STAR TRACKER

As an early adopter of astronomical technology, Andrea Ghez is revealing secrets about the giant black hole at the Galaxy's centre.

BY ANN FINKBEINER

The technology was a complete joy, says Andrea Ghez, thinking back to the mid-1980s and her first time helping out at an observatory. She wanted to learn everything. "How to open the dome! How to fill the instrument with liquid nitrogen! Develop the plates! Reduce the data! Coding!"

And then there was the science. Ghez did not know much at the start; she was majoring in physics at the Massachusetts Institute of Technology (MIT) in Cambridge, working for an astronomer as her undergraduate research experience. But as she learned more about his research into unusual cosmic sources of X-rays, Ghez became enthralled by the thought that some of those sources might be black holes — singular points with a gravitational pull so strong that not even light can escape them. "It got me completely fascinated by black holes," she says. By the time she had spent two undergraduate summers working at telescopes in Arizona and Chile, Ghez was hooked. "I fell in love with the whole profession."

Now an astronomer at the University of California, Los Angeles, she still feels the same. Her fascination with black holes has led her into a pioneering, decades-long study that has proved the existence of the biggest black hole in our cosmic neighbourhood: the 4.1-million-solar-mass behemoth that lies at the centre of the Milky Way[1,2] (see 'The monster in the middle'). This work earned her a MacArthur 'genius' award in 2008, and half of the Crafoord prize, astronomy's Nobel, in 2012.

Ghez's love of technology helps to explain why her quest has been so fruitful. Most astronomers use only the tools they know, but Ghez is an enthusiastic early adopter — first in line to try out cutting-edge detectors and optical techniques that are barely out of the laboratory. "I like the risk of a new technology," she says. Maybe it won't work. But maybe it will open a fresh window on the Universe, answering "questions you didn't even know to ask", she says. "Any time you look, you're astounded!"

Reinhard Genzel, a director of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany — the co-winner of the 2012 Crafoord prize and Ghez's sharpest competitor on the Galactic Centre work — puts it very simply. "Andrea," he says, "is one of a rare adventurous class."

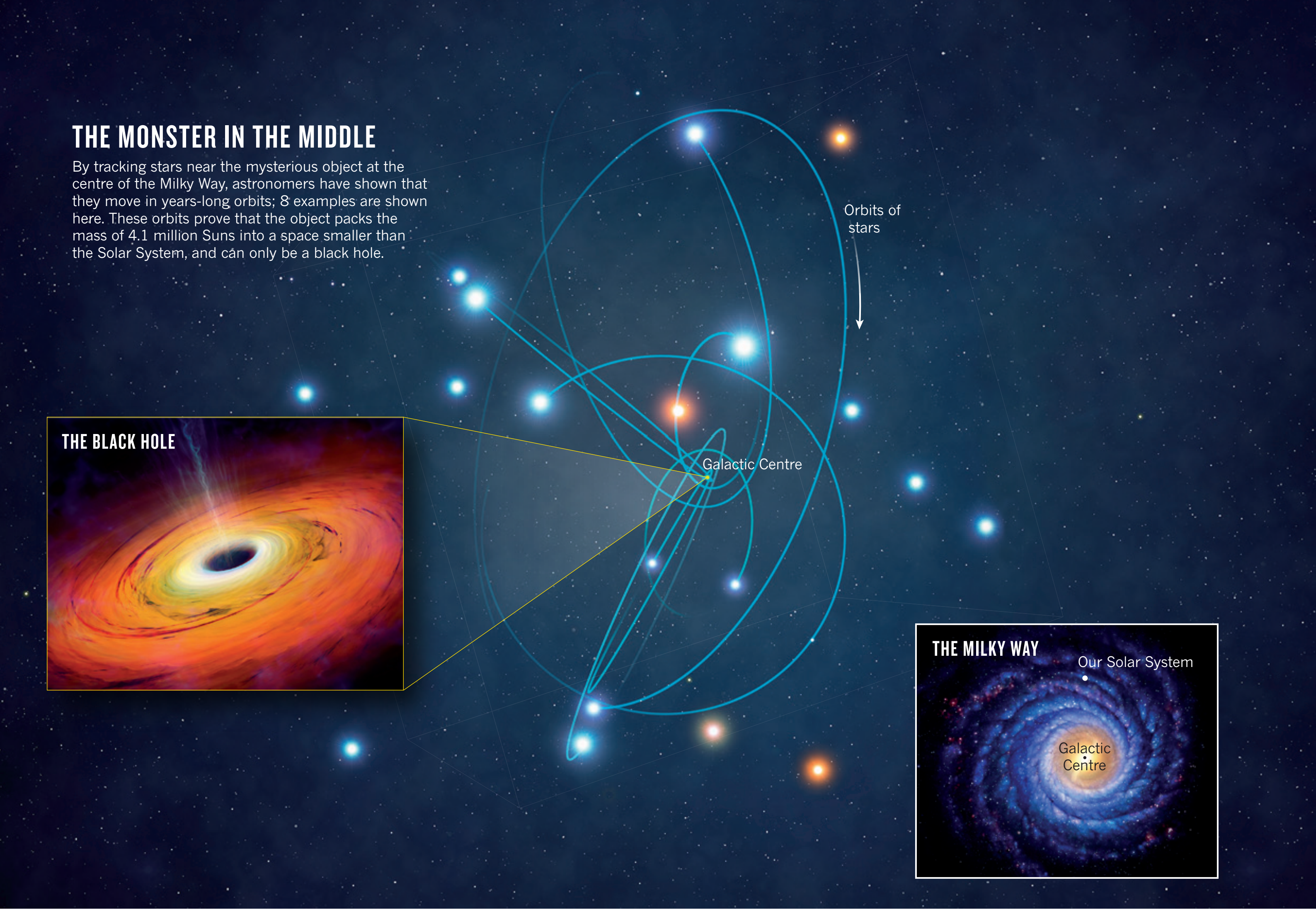
DEEP FOCUS

Ghez's devotion to her work would make her seem fierce — if she weren't always smiling, and her sentences didn't keep exploding into verbal capitals. As it is, with her barely controlled curls, straight-across eyebrows and direct gaze, she conveys a cheerful intensity. She doesn't digress when she talks; she focuses. And she has always had a certain determination.

According to Ghez family legend, when 4-year-old Andrea watched the first Apollo Moon landing with her parents in Chicago, Illinois, on 20 July 1969, she announced that she, too, was going to the Moon as an astronaut. True, she also wanted to be a ballerina. But while attending the progressive University of Chicago Laboratory Schools, she says, she became "really clear" that she loved mathematics and science. That passion took her to MIT in 1983 and then, after her epiphany in the observatory domes, to the California Institute of Technology (Caltech) in Pasadena for graduate studies in astronomy.

Caltech, Ghez explains, "had the best toys by far". Among them was the 5-metre Hale Telescope, then one of the world's largest, on California's Palomar Mountain. But the toy that particularly captured Ghez's interest was an experimental speckle imager, an instrument intended to get around astronomers' eternal problem with air. Earth's atmosphere is transparent but turbulent — a collection of bubbling 'cells' that are warmer here, cooler there, and constantly moving. Looking at the sky through all that is like looking at pebbles on the bottom of a rippling stream: the light coming into the telescope

➲ NATURE.COM
Read more about the Milky Way at:
go.nature.com/uoot1n



MARK GARLICK

flickers, dances and fragments, smearing the point-like image of each star into a fuzzy ball.

Speckle imaging freezes the dancing images in place with a camera that captures very short exposures every few milliseconds, taking maybe 10,000 or more shots in total. The result is a sequence of very faint images in which the distorted light from each star produces a scattering of spots: the speckles. Computer processing recombines the speckles into one spot per star. Then all the exposures can be aligned and stacked to produce a final image with the worst of the atmospheric smearing removed.

> "That's the evidence for a black hole. There are no alternatives we know of."

At the time, speckle imaging was well established but done mostly at optical wavelengths and used infrequently, because it was so computationally intensive. Ghez joined a Caltech group that was developing a speckle imager capable of working at infrared wavelengths emitted from interstellar-dust-shrouded objects such as active galaxies: spirals and ellipticals that had dusty but exceptionally bright regions at their centres. The thinking was that both the dust and the light emissions came from vast quantities of stars and gas spiralling into black holes millions or billions of times the mass of the Sun. Ghez was given the job of helping to write image-analysis software to give the speckle-imaging device the highest possible resolution. "Oh, this sounds great," she says, remembering her reaction. "Black holes. Technique. I'm good."

In the end, however, the imager couldn't quite see the nuclei of active galaxies. So for her PhD dissertation, Ghez turned to brighter targets: newborn stars in our Galaxy. Astronomers knew in broad terms that stars are born in thick, interstellar gas clouds, when gravity pulls the gas into hot, dense knots that ignite with thermonuclear fusion. But they didn't understand why a substantial fraction of the stars in the Sun's neighbourhood are binaries: pairs of stars that orbit one another, often at close range. Were binaries born that way? Or did they somehow pair up later in life? Theory was not much help; the available star-formation models focused on single stars such as the Sun.

Ghez wanted to resolve the issue with data: do binary stars form as binaries, yes or no? (She had developed a taste for questions that could be answered crisply. "If you ask mushy questions," she says, "you usually get mushy answers.") Beginning in 1990, Ghez used her speckle-imaging techniques in two known star-forming regions to survey T Tauri objects — Sun-like stars just beginning their lives. With the higher resolution, she could see that many of the infant stars were indeed binaries, too young and too close together for the companions to have formed separately and then coalesced[3]. Ghez's finding continues to have implications for issues such as the search for extrasolar planets, because the complex gravitational fields in a binary system are thought to make it difficult for planets to form in the vicinity.

Ghez focused on this topic exclusively until 1994, when she was hired at the University of California, Los Angeles, and gained access to a 10-metre instrument opened only a few years before at the Keck Observatory on Mauna Kea in Hawaii, and jointly owned by Caltech and the University of California. The biggest of a new generation of very big telescopes, Keck was ideal for catching the light of faint objects. But like all telescopes on the ground, its resolution was limited to what the atmosphere allowed. So Ghez applied her expertise in speckle imaging, realizing that its high resolution, combined with the telescope's prodigious light-gathering power, would finally let her look at black holes.

Astronomers had long suspected that a supermassive black hole lay at the centre of every galaxy; active galaxies were the ones that just happened to have above-average quantities of matter feeding the black hole. If that

Andrea Ghez wants to find out what lies at the heart of our Galaxy.

KYLE ALEXANDER

was true, a giant black hole ought to lie at the centre of the Milky Way. That region is difficult to observe from Earth because there is a lot of interstellar gas and dust in the way and only certain wavelengths of radiation can make it through. But observations in γ-rays, X-rays and radio and infrared emissions were consistent with the presence of gas moving at high velocities, and stars crowding together in high numbers. They had to be orbiting something massive and hard to see.

But what? To remove any doubt about the nature of the central object, observers would have to show that it was too small to be anything but a black hole. (The fundamental equations of gravity guarantee that, for a given mass, a black hole is smaller than any possible system made of ordinary matter.)

Ghez and her team decided to tackle the problem with a straightforward but tedious strategy: track stars for years and decades as they orbit the central object. The radius and period of each orbit would give the central object's mass, and the distance of closest approach would put an upper limit on its size. The astronomers started in 1995 by mapping the positions of stars in a dense cluster near the suspected location of the black hole. Every year or so, they mapped the positions again.

"With two points you draw a line and get the velocity," says Ghez. "With three points, you actually believe your line." And then you keep going. "You wait long enough, keep taking pictures" and you should be able to start tracing out the curves of the stars' orbits. By 1999, Ghez and her colleagues had done exactly that with three stars[4].

SEEING THE LIGHT

These observations showed the orbit in only two dimensions, projected onto the plane of the sky. Getting the full orbit required the third dimension, the star's motion towards and away from Earth, which meant measuring the spectrum of the light it emitted and watching how its velocity shifted the wavelength of the spectral lines — measurements that required more light than speckle imaging could supply. Ghez, however, was already working with astronomers developing a more advanced technology called adaptive optics. The idea was to take the light gathered by the telescope and bounce it off a flexible mirror that could be continuously deformed to counteract distortions caused by the atmosphere. The technique wasted much less light than speckle imaging did, so it promised higher resolution and the ability to capture the spectra of fainter objects. Ghez was doing proof-of concept observations, and was "right there and ready to snatch it up the minute it was ready to go", she says.

In June 2002, Ghez and her team used adaptive optics to observe one of their three stars, called S0-2, and found that by adding in older speckle data they could map its complete orbit[1]. The orbit took 16 years, implied a central mass of 4.1 million Suns and showed that the star's closest approach to that mass was less than twice the distance from Pluto to the Sun — meaning that the central object was no larger than the Solar System. With that much mass in that small a space, says Ghez, "that's the evidence for a black hole. There are no alternatives that we know of."

That result was satisfying but not unexpected. Much more surprising was that S0-2's spectrum showed it to be less than 10 million years old. No star orbiting close to a black hole should be that young, because the black hole's tidal forces would shred any cloud of gas and dust before it could form. There was no good explanation for why the young stars are there, says Thomas Prince, an astronomer at Caltech and Ghez's first adviser, "and there still is not".

In subsequent years, as adaptive optics improved, Ghez and her team measured the velocities of thousands of stars in the Galactic Centre, and estimated the orbits of about two dozen; the latest is a star named S0-102, which has the shortest orbit yet at 11.5 years (ref. 2). Most of them also proved to be equally young and enigmatic. "It's beautiful work really," says Rosemary Wyse, an astronomer at Johns Hopkins University in Baltimore, Maryland, who studies the Milky Way. "It's one of those painstakingly technical tours de force that produces good science results."

Only one other team in the world is doing this type of work: Genzel's. Both groups have access to large telescopes and sophisticated adaptive-optics systems, and the word is that competition is fierce — which neither Ghez nor Genzel denies, although they try to play it down. Perhaps more important is that they agree on the same measurements on the same stars, differing mainly in interpretations.

The latest example concerns an object that might help to show how a black hole destroys its prey. Both Ghez and Genzel agree that it is hot, red and heading straight towards the Galactic Centre. Genzel says that it is a cloud of gas with the mass of three Earths, that it will be torn to smithereens by the black hole and that in the process it will radiate X-rays fiercely[5]. Ghez maintains that it is hard to say what the object is; it could equally be a star moving through gas, in which case the black hole is unlikely to disrupt it. Genzel says that the object's closest approach to the black hole will be this autumn; Ghez says maybe later and in any case the timing is uncertain. Avi Loeb, an astronomer at Harvard University in Cambridge, Massachusetts, agrees with both Ghez and Genzel that this kind of competition over difficult, expensive observations makes the resulting astronomy more credible. "Overall," he says, "it's good for science."

Ghez is already looking to the next technologies she can adopt. She is on the scientific advisory committee of the Thirty Meter Telescope, which is due to start observations from Mauna Kea towards the end of the decade and will gather roughly ten times more light than Keck. She is also advising the developers of a version of adaptive optics that promises even higher resolutions than are currently available.

"I'm positioning myself," says Ghez. "I want to know how to use these systems, I want to know how to use the data, I want this all to work." Like other great scientists, says Thomas Soifer, an astronomer at Caltech and another of her early advisers, "she has this single-minded attitude of, 'I'm going to beat this problem into submission'".

Ghez is 47 years old and the stars that she has been tracking since 1995 have orbits ranging from tens to hundreds of years. How long does she plan on living? "I don't know," says Ghez. "I figure the more fun I have, the longer I'll live." ■

Ann Finkbeiner *is a freelance writer in Baltimore, Maryland.*

1. Ghez, A. M. *et al. Astrophys. J.* **586,** L127–L131 (2003).
2. Meyer, L. *et al. Science* **338,** 84–87 (2012).
3. Ghez, A. M., Neugebauer, G. & Matthews, K. *Astron. J.* **106,** 2005–2023 (1993).
4. Ghez, A. M., Morris, M., Becklin, E. E., Tanner, A. & Kremenek, T. *Nature* **407,** 349–351 (2000).
5. Gillessen, S. *et al. Nature.* **481,** 51–54 (2012).