orbit and ask the observer community to follow up. Then amateurs take a look at the Minor Planet Center's follow-up list and say, 'All right, if this object has been just discovered, it needs additional observations so that the orbits can be computed more accurately.'"

> "We had an object about the size of a small or fairly good-sized automobile that actually hit in October 2008. It was discovered about 24 hours in advance"

With sufficient observations in hand, it's time to crunch the numbers. Yeomans says the Minor Planet Center sends preliminary orbit data to the Jet Propulsion Laboratory in Pasadena, California, as well as a team in Pisa, Italy: "As more and more data comes in, we in our office here and our colleagues in Pisa also, run the orbits for these objects forward 100 years and see if there's any interesting close-Earth approaches. And if there are, we also do impact probability calculations."

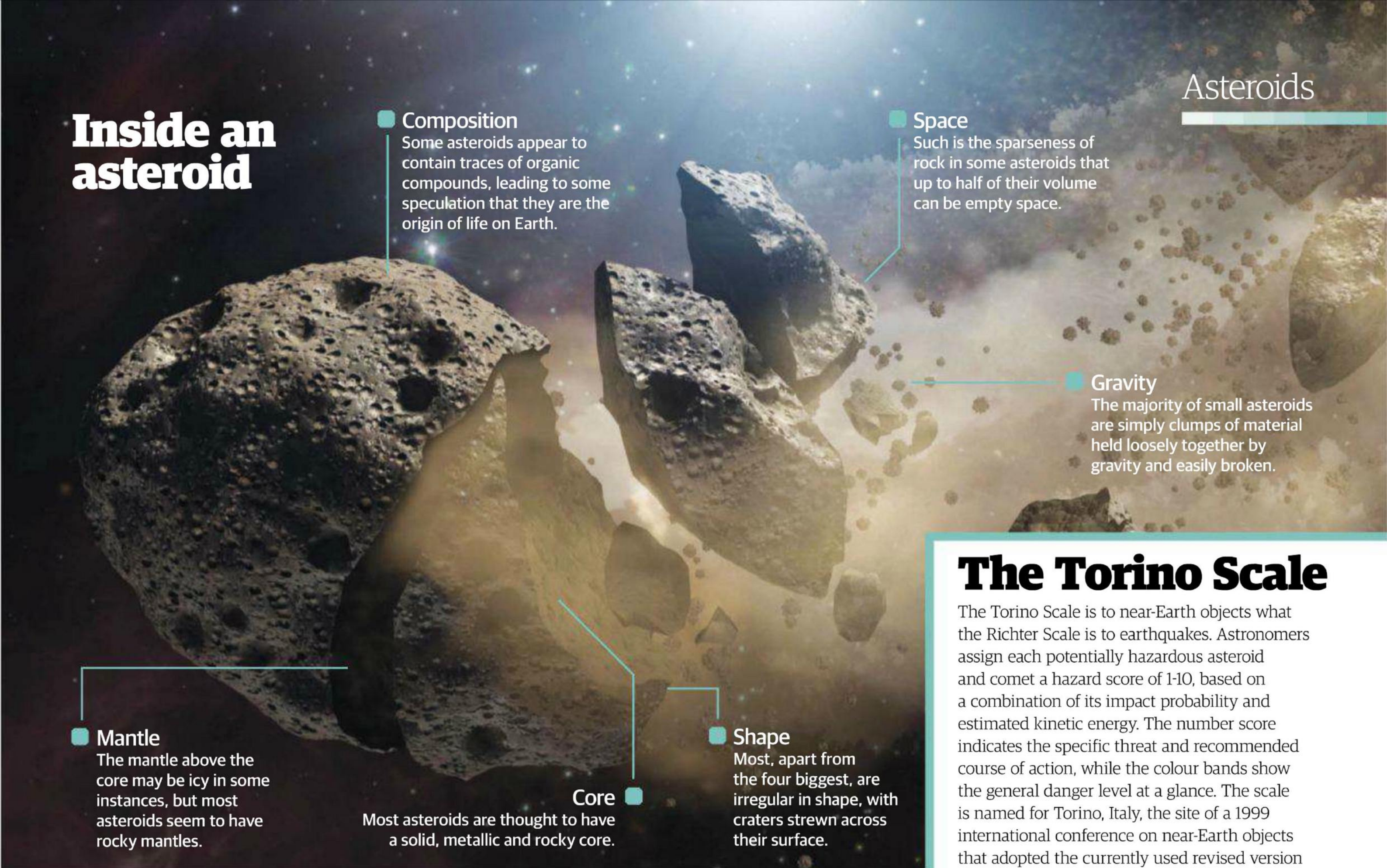
To understand the risk of impact, astronomers consider the uncertainty ellipsoid – the possible positions and orbits of the object – and then perform a Monte Carlo analysis to assess the chance of a hit.

"The Monte Carlo analysis takes every orbit in that uncertainty ellipsoid, even the ones at the edges, runs them forward 100 years, and asks will that orbit run into the Earth," Yeomans says. "Then you take another one inside the uncertainty ellipsoid at the current time and run it forward 100 years and ask will that orbit hit the Earth at any time. If a hundred out of a thousand hit, you have a ten per cent impact probability."

To date, Yeomans says, the analysis hasn't shown any objects with a high likelihood of hitting us: "Dozens of them have non-zero impact probability, but most of them are extremely small. They're 10^{-5}, 10^{-6}. There are none that reach one per cent. There are some that reach 1 in 500 or 1 in 300. That's about as high as we get at the moment."


The NEO Program hopes to locate at least 90 per cent of the asteroids and comets that approach Earth

Inside an asteroid



Yeomans says NASA's first priority has been to find the asteroids that are big enough to cause worldwide problems if they struck Earth: "Their initial goal was to find at least 90 per cent of the near-Earth asteroids that were larger than a kilometre (0.6 miles). There's about a thousand of those, and we've discovered already about 94 per cent, about 940 of them. And none of them represent a threat in the next century."

While the search for the missing six per cent goes on, the hunters have broadened their scope. "Now NASA's goal is to find 90 per cent of the objects 140 metres (459 feet) and larger, because those are the objects that cause regional damage or tsunamis should they hit," Yeomans says. "About 40 per cent of those have been found, and none of those represent a significant threat in the next hundred years."

For smaller asteroids, Yeomans reports more modest progress: "When you get down to around 30 metres [98 feet], we've found less than one per cent of the total population, because there's so many of them. For those guys, it might make sense to have a telescopic survey engineered to find them on their last approach, because you're not going to discover them until they get very close or they're about to hit."

Yeomans says, in these cases, an early warning system makes more sense than deflecting the threat. "If it's only a 30-metre [98-foot] object, it would be sufficient to find it a few days in advance of an impact because you know the line along which it will strike, and if that line went through any populated areas you could evacuate. More than likely it would hit over the ocean and not be a problem. We could do the calculation and say, 'All right, if it's going to hit the Earth, it's going to hit along this line, which could run from South America out to the Pacific Ocean to China, say.' And if any of that line goes near a population centre, we could say, 'All right, you folks would be wise to move a couple of hundred kilometres from that line.' You don't have to go and stop each one; you just have to know it's coming."

If we detect a larger threat – the sort that could devastate a wide area or wipe out humanity – we'll need to alter its path. Contrary to Hollywood predictions, blowing it up wouldn't be a good option, as it would only create more chunks to contend with.

Yeomans describes the more practical reality: "The easiest technique would simply be to run into it with a spacecraft and slow it down or speed it up so that in 20-30 years, when it was predicted to hit the Earth, it wouldn't. We would alter its trajectory just a bit, a millimetre or two a second."

NASA took this plan through a successful dry run in 2005 with its Deep Impact probe. "We purposely ran into a comet, Tempel 1," Yeomans says. "But the technology that was employed would be the same that would be used to hit an asteroid. So, we've demonstrated that it can be done. All you have to do is find it early enough that will give you enough time to get your spacecraft up there and run into it several years in advance of the projected impact because you need time for the change in velocity to build into a change in the position at the time."

Another possibility is to attach solar sails that would use the Sun's energy to nudge the object into a different orbit. Some have even proposed detonating a nuclear bomb far enough away that it doesn't break the asteroid apart, but irradiates the surface, making the asteroid recoil enough to shift its trajectory.

The elaborate schemes are conjecture at this point. "For my money, the simplest and easiest technique is the best," Yeomans says. "And simply running into it, if you have the time, is the way to go."

The Torino Scale

The Torino Scale is to near-Earth objects what the Richter Scale is to earthquakes. Astronomers assign each potentially hazardous asteroid and comet a hazard score of 1-10, based on a combination of its impact probability and estimated kinetic energy. The number score indicates the specific threat and recommended course of action, while the colour bands show the general danger level at a glance. The scale is named for Torino, Italy, the site of a 1999 international conference on near-Earth objects that adopted the currently used revised version of the scoring system.

No hazard	0	At this level the likelihood of an asteroid or comet striking Earth is effectively zero.
Normal	1	A near pass is predicted, but it poses no unusual level of danger and a hit is extremely unlikely.
Meriting attention by astronomers	2	Makes a near pass and may merit attention, but inspection will likely reduce threat.
	3	A collision has a 1 per cent or greater chance, capable of localised destruction.
	4	The threat of a collision remains one per cent, but observations will probably deem it no threat.
Threatening	5	A close encounter that could cause regional devastation. Critical attention needed.
	6	Poses a serious but uncertain threat of global catastrophe, requiring contingency planning.
	7	A close encounter that would require immediate planning if it is within a century.
Certain collisions	8	A collision with Earth is certain. Localised destruction or a tsunami will result.
	9	Unprecedented devastation, including major tsunami. Occurs every 100,000 years.
	10	May threaten the future of civilisation. Occur less than once per 100,000 years.