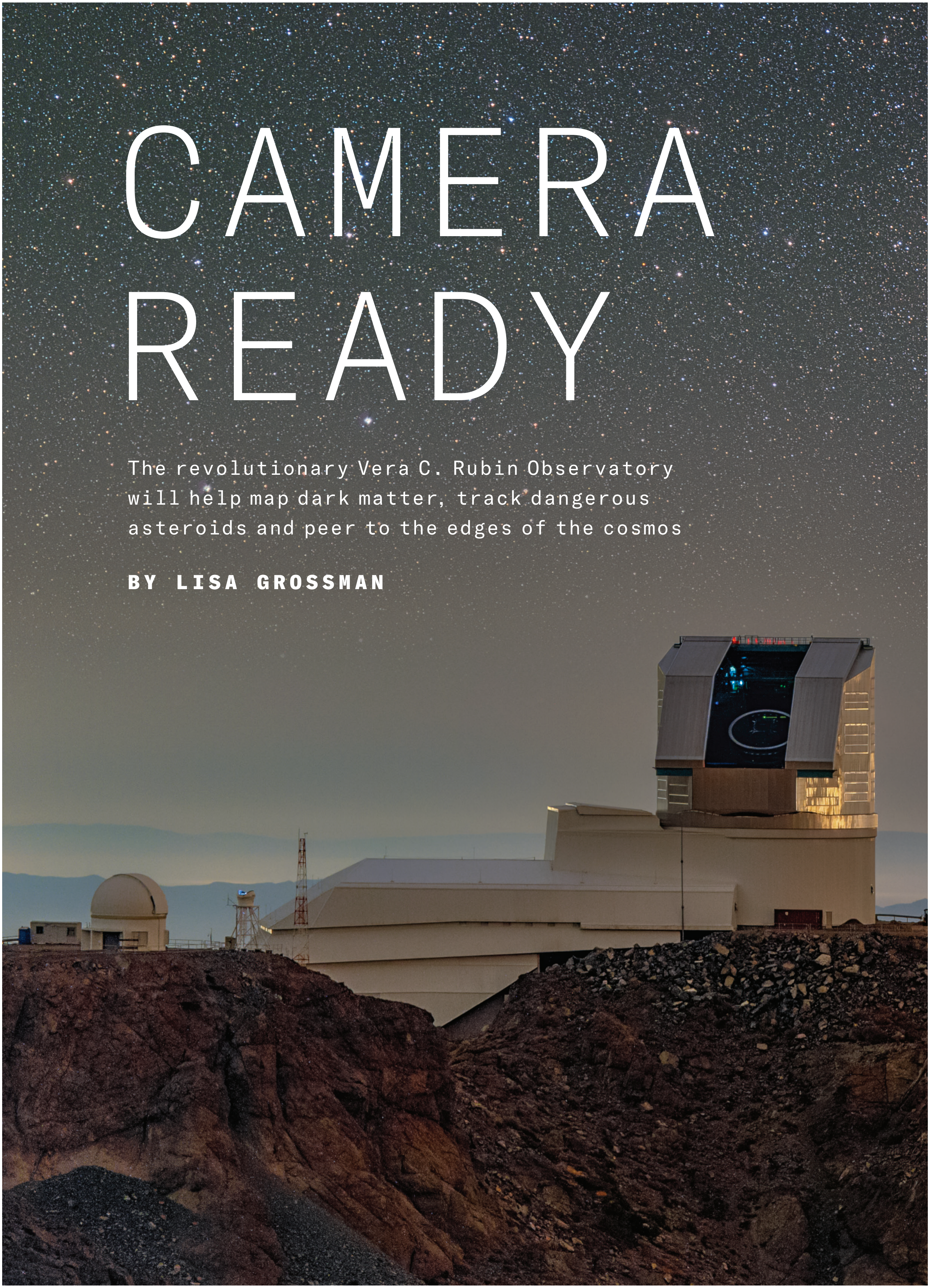
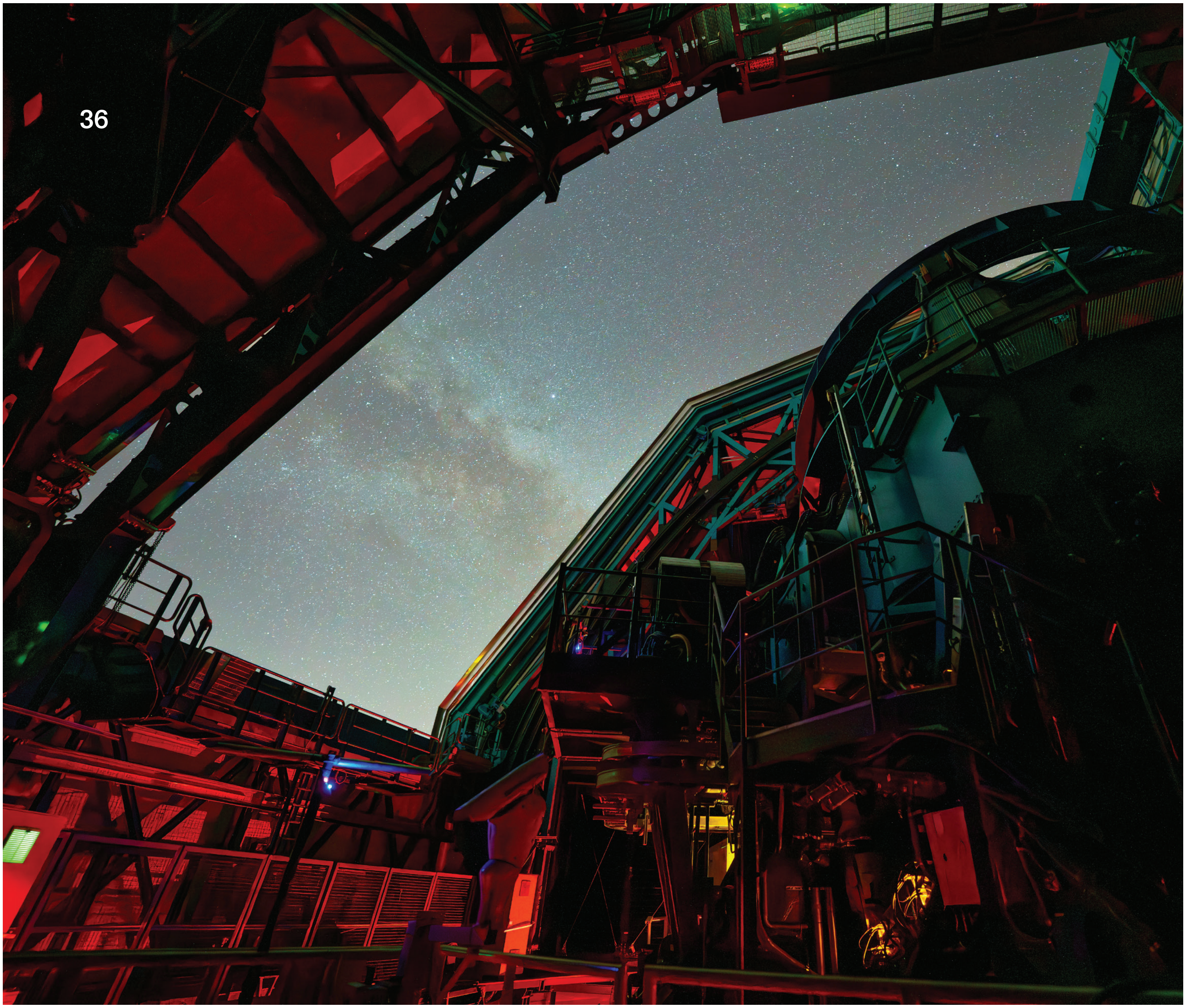
CAMERA READY

The revolutionary Vera C. Rubin Observatory will help map dark matter, track dangerous asteroids and peer to the edges of the cosmos

BY LISA GROSSMAN



Built on a flat mountaintop high in the Chilean Andes, the Vera C. Rubin Observatory was named to honor the work of a trailblazing U.S. astronomer.



AT 3 A.M. ON A CRISP MAY NIGHT IN CHILE, ALL SEEMED WELL WITH THE WORLD'S LARGEST DIGITAL CAMERA. UNTIL IT DIDN'T.

Inside the newly built Vera C. Rubin Observatory, site project scientist Sandrine Thomas was running tests when a flat line representing the camera's temperature started to spike. "That looks bad," she thought. She was right. Worried scientists quickly shut down the telescope.

I arrived a few hours later, jet-lagged but eager to get my first glimpse at a cutting-edge observatory that astronomers have been awaiting for more than 25 years.

Perched on a high, flat-topped mountain called Cerro Pachón, the Rubin Observatory was conceived back in the 1990s to give astronomers the unprecedented ability to probe the cosmos in every dimension. With a wide and deep view of the sky, Rubin can investigate some of the universe's slowest, most eternal processes, such as the assembly of galaxies and the expansion of the cosmos. And by mapping the entire southern sky every couple of nights, it can track some of the universe's fastest and most ephemeral events, including exploding stars and visits from interstellar comets.

At the end of its planned 10-year survey, Rubin will have taken 2 million images with 2,300 megapixels each, capturing more of the cosmos than any other existing telescope.

"For the first time in history, the number of cataloged celestial objects will exceed the number of living people!" Željko Ivezić,

PREVIOUS SPREAD: RUBINOBS/NOIRLAB/SLAC/NSF/DOE/AURA/P. HORÁLEK/ INSTITUTE OF PHYSICS IN OPAVA an astronomer at the University of Washington in Seattle, and colleagues wrote in a 2019 overview paper in the *Astrophysical Journal*.

As Rubin's director of construction, Ivezić might have worried that the project's scientific goals would be accomplished by other telescopes during the decades it took to build the facility. But, he says, the questions the team set out to answer when the project was dreamed up remain unresolved. "To answer them, you need something like Rubin," Ivezić says. "There is no competition."

In an unusual move, Rubin data will be made available online to anyone in the world, from professional astronomers to elementary school students. "That's a huge democratization of science," Ivezić says. The hope is that these data will help solve fundamental mysteries of the universe that can't be tackled any other way.

But first, Thomas and her team had to get the camera back online.

FROM DARK MATTER TO ASTEROIDS

The idea that led to Rubin's construction came during another 3 a.m. vigil almost 30 years ago, on the next mountaintop over from Cerro Pachón.

It was January 1996, and astronomer Tony Tyson, then with Bell Laboratories, and his colleagues had recently brought a new digital camera to a 4-meter telescope sitting on Chile's Cerro Tololo. The camera used what was then a relatively new technology called charge coupled devices, or CCDs. These silicon chips convert particles of light to electrons, which can then be turned into an image of the light source. CCDs started to be used in astronomy in the 1970s and quickly became the industry standard, replacing slow and bulky photographic plates. Several CCDs arranged in a mosaic act as one large camera, converting more electrons to more pixels and delivering higher-resolution images.

Tyson's camera, the most powerful in the world at the time, was made up of four CCDs. He and colleague Gary Bernstein built it to make a map of dark matter, the mysterious substance thought to make up 80 percent of all matter in the universe. Astronomers don't know what it is, but because of its gravitational effects on regular matter, they're pretty sure it's there.

One of those effects was discovered in the 1970s by astronomer Vera Rubin, the new observatory's namesake. Based on a galaxy's visible matter, you would expect stars to orbit slower the closer they are to the disk's edge, like planets in the solar system do. Instead, Rubin and her colleague Kent Ford noticed that stars at the edge were whipping around the galactic center so fast they should have been flung into space. The best explanation was that some other, unseen matter must be holding galaxies together.

There's another way dark matter can make its presence known. Matter warps the fabric of spacetime, and that changes the path of light as it speeds through the universe. Clumps of dark matter can therefore distort the images of visible objects in the background. This effect, called weak lensing, is the only way to "weigh" the distribution of dark matter in the universe, Tyson says.

That's what Tyson had come to Chile to do. But one night as he, Bernstein and some other astronomers sat in the telescope control room, Tyson had a revelation. He looked around and said, "Guys, we can do better than this." They could, in principle, build a bigger quilt of CCDs to create a much more powerful telescope. Computers were getting better and faster all the time, so they could keep up with the flood of data such a telescope would gather. All they needed were a few technical improvements.

Tyson decided to make this

↖ Rubin's dome opens to let the camera survey the sky, then closes to protect it from the elements. → The crew works in shifts through the night from a control room in a separate part of the facility.

THIS SPREAD, LEFT: RUBINOBS/NSF/DOE/NOIRLAB/SLAC/AURA, H. STOCKEBRAND; RIGHT: MARCOS ZEGERS/*THE NEW YORK TIMES*/REDUX new observatory his pet project. He rushed to submit a proposal to the 2000 Decadal Survey on Astronomy and Astrophysics, the major wish list of U.S.-led missions that astronomers think should get federal funding. His project would survey the whole sky in search of weakly lensed objects and map all the dark matter we can detect.

"I had called it the Dark Matter Telescope because that's what I wanted to do," he says. "But perhaps cleverly, on the last page, I had a picture of an Earth-threatening asteroid."

After all, such a telescope could do a lot more than map dark matter. A large enough digital camera, combined with a wide-eyed telescope, could also "make unique inroads in the ... universe of things that move and explode," Tyson says. That includes asteroids as well as pulsating stars, hungry black holes and any doomed stars that get too close to them. Such a telescope could map out millions of objects in our solar system, plus millions of supernovas and billions of galaxies. It could help answer questions that astronomers didn't even know to ask at the time (see Page 40).

That first proposal wasn't selected, but the astronomy community ranked it highly enough that Tyson and colleagues thought it was worth pursuing. Start-up funding from Bell Labs, along with a $20 million gift from former Microsoft developer Charles Simonyi, $10 million from Bill Gates and support from the U.S. National Science Foundation and Department of Energy, helped them start designing and building components.

In 2010, the project got top billing in the decadal survey, setting the stage for full funding led by NSF and DOE. The team initially dubbed the instrument that would anchor the observatory the Large Synoptic Survey Telescope: the telescope that will get the big picture.

FUN HOUSE MIRRORS

True to that project name, the observatory has what's now the largest digital camera ever built. It weighs about 3,000 kilograms and, at 1.65 meters wide, is bigger across than I am tall. It combines 189 individual CCDs, which deliver their data within seconds of taking an image. Its sensor has roughly the same number of pixels as 260 smartphone cameras.

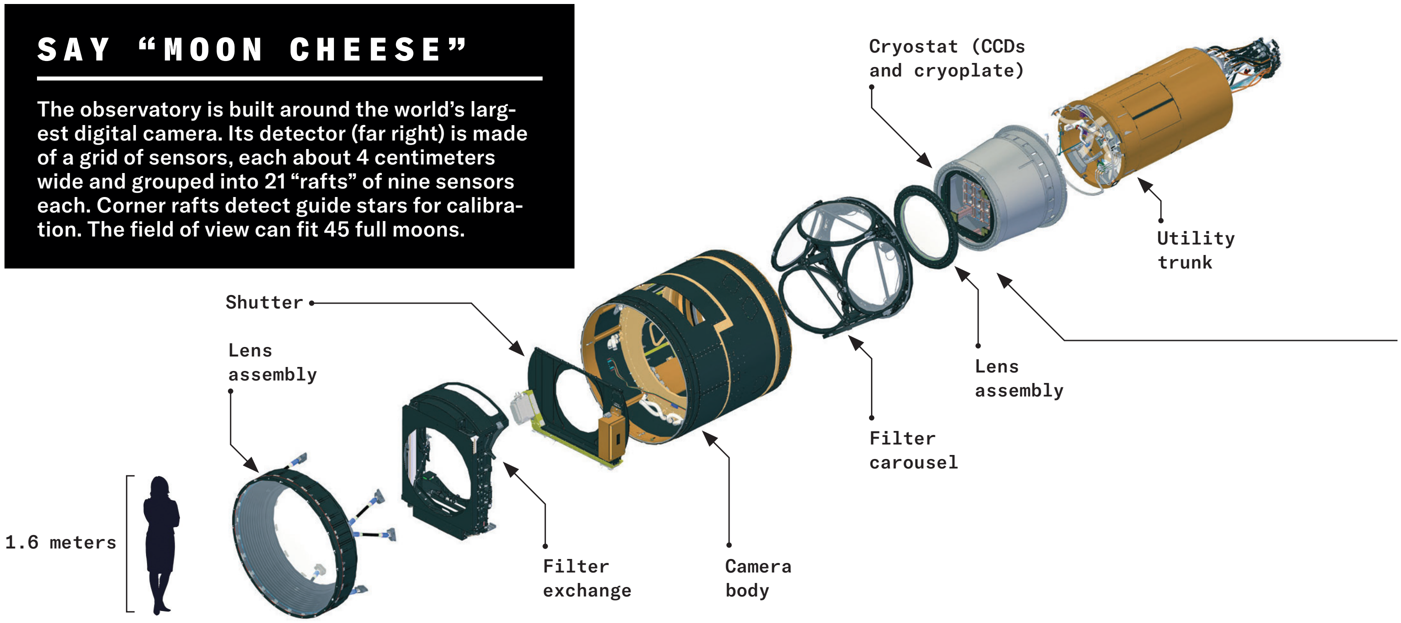
In addition to demanding a record-setting camera, the observatory's science goals dictated its shape and structure. Want a survey that goes wide, fast and deep all at the same time? There are only so many ways to build an instrument to do that. For instance, to cover the whole sky every three or four nights, each snapshot must include an area equivalent to 45 full moons without blurring at the edges. Rubin therefore needs an enormous, unusual set of mirrors.

Rubin's telescope starts out the way most do: An 8.4-meter-wide primary mirror collects a tremendous amount of light in each exposure. That mirror reflects light onto a secondary mirror. At 3.5 meters wide, Rubin's is currently the largest secondary mirror ever built for astronomy.

Normally, that secondary mirror would focus the light onto a camera or detector. But even when the mirrors are perfectly constructed, the nature of optics means objects

SAY "MOON CHEESE"

The observatory is built around the world's largest digital camera. Its detector (far right) is made of a grid of sensors, each about 4 centimeters wide and grouped into 21 "rafts" of nine sensors each. Corner rafts detect guide stars for calibration. The field of view can fit 45 full moons.



SLAC, ADAPTED BY B. PRICE

that are not directly in the center of the telescope's view can appear blurred or distorted, creating properties called aberrations.

To correct those aberrations, Rubin uses a third mirror. In an unusual setup, the tertiary mirror is made from the same piece of glass as the first, as a 5-meter-wide dish with deeper curvature in the inner part of the primary mirror. This saves space and makes the telescope easier to align, Thomas says, because two of the mirrors can never go out of alignment.

By the time the light bounces into the car-sized digital camera, which is suspended in the middle of the secondary mirror, every point of light in the whole field of view looks needle-sharp.

To catch as many faint objects as possible, the telescope has only five seconds between shutter snaps to move on to a new place in the sky. On a normal night in the control room, you can hear the shutter clicking every 30 to 50 seconds, all night long. Thomas finds the sound soothing. "When you can't hear anything, you know something might be wrong."

"FOR THE FIRST TIME IN HISTORY, THE NUMBER OF CATALOGED CELESTIAL OBJECTS WILL EXCEED THE NUMBER OF LIVING PEOPLE!"

—Željko Ivezić and colleagues

Snapping images at these speeds kept the telescope on the ground — space telescopes can't move quickly enough. It also means that after the telescope slews to a new position, it has to stop on a dime, which is why the huge instrument is very compact.

"If you move, you will take a blurry image," Thomas says. "You can imagine, if you have a long telescope and you move it, it's going to vibrate a little bit."

Rubin's location on Earth is also key. Cerro Pachón is high and dry and far from the glare of city lights, which means it's an ideal place to build such a sensitive observatory.

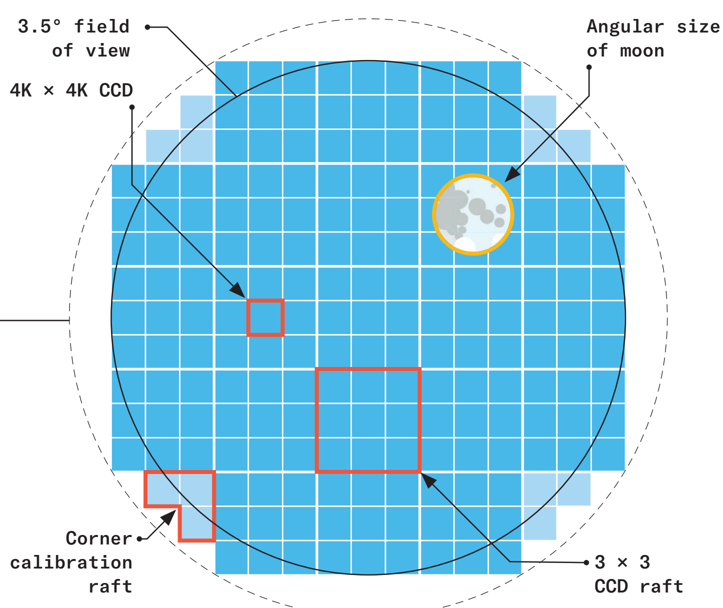
To get to Cerro Pachón back in May, I had to take an overnight flight from New York to Santiago, then a second flight to the seaside city of La Serena. From there, a local driver who was familiar with the sinuous, dusty, unpaved roads ferried me and three other journalists into the clay-colored mountains. As the ear-popping drive wound ever higher, I kept my eyes trained on the line of telescope domes glinting in the distance. I couldn't stop smiling.

Once on the ridge, the air was so dry I could feel it parching my nostrils and throat, and so clear I could see for miles in every direction. Aside from other telescopes and temporary buildings set up to support workers, all I could see were rocks and scrubby plants, with the occasional wild horse or viscacha, a local rodent that Thomas described as a bunny with a squirrel tail.

The observatory was still an active construction site, so we all had to wear reflective yellow vests and helmets to walk around. Some of the mountaintop crew bedecked their helmets with stickers, including custom-made ones of the facility's human namesake, Vera Rubin.

For almost a year while planning this visit, I had looked forward to seeing the massive telescope in action. The team had opened the camera shutter to the sky and let in its first photons about a month earlier, and it had dutifully taken data every night since then. The idea was for me and the other journalists to watch as the telescope took some of its earliest complete images.

But when I arrived, it had been a mere eight hours since Thomas had exchanged frantic messages with the camera crew and



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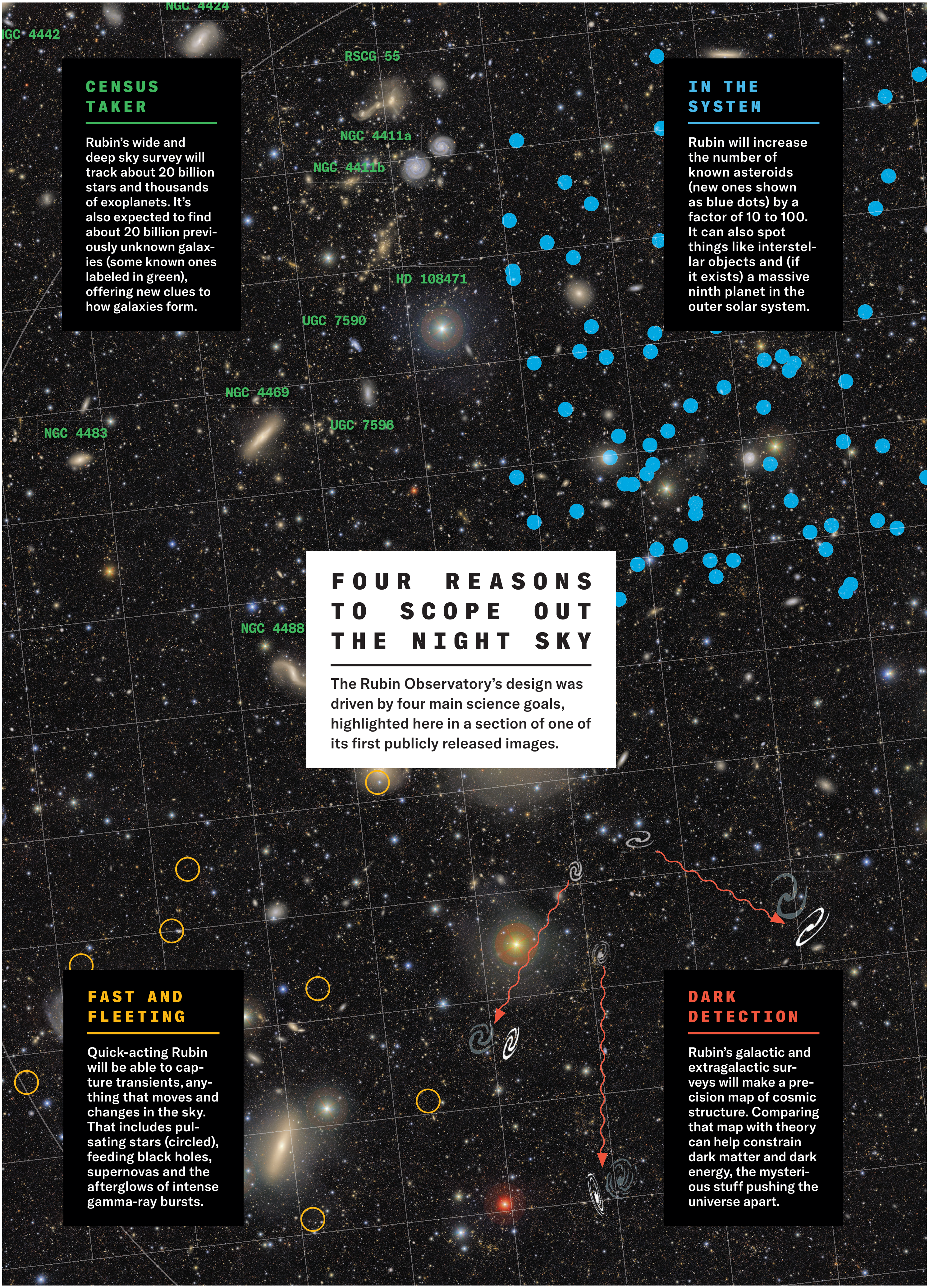
FOUR REASONS TO SCOPE OUT THE NIGHT SKY

The Rubin Observatory's design was driven by four main science goals, highlighted here in a section of one of its first publicly released images.



CENSUS TAKER

Rubin's wide and deep sky survey will track about 20 billion stars and thousands of exoplanets. It's also expected to find about 20 billion previously unknown galaxies (some known ones labeled in green), offering new clues to how galaxies form.

IN THE SYSTEM

Rubin will increase the number of known asteroids (new ones shown as blue dots) by a factor of 10 to 100. It can also spot things like interstellar objects and (if it exists) a massive ninth planet in the outer solar system.

FAST AND FLEETING

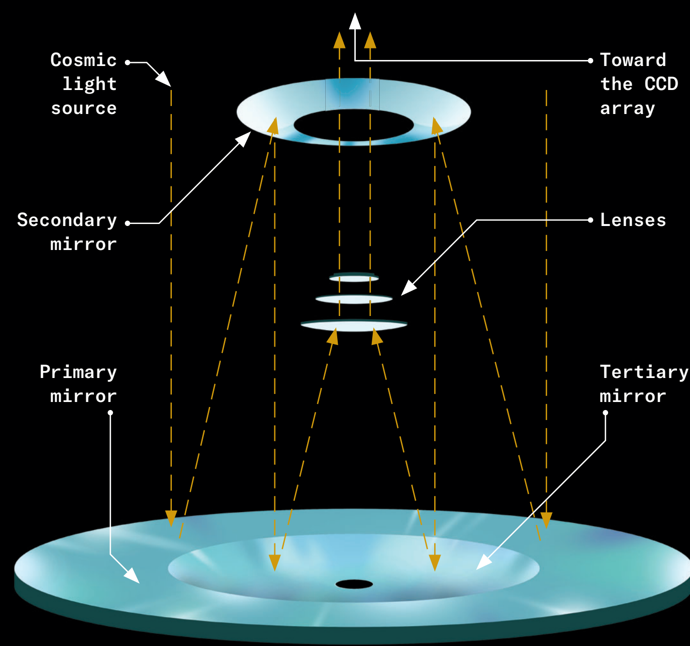
Quick-acting Rubin will be able to capture transients, anything that moves and changes in the sky. That includes pulsating stars (circled), feeding black holes, supernovas and the afterglows of intense gamma-ray bursts.

DARK DETECTION

Rubin's galactic and extragalactic surveys will make a precision map of cosmic structure. Comparing that map with theory can help constrain dark matter and dark energy, the mysterious stuff pushing the universe apart.

MIRROR, MIRROR (MIRROR)

Rubin's telescope uses a unique set of three mirrors, two of which are made from a single piece of glass. Light hits the 8.4-meter-wide primary mirror, reflects onto a 3.5-meter secondary mirror above it and bounces to the inner, 5-meter tertiary mirror below. Then it finally passes through a hole in the secondary mirror to enter the camera.



reluctantly shut down the telescope. When Thomas took me on a tour of the observatory, the whole structure was lying motionless, aimed at the horizon. We passed the camera team on a catwalk ledge on our way up to the dome.

"Is my camera moving yet?" Thomas asked the team cheerfully. "Make it work!" She turned to me. "We try to have a positive attitude, but we are all very bummed."

The silver lining was that I had an excellent view of the unusual primary mirror. Staring into it was like looking at a fun house reflection. Stripes of light and dark, reflected from the dome and other parts of the telescope, looked nearly straight in the outer part of the mirror but warped and wobbled in the inner part. I swayed back and forth, then crouched down and slowly stood up to see how the shapes changed. It was dizzying.

KEEPING IT COOL

The mystery of the malfunctioning camera led Thomas and her team to investigate another fundamental aspect of the telescope's design: temperature control.

It's crucial to keep the camera's detector cold. Thermal energy can trigger CCDs to release electrons, which could mimic signals from objects in space. Keeping the temperature as low as possible helps ensure that the detector reports only photons that actually come from the sky. And Rubin is going to collect an unprecedented number of photons. The plan is to observe the entire night sky visible in the Southern Hemisphere every three to four days. The camera shutter will open for 30 seconds per picture, for 1,000 pictures per night, every night for 10 years.

The instrument has a –123° Celsius metal cryoplate at the back of the detector, and another "cold" plate at –40° C behind that, all sealed in a vacuum. Refrigeration lines carry cooling liquids through the camera before snaking out the back of the telescope. Even the outside of the sparkling dome is specially designed to reflect sunlight away from the telescope.

Thomas and her colleagues were therefore anxious to figure out why the cryoplate had suddenly warmed up at 3 a.m. on that May night.

Crises are expected during the commissioning phase, when the crew puts a new telescope through its paces. "You test it all in the lab," says Rubin commissioning scientist Kevin Fanning, a researcher with the U.S. SLAC National Accelerator Laboratory. "And reality is always slightly different."

Still, Rubin had been working surprisingly well for the past month, Fanning says. This was its first crisis. But the effects could be worse than just detecting phony photons, commissioning scientist Sean MacBride of the University of Zurich told me during my visit. As the temperature goes up inside the frigid case that holds the CCDs, the pressure goes up too. Materials in the camera may then release gases that could get stuck on the sensors, which would be "really, really bad for the long-term health of the system," MacBride said.

"The probability is fairly low, but the consequence is pretty serious," he said. "This is on the top-five list of scariest things that could happen to the camera."

By midafternoon, the camera seemed to have gone back to normal all on its own. That was a clue,

BOTH IMAGES: RUBINOBS/NOIRLAB/SLAC/NSF/DOE/AURA, ADAPTED BY B. PRICE

Fanning said at the time.

Winter in Chile was just beginning, and on the night of the incident, the outside temperature had dropped to 5° C for the first time since the camera had been installed. "Today's warmer, and it seems to have recovered," he said. "So we have two data points now."

Maybe the issue was related to the outside temperature. But that was a paradox. Why would the cryoplate warm up as the outside air cooled off? And why was the critical temperature around 5° C, not zero? "There's not a lot of things that change state at that temperature," Fanning said. It was puzzling.

At a planning meeting at 4:45 p.m. on May 9, Fanning proposed an experiment: Deliberately cool the telescope dome down to 5° C and see if the cryoplate glitched in the same way. "Then we'd have three data points." The team decided to wait for the temperature outside the dome to drop below the temperature inside, then open the dome a little to let some cold air in and see how the cryoplate reacted.

At 6:30 p.m., the inside temperature was 9.74° C and the outside was 11.69° C. So the team took out a pack of Uno cards and settled in to wait.

OPEN DATA, CLOSING DOORS

By 10 p.m., the temperature outside the observatory hadn't dropped. It had gone up 2 degrees.

"I'm feeling personally disrespected by the weather right now," Fanning quipped. The next morning, though, he was in a good mood. The cryoplate had kept its cool, which reassured the camera crew that the failure had been triggered by the cold outside.

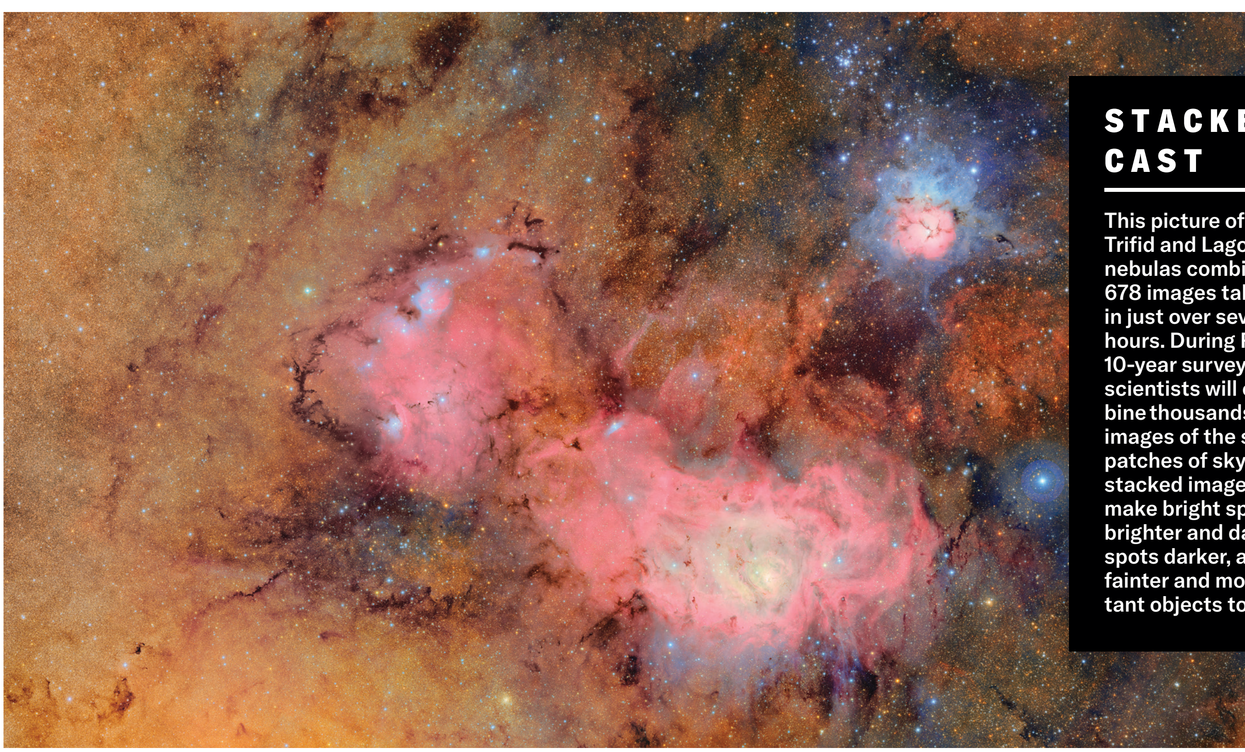
A few theories emerged: Maybe the oil in the refrigerant circuit started to congeal and couldn't cool the cryoplate as efficiently as it normally does. Maybe some water accidentally trapped in a thin pipe froze solid, causing a clog. If they could figure out where the cold spot is, they could wrap it in more insulation, like water pipes in a home.

The crew ended up turning the camera back on that night, and by the next night they were back to normal observations. They're still investigating the issue, Fanning told me, but they plan to add some insulation to the piping between the camera and the cryocompressors. The team is also adding heaters on the affected refrigerant lines and pumping extra heat into the dome.

"It was a difficult weekend, but I am very pleased by the progress we made and how the team got together to pivot back to an on-sky program so quickly," Fanning said by email. "This is what I love about commissioning new systems!"

In June, the telescope hit another big milestone: releasing Rubin's first images to the public. In an event in Washington, D.C., the Rubin team shared videos made up of hundreds of individual images from about 10 hours of observations.

The preview swooped through a field of 10 million galaxies and tracked over 2,000 previously unknown asteroids creeping across the sky. Rubin will eventually stitch together a patchwork quilt of images, with a new patch added every minute. Stacking images of the same spot over time will help faint objects



STACKED CAST

This picture of the Trifid and Lagoon nebulas combines 678 images taken in just over seven hours. During Rubin's 10-year survey, scientists will combine thousands of images of the same patches of sky. Those stacked images will make bright spots brighter and dark spots darker, allowing fainter and more distant objects to pop.

RUBINOBS/NOIRLAB/SLAC/NSF/DOE/AURA

pop out from the dark background.

About 90 percent of its time will be devoted to the wide and deep survey. But some of the time will be reserved for pointing at things quickly, like responding to alerts for supernovas or the faint ripples in spacetime known as gravitational waves. That's too complicated to do by hand, Ivezić says.

"One astronomer can't do it in their head." So a software named Scheduler will respond to alerts and run the observations autonomously. "It makes our telescope a … robot astronomer, who knows what we care about," Ivezić says.

Rubin will then put out alerts about cosmic events almost in real time, process and store the data on its own servers and let scientists bring in their analysis software. Indeed, anyone will be able to go to the telescope website and play with Rubin data, including students and amateur astronomers. "It's really your ideas and your knowledge and your persistence that determine the science you can do," Ivezić says.

But this open-door research philosophy is coming at a time of contraction for U.S. science. The White House's proposed budget for fiscal year 2026 would cut more than $5 billion from NSF's and more than $1 billion from DOE's science budget. At press time, Congress looked set to reject that proposal but had not yet passed a budget bill.

It was too late for funding cuts to prevent the telescope's completion. But scientists worry about continuity of funding over the next decade, and for the careers of the young scientists who will continue that work.

"Why would you ever build a world-class, unique facility and not … reap the scientific gains from it?" Tyson asks.

The Trump administration has also cut funding for and removed programs focused on diversity, which has included initiatives to encourage women in astronomy. The observatory was named after Vera Rubin in 2019, during the first Trump administration. Trump himself signed a congressional act declaring the moniker, which makes Rubin the first major U.S. observatory named after a woman. The project has had outreach and diversity initiatives baked into the mission since the beginning.

"WHY WOULD YOU EVER BUILD A WORLD-CLASS, UNIQUE FACILITY AND NOT … REAP THE SCIENTIFIC GAINS FROM IT?"

—Tony Tyson

But shortly after Trump's second inauguration, Rubin's biography on the observatory website was altered to remove references to present-day bias in astronomy. The website's Diversity, Equity and Inclusion page was taken down.

Even before concerns about funding set in, experts were worrying about an emerging threat to all ground-based astronomy: satellite megaconstellations.

Rubin is beginning its survey of things that move in the cosmos during an explosion in the number of satellites in the sky. SpaceX began launching its Starlink megaconstellation in 2019, and other companies are getting in on the action. To date, more than 9,000 new satellites have launched as part of megaconstellation projects, and some experts expect we'll have between 50,000 and 500,000 satellites in low Earth orbit in the coming decade. When those satellites cross Rubin's field of view, they leave a long white streak on the detectors, blocking or otherwise marring the telescope's images.

Scientists are finding clever work-arounds, such as data processing software that can tell the difference between cosmic objects and satellite streaks. A 2022 paper also suggested a way to change the Scheduler algorithm to avoid streaks as much as possible, though it would sacrifice about 10 percent of the instrument's observing time. Whether that trade-off is worth it depends on how much science the survey would lose, which isn't clear.

WAKING THE DRAGON

About an hour before I headed down from the mountain back in May, the crew decided everything was healthy enough to activate the telescope. Everyone working onsite that morning, about 15 people, hustled upstairs into the dome to watch. When we entered, the dome was rotating, and it felt like the floor beneath us was moving instead.

The dome was like a cathedral, cavernous and round. But nothing echoed: The telescope filled most of the space, and the dome walls were covered with black corrugated baffling to absorb stray light that also soaked up much of the sound.

Seated in a rolling desk chair with a laptop, Fanning commanded the telescope to do a series of prechoreographed moves designed to test its range of motion: Look up, slew from low to high on an angle, spin around 180 degrees.

Rubin in motion was like a dragon waking up. It moved smoothly, purposefully, with surprising elegance and speed. It leaned its head back, shook out its shoulders and turned its face to the sky, ready to open its eyes. ✖