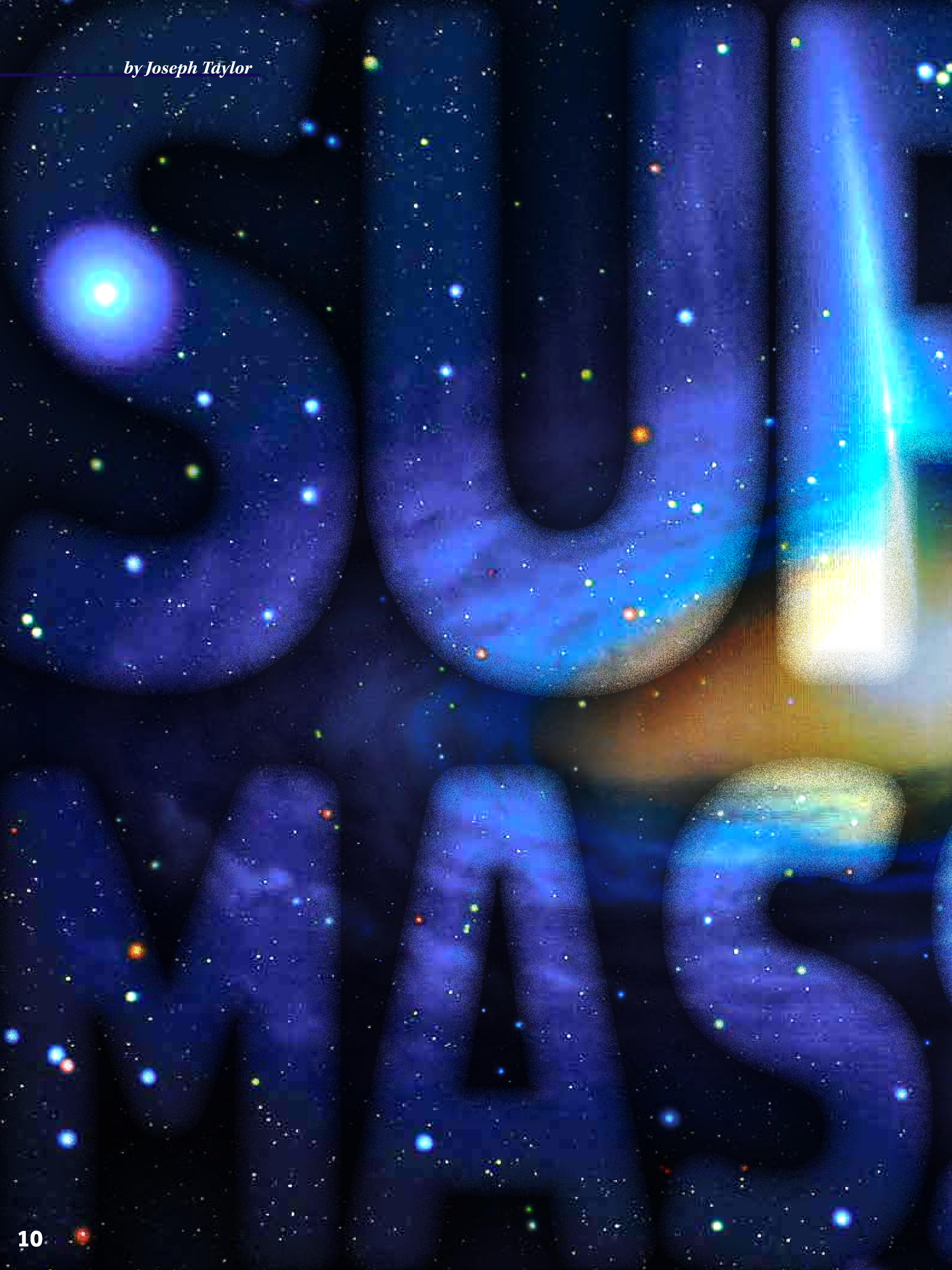
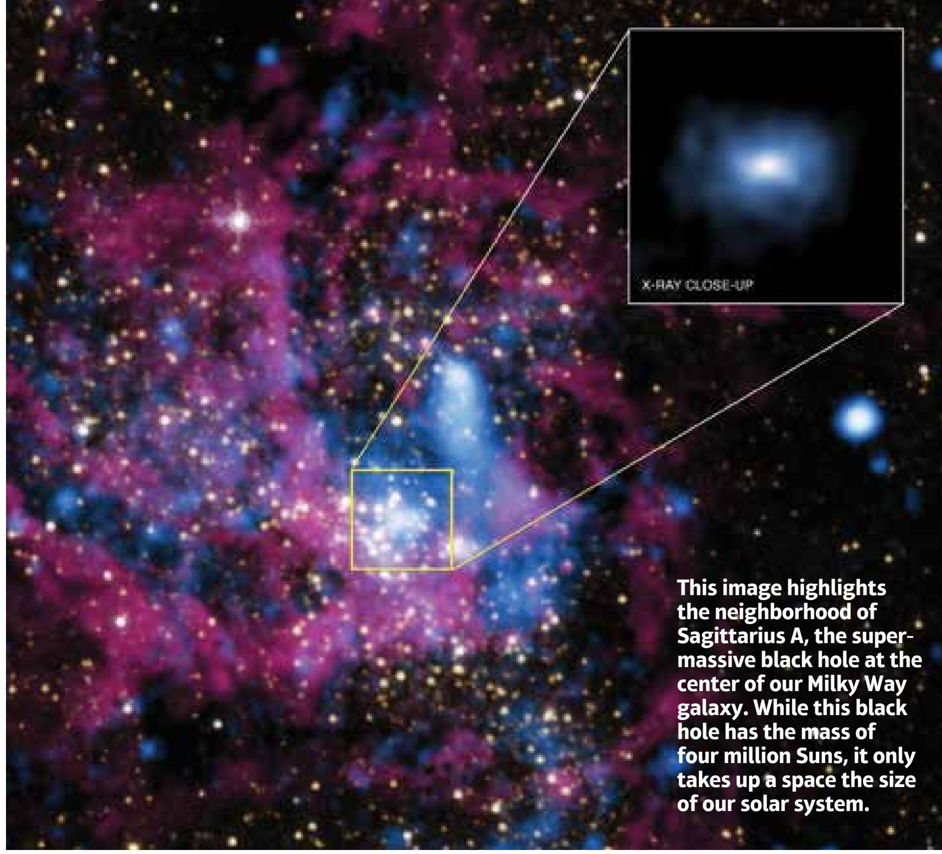


by Joseph Taylor

Astrophysicist Andrea Ghez and the Black Hole at the Center of Our Galaxy

Sitting on her mother's lap in their living room in 1969, four-year-old Andrea Ghez gaped in awe at their boxy television set. For the first time in history, humans were walking on the Moon. Her eyes alight, the young girl applauded along with her mother. For years afterward, when asked what she wanted to be when she grew up, Ghez repeated what she told her mom that day: "I want to be the first woman on the Moon."



This image highlights the neighborhood of Sagittarius A, the super-massive black hole at the center of our Milky Way galaxy. While this black hole has the mass of four million Suns, it only takes up a space the size of our solar system.

A few decades later, Ghez would find herself not an astronaut but an astrophysicist. She had become taken with physics, mathematics, and the mysteries of the universe. And she'd established herself as a trailblazer in the field, solving some of astronomy's biggest mysteries. In 2020, she won the Nobel Prize in Physics for her discovery of a supermassive black hole at the center of our galaxy. She was just the fourth woman to receive this illustrious prize—and, as it happened, the first female astrophysicist.

Ghez upon receiving her Nobel Prize in 2020.

The Girl Who Loved Puzzles

Ghez's dad, Gilbert, was an economics professor. During her summers as a kid, he would provide her and her two younger sisters with logic puzzles. Ghez found these puzzles "really fun," she says in her office at the University of California, Los Angeles (UCLA). She realized she had a talent for finding clues and putting all the pieces together. Soon she was doing any puzzle she could get her hands on, including jigsaws, crosswords, and brainteasers. "I liked the process of solving things," she says.

By the time she entered high school, Ghez knew she was "really good at math," too. Some boys, though, challenged her in math classes, telling her that girls couldn't excel at math. The taunts just made Ghez work harder, and she almost always outperformed everybody else.

At home, her father gave her an essay collection called ***The Road to Infinity*** by Isaac Asimov. It challenged her to think big. What represents the beginning and ending of time? What does it mean to find the edge of the observable universe? "I love the paradoxes you fall into when you start thinking about the big questions,"

Ghez, center, working with colleagues at the Keck Observatory in 1996.

she says. "The idea of the scale of the universe, both in time and space, it just resonates with me."

Encouraged by her chemistry teacher, Mrs. Judith Keane, Ghez decided to apply early to the Massachusetts Institute of Technology (MIT), a university in Cambridge known for its STEM—science, technology, engineering, and mathematics—programs. She was accepted to the school. Ghez began by focusing on math courses but soon realized math was too abstract for her tastes. She found that astrophysics, the study of stars' physical behavior and effects, suited her better—and it used math as a tool. "I just fell in love with it as it really appealed to these things I clearly had been thinking about quite a lot," she says.

Black Holes and Stars

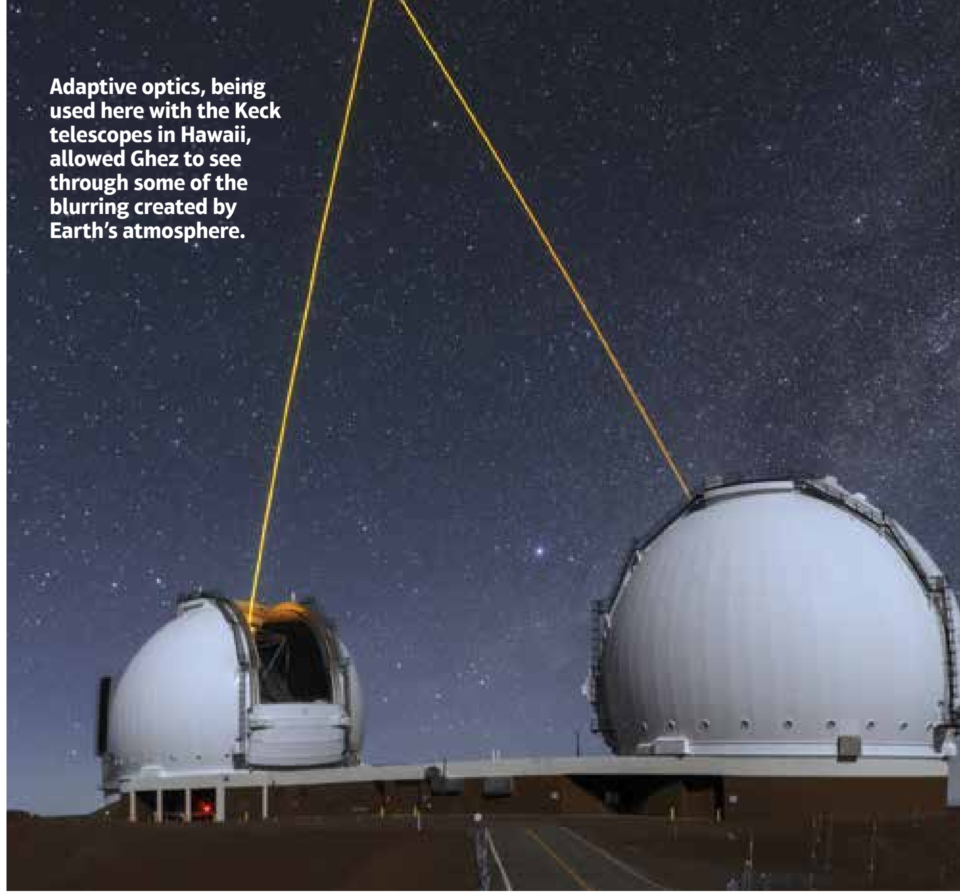
At MIT, Ghez joined a research group searching for mysterious entities in space known as black holes. A black hole is a cosmic body of massive amounts of matter packed into a tiny space. The gravity of this enormously dense object becomes so strong, nothing can escape it—not even light. A black hole is believed to bend space and even alter time. Albert Einstein's theory of relativity predicted black holes, but even he found the thought of them so outlandish he didn't believe they could exist.

For graduate school, Ghez chose another research university: Caltech, in Pasadena, California. There, she quickly joined another group researching black holes, this time searching for possible supermassive black holes. Since the 1970s, some astronomers suspected such entities might lie at the center of some galaxies.

To scour the skies, the group adopted a new optical technique called ***speckle imaging***. This technology combined many exposures from a ground-based telescope into one high-resolution image. But it turned out that while speckle imaging was an advance, it wasn't developed enough to work with black holes. So, Ghez faced a decision: either pursue the enigmatic science of black holes or stick with the practical technique. Ghez chose the technique—which led her to studying stars.

She landed on a scientific question she was interested in researching: whether stars are born alone or in pairs or triplets. "It became clear that this question of understanding how stars are formed and whether or not they form as binaries, was a perfect question to answer with this tool," she says.

A star's birth—which takes place deep inside murky clouds of dust and gas known as nebulas—was not well understood. Speckle imaging let Ghez peer into emerging star systems at stars. She wrote about this research for her PhD paper in 1992 and announced her findings in a scientific article in 1993. "Most, if not all, T Tauri stars [newly formed stars that change in brightness] have companions," she wrote. In finding that most stars are born as twins, Ghez had solved an astronomy mystery. But she was just getting started.



Adaptive optics, being used here with the Keck telescopes in Hawaii, allowed Ghez to see through some of the blurring created by Earth's atmosphere.

The Galaxy's Center

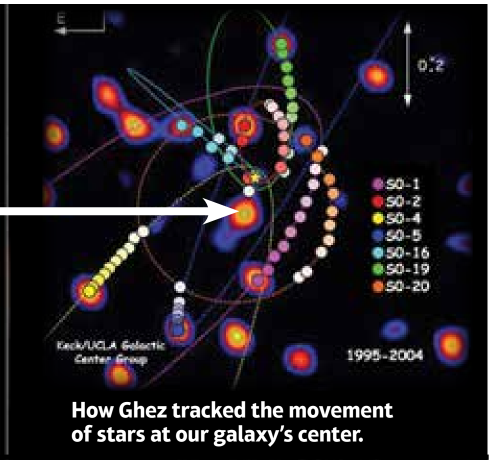
In 1994, Ghez began teaching astronomy at UCLA. The year before, UCLA had completed construction of the first of its two massive Keck telescopes on the mountain of Mauna Kea on the island of Hawaii. When the second one was completed in 1996, they were the two largest astronomical telescopes in the world. Meanwhile, thanks partly to Ghez, the speckle imaging technology, though still not perfect, had become more precise.

Energized by the promise of these developments, Ghez felt the time was right to begin searching for a possible black hole at our galaxy's center. She had trouble convincing others, though; her first official request to use the Keck

WHAT IS ADAPTIVE OPTICS?

Earth's atmosphere interferes with telescopes' ability to capture stars and other objects in space clearly. Adaptive optics is an intricate technique that helps Earth-based telescopes eliminate about half of atmospheric fuzziness in real time. With this technology, astronomers shine a laser into the sky to create an artificial guide star. Earth's atmosphere blurs the guide star image, but a ground-based computer programmed with what it should look like adjusts the telescope's mirror to compensate for the differences—sometimes hundreds of times a second.

Our Milky Way galaxy



How Ghez tracked the movement of stars at our galaxy's center.

THE SIZE OF A BLACK HOLE

Most black holes are stellar mass; they range from three to 100 times the mass of the Sun. Supermassive black holes are giant; they are millions or billions of times as massive as the Sun. Intermediate black holes are the mass of 100 to 1,000 Suns; they are much less prevalent and have only been indirectly shown to exist.

telescope was denied. She persisted and refined her pitch the following year. This time, her request to use the telescope was granted.

In 1996 and 1997, Ghez and some colleagues trained the Keck on the center of our Milky Way galaxy. They focused on the neighborhood of Sagittarius A in the constellation of Sagittarius. Ghez sometimes refers to it as our galaxy's downtown, with Earth located 26,000 light years away in a sleepy suburb. For the first time, scientists were able to peer into this dense mix of light, gas, and dust and track individual stars.

The findings were striking: Stars were moving at unusually rapid speeds, about 12 thousand kilometers per second, or 27 million miles per hour. "They were hauling," Ghez says. Traveling that fast could only mean that they were orbiting something huge (about four million times the mass of our Sun), as well as heavy and invisible. Ghez and her team shared their observations in an astronomy journal article in 1998, and stated their conclusion: "Our galaxy harbors a massive central black hole."

Collecting More Evidence

Though her measurements had been painstaking, not every scientist was ready to accept Ghez's monumental results. Ghez pressed on studying the galactic center, observing more stars move over time. She found one star speeding up, which suggested a gravitational force pulling on it. Then, a moment came in 2001 that left her giddy with joy. She saw a

Ghez at work more recently.

star start to move in a curve. The star, which they named SO-2, had to be orbiting a black hole. A quick mathematical analysis showed Ghez and her team they would be able to see some stars complete orbits in 10 to 16 years.

In the meantime, Ghez was shifting away from using speckle imaging and toward a more powerful technique called ***adaptive optics***. Adaptive optics eliminates about half the blurring created by the Earth's atmosphere. "If you look at yourself in a circus funhouse mirror, you look completely distorted," Ghez likes to say. "And the goal of adaptive optics is to introduce a second mirror that's the exact opposite shape and make you look flat again."

Using adaptive optics, Ghez and her team produced several significant findings about the galactic center. For the first time, they were able to make out a Sagittarius star's rainbow of light, or spectra, which reveals its characteristics. To the surprise of astronomers, they discovered the stars circling the black hole were young, not old. They also found that the orbits of stars closest to the black hole and its pull are chaotic. And they discovered that as objects get close to the black hole, they become elongated, and, as they move away from it, they become more compact.

'Stick-To-It-Iveness'

Today, the Milky Way's central supermassive black hole is not only considered established fact, but it's thought that a black hole is located at the center of every galaxy. Indeed, Ghez says, it appears the development of galaxies and black holes are in some way related.

Ghez explains that though scientists have been able to observe stars complete revolutions around the black hole, they have only been able to see the brightest stars there. "We can't see a typical star like the Sun," she says. "And in our galaxy most stars are low mass, which are faint." The only way to be able to see the more typical stars, she believes, is to build larger telescopes and develop the next generation of adaptive optics. Her work continues.

"The black hole discovery really took a lot of stick-to-it-iveness to do it, but it was incredibly rewarding," Ghez says. "The thing that I'm most proud of is recognizing that there was an opportunity there."

Joseph Taylor is the editor of *Muse*. He feels incredibly lucky to have met with Andrea Ghez for an interview in March 2020, just before the pandemic lockdown in California and months before she won the Nobel Prize in Physics.