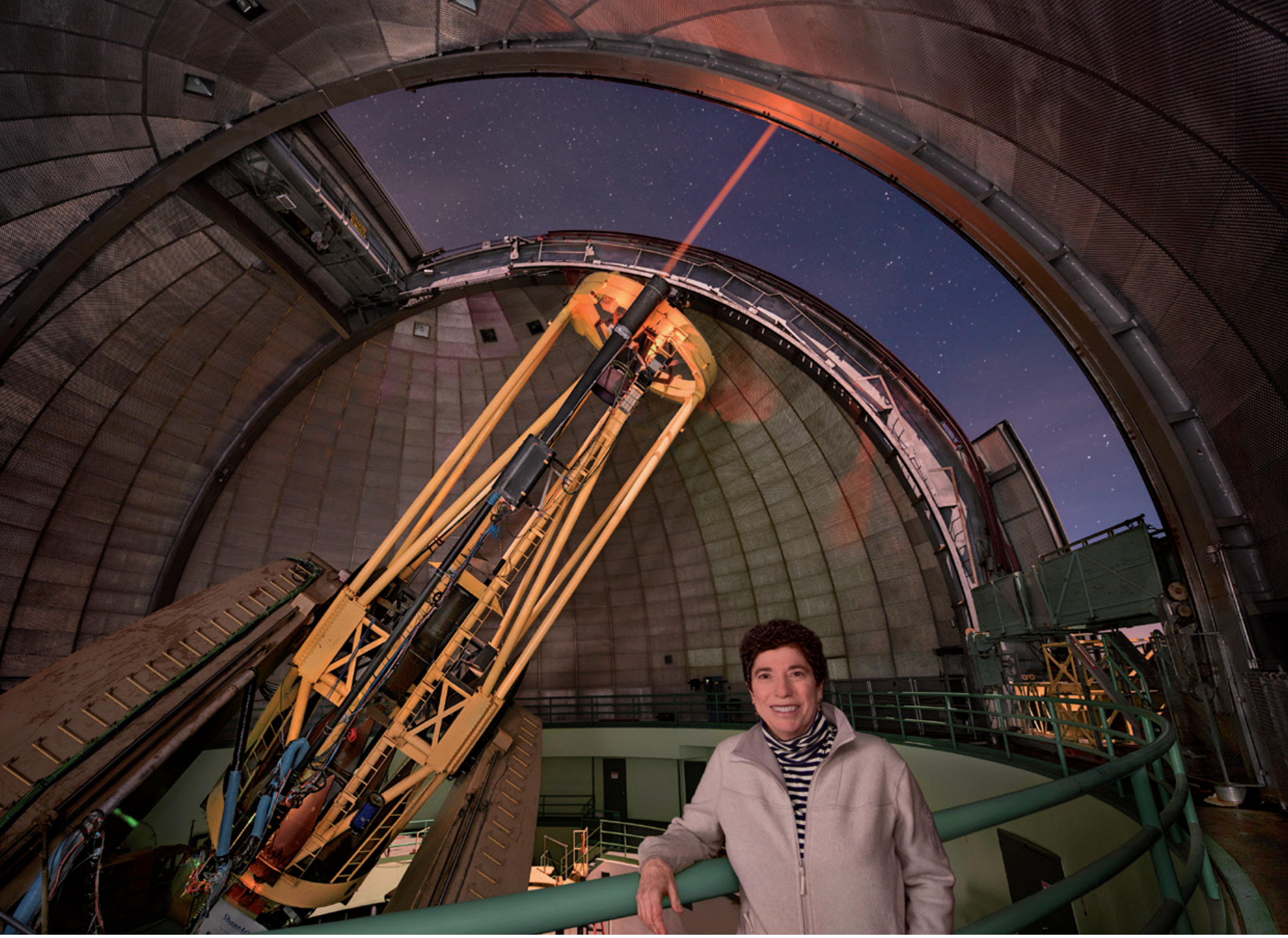


LAURIE HATCH

LASER FOCUS

By firing lasers into the sky, Claire Max has transformed the capabilities of current — and future — telescopes.

BY ANN FINKBEINER

On clear, moonless evenings, most of the biggest optical telescopes around the world begin the night's observations by firing a golden laser beam at the sky.

Claire Max does not like to take credit for this astronomical light show, even though the lasers' widespread use is a tribute to her three-decade campaign to perfect and promote them — an effort that was recognized on 16 January when the American Astronomical Society awarded her its 2015 instrumentation prize. For Max, an astronomer at the University of California, Santa Cruz, self-aggrandizement would be — unbusinesslike. And she is all business; even her way of speaking is careful, like someone who feels obliged to stand behind every word she says. Her passion is reserved for the technology itself. "I still get gripped by it," she says, showing off photograph after photograph of telescopes, lasers and thin beams of light shining upwards as straight as a ruler.

The lasers, Max explains, are a crucial element of the telescopes' adaptive optics, which correct for turbulence in the atmosphere. Without adaptive optics, stars and galaxies viewed at high magnification will dance, distort and blur like stones seen at the bottom of a stream. With adaptive optics, they will remain steady and sharp, allowing telescopes on the ground to routinely equal or exceed the clarity obtained by NASA's Hubble Space Telescope. This capability has allowed current-generation telescopes to carry out high-resolution studies of objects ranging from moons in the outer Solar System to stars at the centre of the Milky Way. And now it is enabling the construction of telescopes measuring 20–40 metres across, as much as four times the diameter and 16 times the light-gathering power of any now in existence.

Max has been involved in this development from its early days: from the first demonstration of laser-assisted adaptive optics to building the prototype and then establishing a centre that spread the technology to telescopes around the world.

Yet Max's greatest triumph has also become her greatest challenge. Last October, at an age when other astronomers might be looking forward to retirement, the 68-year-old Max agreed to serve as interim director of the University of California Observatories (UCO) — the organization responsible for all the astronomical hardware owned by one of the biggest state university systems in the United States. And in that role, 'interim' or not, Max finds herself navigating the professional and cultural chaos in astronomy being triggered by the cost of these next-generation behemoths.

There are three of these telescopes in various stages of planning and construction, each with a price tag in the order of US$1 billion. That cost, says Max, poses a quandary for their owners and funders — among

Claire Max stands next to the 3-metre telescope at California's Lick Observatory.

them the UCO, a key partner in the Thirty Meter Telescope (TMT) that started construction last year atop Mauna Kea in Hawaii. How do they pay for all their older, smaller telescopes? Should the owners give in to financial pressure and close the facilities — even though the telescopes are still essential workhorses for individual researchers and training grounds for young astronomers? Or should they fight to find creative ways to keep all the doors open?

Max's instinct is to fight — using her unique combination of warmth, empathy and determination. So far, she is winning. After three decades of persuasion and consensus-building in pursuit of adaptive optics, says Andrea Ghez, an astronomer at the University of California, Los Angeles, Max has developed a sure instinct for making connections among engineers, academics, funding officers, university administrators and all the others who have a say in telescope decisions.

These are powerful players, says Ghez — "gorillas at the table who'd like you for lunch". And to deal with them, she says, you need someone like Max: "a gorilla with finesse".

FIRST LIGHT

Max took her first look through a telescope in the early 1950s, when the Manhattan native was just 8 years old. "And that was it," she says. "I can still close my eyes and see the mountains of the Moon. So I became an astronomy nut."

That passion led her first to Princeton University in New Jersey, where she earned a PhD in astronomy; then to a postdoctoral appointment at the University of California, Berkeley; to a staff position at the Lawrence Livermore National Laboratory in California; and in 1983, to membership in the Jasons: a group of scientists who meet from time to time to give technical advice on national security, often for the US Department of Defense.

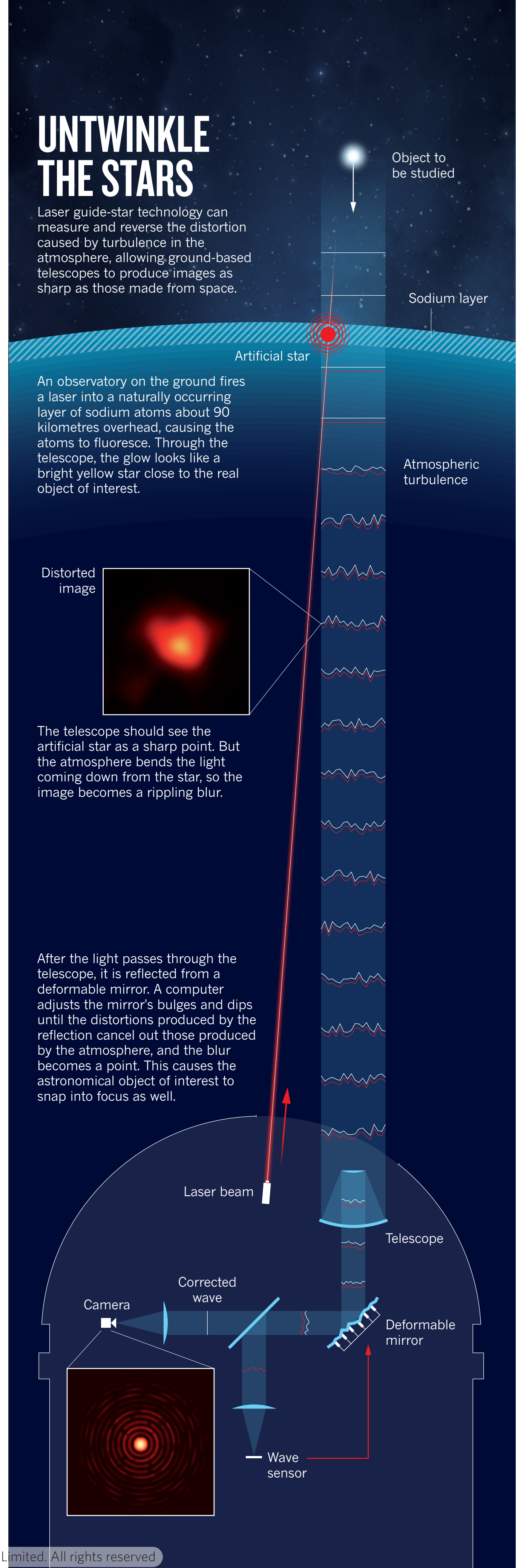
The first Jason study she joined was motivated by the US Air Force's desire to identify potentially hostile satellites — a task for which the atmosphere was just as big a barrier as it was for astronomers. Even with clear skies and a good telescope, turbulence smears out details smaller than about 1 arcsecond in angular diameter — good enough to look up at the Hubble telescope, which is similar in size and altitude to spy satellites, and tell that it is a cylinder, but not much else.

Astronomers had already come up with a potential solution: a flexible mirror that could reflect the light coming into the telescope and deform under computer control. In principle, the distortions introduced by the mirror would exactly cancel out those produced by the atmosphere, restoring the image to near-perfection. But first, the distortion had to be measured, preferably by looking at what the atmosphere did to a bright 'guide' star near the target. And bright stars were not always available near the fast-moving targets of interest to the Pentagon.

That is why the Air Force had asked the Jasons for help — which Max and her colleagues provided in a classified report. Just shine a laser upwards along the telescope's axis, they said. If the laser were tuned to the correct wavelength, the beam would then encounter a naturally occurring layer of sodium atoms floating in the atmosphere about 90 kilometres up and cause the sodium to fluoresce, producing a bright-yellow spot visible from the ground — in effect, a guide star available anywhere in the sky (see 'Untwinkle the stars').

But Max went further. Knowing that the sodium laser guide star would also be invaluable for astronomers, she came up with an additional design that the Air Force had not asked for, but was better adapted to research needs. "I thought it was so cool," she says.

Unfortunately, that design was classified along with all the other sodium laser guide-star technology. So Max, together with sympathetic Air Force scientists who knew the proper channels to follow, spent the next seven years lobbying the military to take the wraps off. And they won: in May 1991, Air Force scientist Robert Fugate was allowed to describe the artificial guide star at an open meeting of the American Astronomical Society in Seattle, Washington. Reactions were mixed:



astronomers who had been working on similar technology but did not have the money to get very far were annoyed to learn that the military had already built it in secret. But most were just excited at the prospect of getting blur-free images anywhere they wanted. "It was just pandemonium," recalls Fugate. They asked "a million questions".

For all the astronomers' enthusiasm, however, the system was still technically demanding, expensive and in need of development that universities could not afford. "People were writing about it," Max says, "but they weren't putting it on telescopes." So shortly after the declassification, Max decided that astronomers needed a proof-of-principle. The idea for how to do that hit during lunch with a colleague, Herb Friedman. "We looked at each other," she says, "and we said, 'Well crap, we're from Livermore, we do lasers.'"

Indeed, the laboratory had an enormous underground laser that was normally used to separate isotopes, but could be tuned to sodium wavelengths. Max and Friedman therefore arranged to have an access cover removed from the roof of the laser tunnel, and a mirror installed to bounce the horizontally pointing laser light through the hole into the sky. Then they set up a small telescope beside the beam to look for the artificial guide star and measure the atmospheric distortions. The set-up must have looked eerie in the darkness, says Max — the tent that covered the telescope glowed yellow with stray laser light; the beam itself could be seen for ten kilometres or more — and one local woman kept calling the police to report that a UFO was sucking up all Livermore's secrets. But their demonstration did prove that the design would work the way that Max expected.

ONE LOCAL WOMAN KEPT CALLING THE POLICE TO REPORT THAT A UFO WAS SUCKING UP ALL LIVERMORE'S SECRETS.

The next step was to master the complex optics and engineering required for the laser system to function on a real telescope. A prototype that Max and her colleagues deployed at the UCO's Lick Observatory in San Jose in the mid-1990s eventually showed that, at least at longer wavelengths, the system allowed the observatory's 3-metre telescope to reach the finest-possible resolution permitted by the wave nature of light (D. T. Gavel *et al. Proc. SPIE* **4007,** 63–70; 2000).

But even that failed to persuade astronomers to embrace the technology. At the time, people thought the laser guide star was "so complicated it would never run in harness" with other astronomical instruments, says Connie Rockosi, one of Max's colleagues. So Max decided that the technology needed "a community of practice" — a central home in which users could learn how to build laser guide stars for themselves. That idea became the Center for Adaptive Optics, which was funded by a $40-million, 10-year grant from the US National Science Foundation (NSF), and which opened on the Santa Cruz campus in 1999, with Max eventually as its head. By 2010, says Max, when the grant ended and the centre had to close its doors, it had grown from a handful of people to nearly 100.

That did the trick. The laser-assisted adaptive-optics systems have to be custom-built for each telescope and are still pricey, running to several million dollars apiece. But astronomers, many of whom were trained at Max's centre, have now retrofitted the technology onto every optical telescope for which it makes sense. That includes almost all the flagship telescopes that currently rank as the largest in the world, from the twin Keck 10-metre telescopes atop Mauna Kea to the four identical 8.2-metre instruments comprising the European Very Large Telescope in Chile.

GOOD RESOLUTION

The bigger the telescope, the more advantage it can get from adaptive optics. At 1 micrometre, a wavelength in the infrared part of the spectrum, which is particularly useful for astronomy, the Hubble Space Telescope's 2.4-metre mirror can produce images with a resolution 0.11 arcseconds. At that wavelength, with the help of the laser guide star, the Lick 3-metre can do somewhat better: 0.08 arcseconds. But 8-metre instruments like those comprising the European quartet in Chile can get all the way down to 0.03 arcseconds — almost four times better than Hubble.

That kind of visual acuity has allowed astronomers to track the stars orbiting the Milky Way's central black hole, image exoplanets around other suns, observe the common, low-mass stars known as brown dwarfs and pursue many other once-impossible studies. In these areas, says David Silva, director of the US National Optical Astronomy Observatory in Tucson, Arizona, "we couldn't have made any advances from the ground" without adaptive optics.

The systems' largest impact, however, will be on the 20–40-metre telescopes that are now under development: the European Extremely Large Telescope and the Giant Magellan Telescope, both in Chile, and the TMT on Mauna Kea. Telescopes this big can collect enough light to study faint, far-off objects such as the first galaxies to form after the Big Bang — but would hardly be worth their billion-dollar cost if they had a resolution of just 1 arcsecond.

Unfortunately, that price tag is also why there are only three of these megatelescopes — which means, in turn, that only a small fraction of astronomers will ever get to use them. At the same time, 'have-not' astronomers at institutions not affiliated with one of the large projects are losing access to the 3- and 4-metre telescopes — even though these smaller instruments are often ideal for large-scale surveys of the sky, or targeted observations of relatively nearby objects. Citing a flat budget and its investment in large projects such as the ALMA radio telescope in Chile, the NSF has withdrawn support from optical telescopes in this class. "For the general astronomer, it's harder and harder to get time," said Richard Barvainis, programme officer for astronomy at the NSF. "It's becoming a major issue."

At the UCO, which is facing its own cash crunch, Max is now in charge of a perfect microcosm of the situation she helped to create. In September 2013, provost Aimée Dorr declared that the University of California's support for the Lick Observatory would end within five years, thanks to construction costs on the TMT; maintenance expenses on the Keck telescopes; and the UCO's declining budget, which has halved over the past decade. The astronomical community responded with a firestorm of protest. It insisted that Lick, in operation since 1888, is still valuable as a test bed for new instruments and as a training ground for graduate students.

So last autumn, Max began her term as interim director of the UCO by walking into Dorr's office and saying "What can we do to make this a win–win?". Dorr was willing to try: Max was not only "credible, straightforward, honest, and moderate", she says, but she could create budgets that at least one previous director had said were impossible. Over the next several months, Max sorted through the UCO's convoluted partnerships and budgets, found ways to move around various pots of money, calmed the firestorm and got the university's funding for Lick reinstated.

Max's next priority is to devise a comprehensive strategic plan for Lick, as well as for the two Keck telescopes. Because Lick has adaptive optics and it is relatively available to astronomers, it could be used for high-precision surveys of a few hundred to a few thousand objects such as quasars — studies, says Max, that "you can peck away one by one and add up to a survey with good statistics".

Max is determined to have this plan in place when the university announces its choice for the permanent director of the UCO. That new director might be her — she has applied for the position — but if not, she says, she will simply go back to being the astronomer-engineer-community builder she has been all along. Along those lines, she is working on multi-laser adaptive-optics systems that can both correct for the atmosphere and widen the field of view. She is also training a particular brand of graduate student — the kind, she says, who "has one hand in instruments and one in astronomy".

That breadth of skills has allowed Max to do what she has done, says Ghez. "A typical astronomer could never do it." ■

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