THE ROCK THAT FELL TO EARTH

When an asteroid was spotted heading towards our planet last October, researchers rushed to document a cosmic impact from start to finish for the first time. Roberta Kwok tells the tale.

Around midnight on 6 October 2008, a white dot flitted across the screen of Richard Kowalski's computer at an observatory atop Mount Lemmon in Arizona. Kowalski had seen hundreds of such dots during three and a half years of scanning telescope images for asteroids that might hit Earth or come close. He followed the object through the night and submitted the coordinates, as usual, to the Minor Planet Center in Cambridge, Massachusetts, which keeps track of asteroids and other small bodies. When the sky began to brighten, he shut down the telescope, went to the dorm down the mountain and fell asleep.

The only thing that had puzzled Kowalski about the midnight blip was the Minor Planet Center's response to his report. Its website posted the discovery right away but when he tried to add more data, the system stayed silent.

Tim Spahr, the Minor Planet Center's director, found out why the following morning. The centre's software computes orbits automatically, but this asteroid was unusually close to Earth. "The computer ran to me for help," says Spahr. He did some quick calculations on Kowalski's data to figure out the path of the asteroid, which was now named 2008 TC_3. "As soon as I looked at it and did an orbit manually, it was clear it was going to hit Earth," he says.

The brightness of 2008 TC_3 suggested it was only a few metres across and, assuming it was a common rocky asteroid, would probably split into fragments soon after entering the atmosphere. But safe as that might seem, Spahr had procedures to follow. He called Lindley Johnson, head of NASA's Near Earth Object Observations programme in Washington DC, on his BlackBerry — a number only to be used in emergencies.

"Hey Lindley, it's Tim," said Spahr. "Why would I be calling you?"

Johnson's response: "We're going to get hit?"

Spahr also called astronomer Steve Chesley of the Jet Propulsion Laboratory (JPL) in Pasadena, California, who at the time was hustling his kids out of the door for school. Chesley hurried into the office, ran a program to calculate the asteroid's orbit and "was astounded to see 100% impact probability", he says. "I'd never seen that before in my life." Chesley calculated that the asteroid would hit Earth's atmosphere less than 13 hours later, at 2:46 UT the next day; the impact site would be northern Sudan, where the local time would be 5:46 a.m.. He sent his results to NASA headquarters and the Minor Planet Center, which circulated an electronic bulletin to a worldwide network of astronomers. A group called NEODys in Pisa, Italy, also confirmed that an impact was nearly certain.

Although several small objects such as 2008 TC_3 hit Earth each year, researchers had never spotted one before it struck. Kowalski's discovery, therefore, provided a unique chance to study an asteroid and its demise in real time, if astronomers could mobilize resources around the world quickly enough.

Soon e-mails and phone calls were flying across the globe as scientists raced to coordinate observations of the incoming asteroid. "IMPACT TONIGHT!!!" wrote physicist Mark Boslough of Sandia National Laboratories in Albuquerque, New Mexico, to colleagues, including a Sandia engineer responsible for monitoring US government satellite data.

"Listen guys, this is happening, this is going to happen tonight." — Alan Fitzsimmons

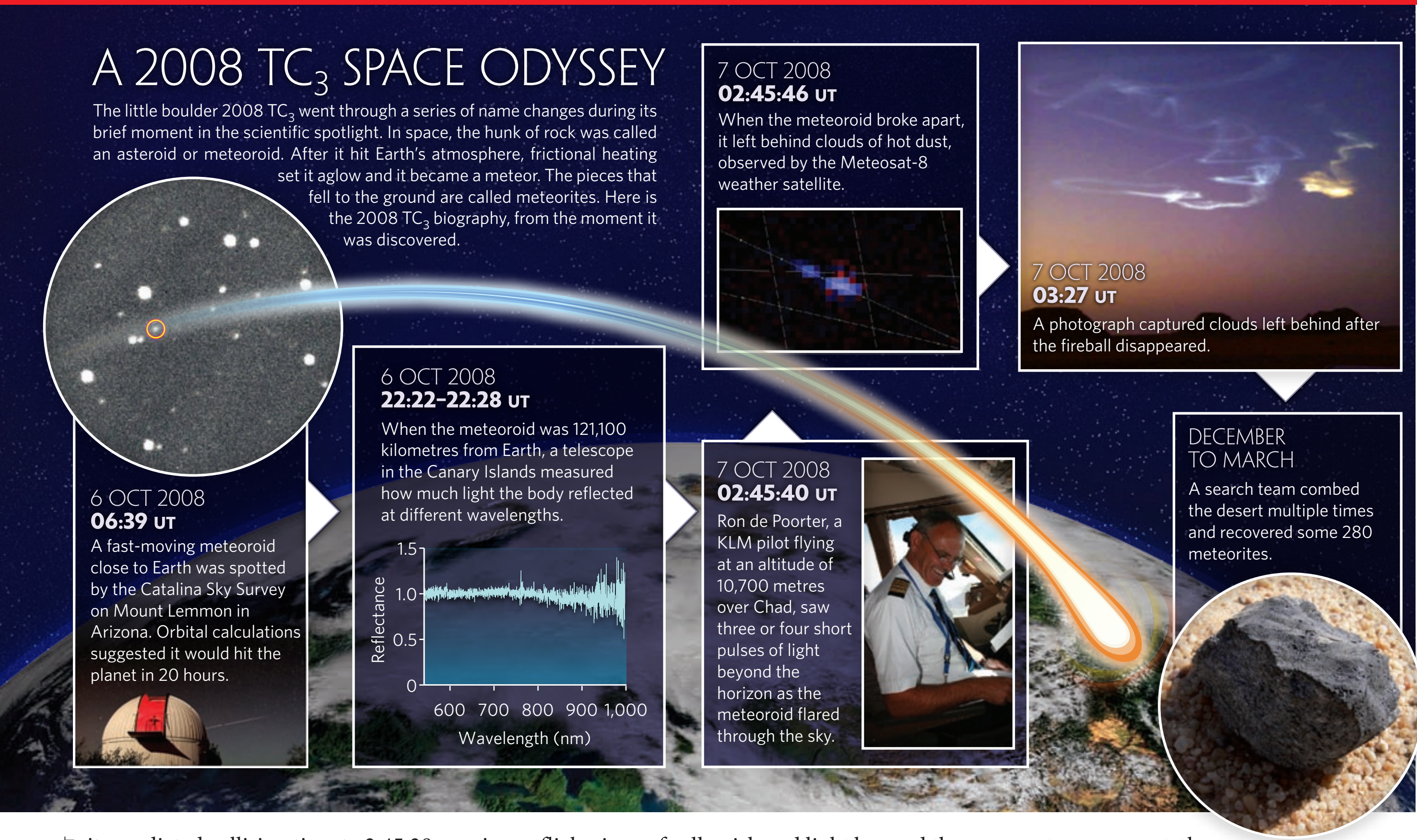
Countdown to impact

Peter Brown, an astronomer at the University of Western Ontario in Canada who heard the news from JPL, ran to his local observatory, fired up the telescope and began tracking the asteroid, which looked like "a very small, faint, fast-moving streak", he says. Alan Fitzsimmons at Queen's University Belfast in Northern Ireland called two of his colleagues, who had just arrived at the William Herschel Telescope at La Palma on the Canary Islands and were not scheduled to use the telescope until the next day.

"Listen guys, this is happening, this is going to happen tonight," he told the researchers, who arranged to borrow an hour of observing time from another astronomer.

All day, observations poured into the Minor Planet Center, which released new data and orbit calculations several times an hour. NASA notified other government agencies, including the state and defence departments, and issued a press release that afternoon saying that the collision could set off "a potentially brilliant natural fireworks display". About an hour before impact, the asteroid slipped into Earth's shadow and out of view to optical telescopes. By then, astronomers from 26 observatories worldwide had already captured and submitted about 570 observations, allowing JPL to refine

P. JENNISKENS



NASA/UNIV. ARIZONA; FULL MOON PHOTOGRAPHY; A. FITZSIMMONS, QUEEN'S UNIV. BELFAST

R. DE POORTER; EUMETSAT & CHMI (Z. CHARVAT); COURTESY OF M. E. ABDELATIF MAHIR/M. H. SHADDAD/P. JENNISKENS; P. JENNISKENS

its predicted collision time to 2:45:28 UT, give or take 15 seconds.

As the countdown progressed, Jacob Kuiper fretted. Kuiper, an aviation meteorologist on the night shift at the Royal Netherlands Meteorological Institute in De Bilt, had seen an e-mail about the incoming asteroid. And he was worried that no one would see the explosion in the sparsely populated Nubian Desert.

With less than 45 minutes left, Kuiper realized he could notify Air France-KLM — the airline to which he routinely issued weather reports — which probably had planes flying over Africa. About ten minutes later, pilot Ron de Poorter received a message print-out in the cockpit of KLM flight 592, flying north from Johannesburg to Amsterdam. The message gave the latitude and longitude of the predicted asteroid impact. De Poorter calculated that he would be a distant 1,400 kilometres from the collision. Still, at the appointed time he and his co-pilot dimmed the instrument lights and peered northeast.

Far above the plane, asteroid 2008 TC_3 hit the top of the atmosphere at about 12,400 metres per second. The collision heated and vaporized the outside of the rock, ripping material from its surface. The impact of rock atoms with air molecules created a brilliant flash that lit the desert below. Less than 20 seconds after 2008 TC_3 entered the atmosphere, calculations suggest, pressure on the rock triggered a series of explosions that shattered it, leaving a trail of hot dust.

From the cockpit of his plane, de Poorter saw flickerings of yellowish-red light beyond the horizon, like distant gunfire. The flash woke a station manager at a railway outpost in Sudan. In a village near the Egyptian border, people returning from morning prayers saw a fireball that brightened and flared out, according to accounts collected later by researchers.

Electronic eyes watched, too. US government satellites spotted the rock when it was 65 kilometres above the ground. Moments later, it was picked up by a European weather satellite, which caught two dust clouds and light from the fireball. An array of microbarometers in Kenya normally used to monitor for nuclear explosions detected low-frequency sound waves from the blast, which Brown later calculated would be equivalent to about 1–2 kilotonnes of TNT, roughly one-tenth the size of the atomic bomb dropped on Hiroshima.

> **"We have never had such concrete affirmation all the machinery works."**
> — Steve Chesley

Tracking of the fireball's trajectory by US satellites showed that JPL accurately predicted the object's location within a few kilometres and a few seconds. "We have never had such a concrete affirmation that all the machinery works," says Chesley.

But for Peter Jenniskens, an astronomer at the SETI Institute in Mountain View, California, the spectacular light show was not enough. For weeks after the asteroid hit, Jenniskens, who studies meteor showers, waited to hear whether someone had found the fallen meteorites. No news emerged. "Somebody needed to do something," he says.

Jenniskens flew to Sudan in early December and met with Muawia Hamid Shaddad, an astronomer at the University of Khartoum who had already obtained pictures of the fireball's trail from locals. Together, they drove north from Khartoum to the border town of Wadi Halfa, asking villagers where the fireball had exploded in the sky. These eyewitness accounts convinced Jenniskens that the rock had disintegrated high in the atmosphere — in good agreement with US satellite data — and that any fragments were most likely to be found southwest of Station 6, a tiny railroad outpost in the Nubian Desert.

Desert search

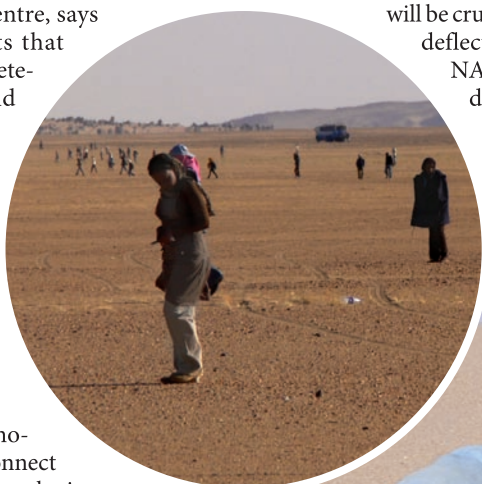
On 6 December 2008, Jenniskens and Shaddad set out with a group of 45 students and staff from the University of Khartoum to scour the area. Team members lined up about 20 metres apart over a kilometre-wide strip, facing a sea of sand and gravel interspersed with hills, rocky outcrops and dry winding riverbeds. Flanked by two pairs of cars and trailed by a camera crew from news network Al Jazeera, the line of searchers began marching slowly east, like the teeth of a massive comb being dragged through the desert.

Towards the end of the day, a car approached Jenniskens with news that a student might have found a meteorite. "I remember thinking, 'oh no, not again,'" says Jenniskens, who had already fielded several false alarms. Still, he jumped in the car and drove to the student, who presented him with a small square fragment, about a centimetre and a half across with a thin, glassy outer layer. The surface resembled the crust that meteorites form after being melted and solidified, and the rock's deep black colour suggested it was freshly fallen. It was the team's first meteorite — and the first time that scientists had ever recovered a meteorite from an asteroid detected in space (see page 485).

The next day, the team walked 8 kilometres and found 5 meteorites, all very dark and rounded. On the third day, a trek of 18 kilometres yielded larger meteorites nearly 10 centimetres across. A few weeks later, a team of 72 students and staff found 32 more, and the most recent field campaign, completed in March, brought the tally to about 280 fragments weighing a total of several kilograms.

Jenniskens couriered a sample to Mike Zolensky, a cosmic mineralogist at the NASA Johnson Space Center in Houston, Texas. Examining the rock, Zolensky discovered that it contained large chunks of carbon and glassy mineral grains resembling sugar crystals. Tests at other labs confirmed that the sample was a ureilite, a type of meteorite thought to come from asteroids that have melted during their time in space. Only 0.5% of objects that hit Earth yield fragments in this category. But 2008 TC_3's pieces are strange even for ureilites: they are riddled with an unusually large number of holes, says Zolensky. "It boggles the mind that something that porous could survive as a solid object," he says.

The findings suggest that 2008 TC_3 broke from the surface of a larger asteroid, as the pores would have been crushed if they were near the rock's centre, says Zolensky. He suggests that future studies of the meteorites' chemistry could help reveal the history of its parent asteroid. Moreover, the new finds might eventually yield clues to how planets form, he says, because the asteroid had melted during its history, a process that young planets go through.



2008 TC_3 gave astronomers a rare chance to connect a dot in the sky with rocks in their hands. "We have a lot of meteorites on the ground and a whole lot of asteroids up there, and forging a link is not easy," says Don Yeomans, manager of NASA's Near-Earth Object Program Office at JPL.

Jenniskens and his team concluded the asteroid belonged to a group called F-class asteroids. These asteroids reflect very little light, and scientists had been unsure what they were made of. The new evidence "opens a huge window", says Glenn MacPherson, a meteorite curator at the Smithsonian Institution in Washington DC, who was not involved in the studies of 2008 TC_3. Although not all F-class asteroids may be the same, he says, the data suggest at least some of them may contain the same material as ureilites, such as carbon and iron.

Clark Chapman, a planetary scientist at the Southwest Research Institute in Boulder, Colorado, says the connection between F-class asteroids and ureilites does not surprise him. But, he adds, "this is a proven link and we don't have many of those".

"It's like finding a man in a dark grey suit 50% farther away than the Moon" — Richard Kowalski

Scientists have tried to figure out the composition of asteroids by studying how they reflect various wavelengths of light and matching these features to meteorite samples in the lab. But such connections are often tenuous unless the reflection signature is very distinct. The most secure example is an asteroid called 4 Vesta, which has been associated with a group of igneous meteorites. No missions have yet returned asteroid fragments to Earth, although a NASA spacecraft orbited the asteroid Eros for a year and landed on it in 2001. Japan's Hayabusa mission attempted to collect a sample from the asteroid Itokawa in 2005; scientists will find out whether it succeeded when the spacecraft returns next year.

Knowing what asteroids are made of will be crucial if we ever need to deflect one, says Yeomans. NASA aims to provide decades of warning if any killer asteroids are headed for Earth so that a strategy can be devised to avoid a collision. That strategy will differ for various asteroids, which can range from "wimpy ex-cometary fluffballs", to solid rock, to slabs of nickel-iron, says Yeomans.

With the advent of new surveys, scientists could spot objects hurtling towards Earth more frequently. Today's surveys have found almost 90% of near-Earth objects with a diameter of 1 kilometre or larger, says Yeomans, but smaller rocks can easily slip by unnoticed. Discovering 2008 TC_3 was like finding "a man in a dark grey suit 50% farther away than the Moon", says Kowalski, who is part of the Catalina Sky Survey, an effort that discovers 70% of all the near-Earth objects found every year. The detection rate will increase with the next generation of surveys, perhaps up to a few Earth-bound asteroids per year, says Alan Harris, a planetary astronomer at the Space Science Institute who is based in La Canada, California. The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) in Hawaii will officially begin observations with its prototype system this year, and the Large Synoptic Survey Telescope in Chile is scheduled to begin full operations in 2016.

In the meantime, Kowalski and his colleagues are still on the job. The night after spotting asteroid 2008 TC_3, Kowalski headed back up Mount Lemmon, heated his dinner and settled down in the telescope's control room. As his discovery plunged towards the desert on the other side of the world, Kowalski was surveying another part of the sky, waiting for the next white dot. ■

Roberta Kwok is a news intern in *Nature*'s Washington DC office.

P. JENNISKENS

Peter Jenniskens (above) led the search for meteorite fragments in the Sudan desert (inset).