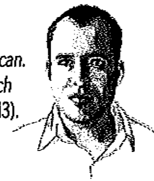
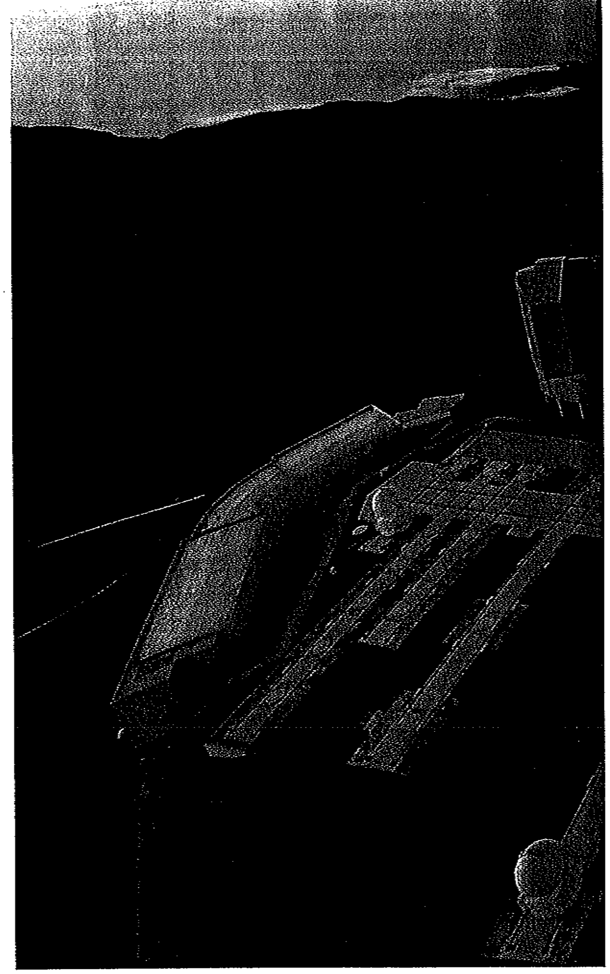


Lee Billings is an associate editor at *Scientific American.* He is author of *Five Billion Years of Solitude: The Search for Life among the Stars* (Current/Penguin Group, 2013).



High in the remote Andes of central Chile, the night sky is so dark that the constellations are hard to see, swallowed up in swarms of fainter stars. The familiar yet alien view can be disconcerting, but something else troubles Bruce Macintosh when he looks up late one May evening in 2014. Even here, at 2,700 meters above sea level, he is still staring through an ocean of air, and the wind is rising. The stars overhead are twinkling a bit too much for his purposes.

Macintosh is here to look for other Earths—or, more precisely, for other Jupiters, which some scientists think are necessary for rocky, habitable, Earth-like planets to exist. He is not interested in finding planets like most astronomers do, watching for months or even years as subtle shifts in a star's motion or brightness gradually reveal the presence of an unseen world. He is after instant gratification: he intends to take actual pictures of remote planets, to see them as points of light circling their distant stars, to look on their gas-swirled faces across the gulf of light-years. Macintosh, an astronomer at Stanford University, calls this "direct imaging."

Besides the wind, there is another reason Macintosh is troubled: 600 kilometers to the north, on another arid Chilean peak, astronomer Jean-Luc Beuzit is trying to do the exact same thing. Beuzit, an astronomer at the Grenoble Institute of Planetology and Astrophysics in France, is Macintosh's friend—as well as his rival. Fate and funding have brought these men to the mountains at the same time to scour the heavens for planets, to learn whether our own is as common as dirt or cosmically rare.

Macintosh's tool of choice in this astronomical race is a multimillion-dollar car-sized complex of optics and sensors called the Gemini Planet Imager (GPI). It is mounted to the immense eight-meter mirror of the Gemini South telescope, a polished disk of silvered glass that would take up an eighth of a regulation basketball court. Macintosh and other astronomers pronounce the instrument's acronym "gee pie," as if they are exclaiming about pastry. Beuzit's answer to GPI is an even bigger, minivan-sized collection of gadgets called SPHERE, for Spectro-Polarimetric High-contrast Exoplanet REsearch instrument. SPHERE is mounted

IN BRIEF

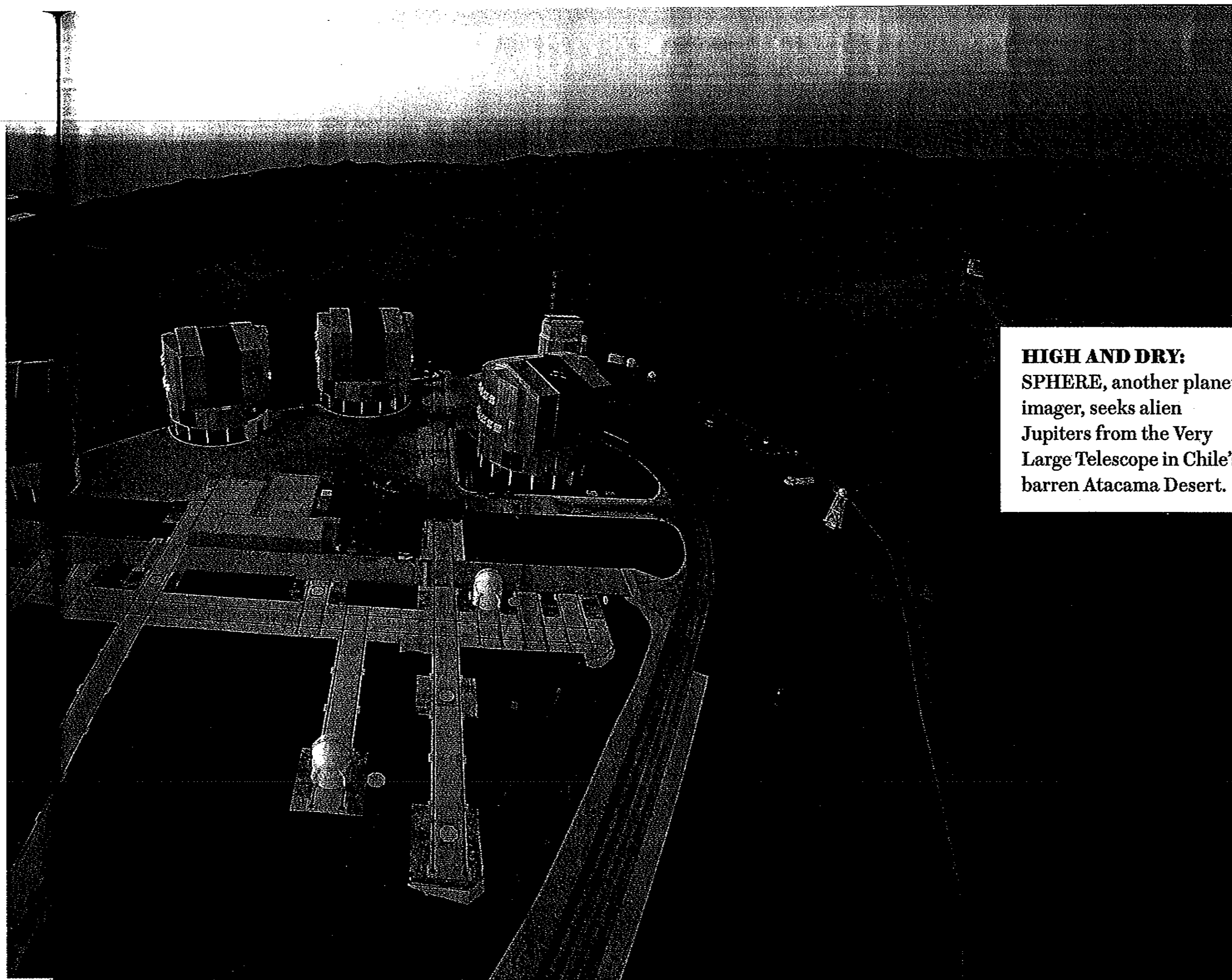
Astronomers know of thousands of planets orbiting other stars but have imaged only a handful. They have discovered and studied all the rest mostly through indirect measurements.

Imaging a planet allows researchers to learn more about its composition, climate and prospects for life. But imaging is hard because planets are faint and close to much brighter stars.

Imaging Earth-like planets is beyond the reach of current telescopes. A new generation of instruments is now taking pictures of bigger, brighter worlds that resemble our own Jupiter.

These new instruments will help scientists learn how giant planets form and how they sculpt their surroundings, preparing the way for future facilities to take pictures of alien Earths.

PRECEDING PAGES: COURTESY OF GEMINI OBSERVATORY/AURA; THIS PAGE: COURTESY OF G. HÜDEPOHL/EUROPEAN SOUTHERN OBSERVATORY



HIGH AND DRY: SPHERE, another planet imager, seeks alien Jupiters from the Very Large Telescope in Chile's barren Atacama Desert.

on another eight-meter telescope, at the European Southern Observatory's Very Large Telescope array. Both projects have been in development for more than a decade but debuted within months of each other. From their remote mountaintop perches, they are surveying mostly the same stars, seeking to be the first with breakthrough snapshots of alien Jupiters.

Of the more than 5,000 worlds discovered orbiting other stars over the past two decades, scarcely any have actually been directly imaged. Taking pictures is hard because even the largest, least inhabitable planets are still very dim and appear very close to their far brighter suns, as seen from far away. Take a picture of a planet—even if it is a small smudge of pixels—and you can learn a lot about that world's composition, climate and possibilities for life. GPI's and SPHERE's quest for Jupiter-like worlds is the state of the art; humans have yet to build telescopes big and sophisticated enough to distill the faint light of an alien Earth from the overpowering glare of an adjacent star. But when and if they do, those facilities will almost certainly use instruments developed from these two projects.

In astronomy, as in everyday life, seeing is believing. Although direct imaging can be fiendishly difficult, it can also be much faster than today's dominant planet-detection techniques, potentially delivering discoveries through pictures that take hours or days to obtain rather than through months or years of painstaking analysis on arcane stellar data sets. Which is why, in this race to take the first pictures of alien Jupiters, it is not a stretch to say that every minute counts.

THE TORTOISE AND THE HARE

TIME WEIGHS HEAVILY on Macintosh as he works in Gemini South's control room late that night in May 2014. He has a boyish face, with a crescent of brown hair and lively eyes that peer from behind thick glasses. He is running on Diet Coke and adrenaline, still jet-lagged from a string of connecting flights from California to Chile. One of his shoes is untied, and a faint smell of smoke wafts through the air from a forgotten dinner of frozen pizza, now carbonized in a nearby toaster oven. As he gazes at a bank of computer screens monitoring GPI's vitals, it seems only his body is in the room—his mind is elsewhere, in the adjacent dome housing the eight-meter telescope, following beams of light bouncing through the innards of his instrument.

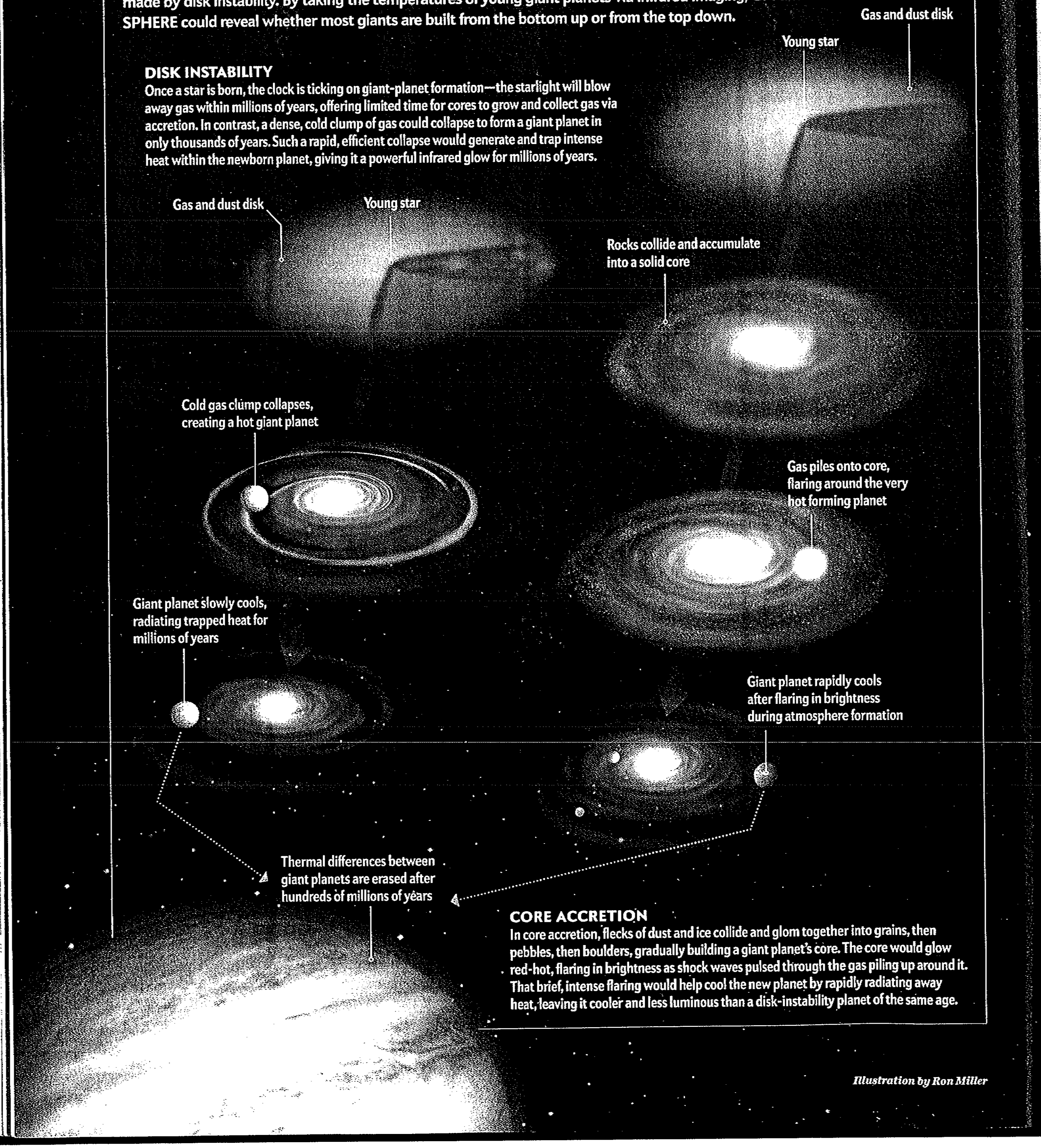
Before GPI can start finding new planets, it first must go through "commissioning," an extended sequence of tests and calibrations that started in late 2013 and, by this time in May 2014, is in the final stages. The work is tedious and unglamorous—no one has ever won a prize for making sure an instrument operates prop-

Birth of a Gas Giant: Two Scenarios

Planets form from the same disks of gas and dust that give birth to suns. A process called core accretion can make giant planets from the bottom up, as tiny objects stick together to gradually build bigger ones, assembling a large core that sweeps up a thick atmosphere. But a faster, top-down pathway called disk instability exists, in which clumps of gas collapse directly into planethood. On average, young giants made by core accretion should be cooler than those made by disk instability. By taking the temperatures of young giant planets via infrared imaging, GPI and SPHERE could reveal whether most giants are built from the bottom up or from the top down.

DISK INSTABILITY

Once a star is born, the clock is ticking on giant-planet formation—the starlight will blow away gas within millions of years, offering limited time for cores to grow and collect gas via accretion. In contrast, a dense, cold clump of gas could collapse to form a giant planet in only thousands of years. Such a rapid, efficient collapse would generate and trap intense heat within the newborn planet, giving it a powerful infrared glow for millions of years.



CORE ACCRETION

In core accretion, flecks of dust and ice collide and glom together into grains, then pebbles, then boulders, gradually building a giant planet's core. The core would glow red-hot, flaring in brightness as shock waves pulsed through the gas piling up around it. That brief, intense flaring would help cool the new planet by rapidly radiating away heat, leaving it cooler and less luminous than a disk-instability planet of the same age.

Illustration by Ron Miller

erly. In a race measured in minutes, GPI has a quarter-million-minute lead over SPHERE, which, by this same time, has only just begun the commissioning process. That is small comfort to Macintosh, however, because SPHERE has a more capable suite of instruments and more guaranteed telescope time than GPI, which should allow SPHERE to observe a greater number of stars in a larger field of view at higher spectral resolutions across a wider range of wavelengths. In other words, even though GPI is out front, like the hare in Aesop's famous fable, SPHERE could still come from behind, tortoiselike, and find the sought-after planets first.

The twinkling of the stars comes from turbulence in the atmosphere, which has pushed the GPI team behind schedule. Waiting for the wind to die down, Macintosh tells me stories from years ago, when he, Beuzit, and other high-ranking members of the GPI and SPHERE teams would carouse at astronomy conferences around the world, their future conflict far from their minds. Those times are long past. "We'd get together, drink heavily and trade stories," Macintosh says. "Even now, they aren't really the enemy—the clouds are the enemy. And the wind."

After half an hour, the winds have abated. "Okay, let's look at HD 95086," Macintosh says, spinning in his chair to address the dozen or so team members in the room. They spring to action, keying commands into the computers controlling the telescope in the dome next door. Within moments the telescope has slewed to the target, a bluish-white dwarf star 300 light-years from Earth, in the constellation Carina. HD 95086 is a young star in astronomical terms—only about 17 million years old—and bears a giant planet five times more massive than Jupiter, orbiting approximately twice as far out as Pluto. Earlier, less capable direct-imaging projects have seen this planet before—the team will calibrate GPI by comparing its new images with the earlier results.

Most planets are far fainter than their stars, flecks of dust around nuclear fireballs. Young Jupiters are different. They are more like embers cooling far from a campfire, which is why GPI or SPHERE has any hope of seeing them.

Like all the worlds that GPI seeks, this particular planet has scarcely cooled at all since its formation. It glows brightly in infrared light. In terms of brightness, most planets are millions or billions of times fainter than their stars, flecks of dust on the cusps of thermonuclear fireballs. Young Jupiters are different. They are more like red-hot embers cooling far from a campfire, which is precisely why GPI or SPHERE has any hope of seeing them and learning how exactly they formed and evolved.

JUPITER'S SECRET ORIGINS

AMONG EXPERTS, it is an embarrassing open secret that no one really knows how the largest object orbiting our sun came to be. But the experts desperately want to find out because Jupiter and other giant planets are the architects of planetary systems, shaping all that surrounds them.

Most of the known giant planets around other stars are not really like Jupiter at all. Many exist in scorching half-week orbits alien to anything in our own solar system. The prevailing theory is that these hellish worlds were born much farther out, only to spiral down to hug their suns because of gravitational interactions with other planets or flows of gas. That migration would be bad news for habitability—along the way, the gravitational field of an in-spiraling giant planet would most likely toss any small, rocky planets out into the interstellar dark or down into the fires of its star. Such giant worlds are too close to their stars to be directly imaged with today's technology.

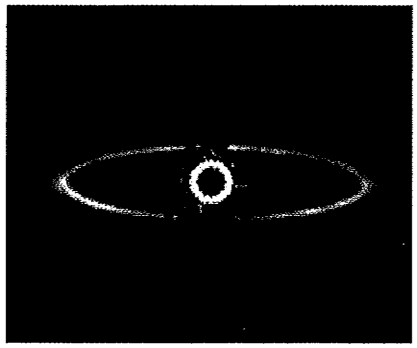
Like its much hotter exoplanetary cousins, Jupiter probably also migrated early in its life, but for reasons unclear, its migration was only temporary and did not bring the giant planet within spitting distance of the sun. Instead it perhaps ventured about as far in as present-day Mars, before retreating back to the outer solar system, where it has stayed ever since. And although the motions of a giant planet can sabotage a planetary system's habitability, in Jupiter's case they seem to have made our solar system a more hospitable place. At the least, Jupiter's peregrinations are thought to have flung water-rich comets and asteroids down to our already formed planet, delivering life-giving oceans. At most, Jupiter's plunge into the inner solar system might have even cleared out other preexisting planets, allowing Earth to form in the first place. Even so, what Jupiter gives, it could take away. Millions of years from now, Jupiter may pummel our planet again with more giant asteroids or comets, generating cataclysmic impacts that would boil off our oceans and steam-cook our biosphere.

All these details, to some degree, can be traced to the nature and timing of Jupiter's mysterious formation. This much is certain: just more than four and a half billion years ago, a cold cloud of gas and dust collapsed to form our sun. The remnants of the cloud that did not fall into our nascent star spun out into a disk, and from this material planets formed. Rocky worlds, being relatively small, are easy to assemble in a bottom-up process called core accretion, where colliding rocks gradually glom together over as much as 100 million years. Most researchers suspect Jupiter formed in the same way. But to do so, it would have had to form far faster, building up Earth-sized cores in perhaps 10 million years, time enough to sweep up huge atmospheres before the gassy feedstock is blown away by the intense light of a young star.

Another possibility exists. Giant planets could also form much like stars do in a top-down process called disk instability. In this scenario, something like Jupiter would achieve planethood through the direct, rapid collapse of a cold, overdense clump of gas and dust in the outer region of a circumstellar disk. It is almost impossible to distinguish between these two scenarios for Jupiter today because essentially all the evidence is literally buried below the giant planet's dense, thick atmosphere.

Fortunately, there is another way to test whether giant planets form from the bottom up or the top down: you can take their temperatures. A top-down formation directly from a collapsing clump of gas would happen so quickly that an enormous amount of heat would be trapped within the planet. A bottom-up formation would instead produce giant planets that, though still initially red-hot, would be relatively cooler. "As more and more gas falls onto a rocky core, it's impeded by the gas below it, by the atmosphere forming around the core," says GPI collaborator Mark Marley, whom I speak to later, a planet-formation theorist at the NASA Ames Research Center who helped to model the process. "A shock develops as the gas slows down, and most of the energy of that infalling gas radiates out, which flash-cools the forming planet. So when you stop dumping gas on, the planet is much cooler than it would've been from a direct collapse."

Thus, a giant planet's temperature is effectively a memory of its birth. The older the planet gets, the more it cools, and the more its memory fades. Some four and a half billion years old, Jupiter long ago forgot how it formed. But giant planets younger than a few hundred million years—the very planets GPI and SPHERE are trying to image in the infrared—should still have their thermal memories intact. Surveying hundreds of bright, youthful nearby stars, both projects may probe the temperatures and histories of dozens of giant planets, unraveling the secret of their formation and shedding light on how habitable systems like our own came to be.



UNBLINKING EYE: Light from the star HR 4796A is filtered out in this SPHERE image, revealing a faint ring of dust, perhaps sculpted by an unseen planet.

IMAGING AN ALIEN JUPITER

AS THE GPI TEAM PREPARES to observe HD 95086, a monochrome circle materializes on one of Macintosh's screens. It seems to contain a heavily pixelated fluid, like a digitized close-up of a rushing river or an untuned television awash with static.

"You're looking at the wind," Macintosh says. "That's starlight shining through atmospheric turbulence and falling on a detector that drives our adaptive optics." Adaptive optics are computer-controlled deformable mirrors that change their shape hundreds or even thousands of times a second to combat atmospheric distortions, allowing astronomers to capture images of celestial objects that rival those available from space telescopes. With a few keystrokes and verbal commands to his team, Macintosh powers up GPI's adaptive optics. Mounted underneath the eight-meter telescope, GPI's two deformable mirrors—an off-the-shelf glass "woofer" and a smaller, custom-built "tweeter" packed with more than 4,000 actuators—are now rippling and curling in synchrony, matching each transient light-smearing pocket and flow of overlying air with a corresponding dip or spike in their surfaces, sculpting the rays of starlight back to near perfection. The result seems magical: the turbulent circle on Macintosh's screen becomes smooth and placid, as if the atmosphere overhead has suddenly disappeared. HD 95086 is now a brilliant glare on-screen. There is no sign of a planet.

To reveal the star's known planet, Macintosh engages another device, a coronagraph, that strips out most of the starlight: the light encounters a series of masks that filter out 99 percent of the photons. The ones that make it through are focused and aimed at a mirror with a central hole polished to atomic-scale smoothness. "The star's light falls down the hole," Macintosh explains, whereas a planet's light will instead bounce off the mirror and go deeper into the instrument, reaching a supercooled spectrograph that splits the light into its constituent wavelengths (or colors).

The picture on-screen is now a lumpy halo of white light surrounding a deep, central shadow where HD 95086 should be. The lumps—called speckles—are formed from unwanted starlight that leaks through the coronagraph. Speckles can obscure a planet in GPI's images or even masquerade as one. To distinguish between speckles and planets, the team takes a sequence of exposures at various infrared wavelengths. "The separation between a star and a speckle is proportional to the wavelength of light in an image," says GPI's project scientist James Graham, a professor at the University of California, Berkeley, as we stare at the screen. At shorter, bluer wavelengths, a speckle will appear closer to a star; at longer, redder wavelengths, that same speckle will appear farther away, Graham explains. "So when you see the whole [wavelength] sequence, the speckles will move. A planet won't."

Macintosh scrolls back and forth through the stacked exposures like frames in a movie, and the halo seems to breathe, expanding and contracting as all the lumps move in unison. All the lumps, that is, save for one: a lone, fixed dot of planetary light fished from a sea of stellar speckles. In less than half an hour, we have gone from seeing only the wind to staring at a distant world around another star. Further analysis of the planet's spectrum from GPI data hints that the planet is extremely red, perhaps the result of an excess of light-scattering dust in its upper atmosphere. It is a small but thrilling detail to learn about a world that is 300 light-years away.

Not all targets are so difficult to see; closer, brighter stars can give up some of their secrets far more readily. Earlier, the GPI team had needed only a single 60-second exposure to capture an image of Beta Pictoris b, a hot, young giant planet 63 light-years from Earth that orbits its star at almost twice the Jupiter-sun distance. The ease of seeing that planet suggests that direct imaging, at last, is becoming routine: a slightly older direct imager on Gemini South had previously taken a similar image of Beta Pictoris b, although it required more than an hour of observation and extensive postprocessing. The new images allowed the GPI team to estimate the orbit of Beta Pictoris b with higher precision than ever before, revealing that in 2017 it might transit across the face of its star as seen from Earth—a rare alignment that would be a boon for scientists seeking to learn more about the distant giant.

In the remaining hours before sunrise, the GPI team images binary stars, faint debris disks, and even Saturn's moon Titan, peering down through its thick, hazy, hydrocarbon-filled atmo-

COURTESY OF JEAN-LUC BEUZIT ET AL./EUROPEAN SOUTHERN OBSERVATORY/SPHERE CONSORTIUM sphere to its blotchy surface. Near dawn, when the glow of the approaching sun begins filtering up from the horizon, Macintosh leans far back in his chair and sighs, exhausted but satisfied.

On the final night of the six-day run, the GPI team finds its first planet, orbiting a 20-million-year-old star at twice the Jupiter-sun distance. Macintosh is not the first to notice it—Robert de Rosa, a postdoctoral student at U.C. Berkeley, spies the flickering dot while looking over another teammate's shoulder at some otherwise unremarkable GPI images. Subsequent observations show it to be between two and three times Jupiter's mass, with a methane-filled atmosphere hot enough to melt lead. The planet is 100 light-years from Earth, but it is the closest thing to Jupiter astronomers have ever seen.

"This is the first planet anyone has ever found that looks like a warm version of Jupiter rather than a very cool star," Macintosh says. "This planet may be young enough to still 'remember' its formation process. With enough observations we could pin down its mass and age and figure out whether it formed from the bottom up, like we think Jupiter did, or from the top down, like a star."

When Macintosh tells me, he also vows me to secrecy until the GPI team can write and submit a paper. "SPHERE could very easily see this, too," he says. "We don't know if they've looked yet at the same star. We are all nervous we'll get scooped."

FIRST LIGHT FOR THE FUTURE

SHORTLY AFTER DAWN, I leave Gemini South, catch an airplane north, rent a car and speed on a lonely highway through Chile's high, dry Atacama Desert, traveling more than 600 kilometers door-to-door to reach SPHERE before night falls. I arrive at SPHERE's observatory, the Very Large Telescope, just after sunset. In a cramped control room Beuzit, the project's leader, is marshaling his troops as the commissioning begins. The astronomers are hunched over computer screens, quietly conversing in French, German and English, trying to ignore the cameras and boom microphones of a visiting documentary film crew. Beuzit, with his unkempt dark hair and beard, looks a bit like the late film director Stanley Kubrick. He drifts from station to station, sipping espresso, pausing here and there to listen and advise. A recently emptied bottle of Laurent-Perrier champagne sits on a nearby bookshelf, "SPHERE 1st Light" scrawled in black marker on its label.

SPHERE performs admirably during commissioning, producing gorgeous pictures of a variety of celestial targets, including a faint dust ring around HR 4796A, an eight-million-year-old star 237 light-years from Earth in the constellation Centaurus [*see illustration on opposite page*]. Later, as I gaze at the ring with the blotted-out star at its center, I feel like I am being watched—it looks like an enormous eye, staring across the interstellar gulf. But despite those pretty pictures, on the night of my visit, SPHERE is not quite ready to go discover new planets, Beuzit tells me. Not all is well with the system's adaptive optics: some of the mirror-bending actuators on SPHERE's €1-million, 1,377-element deformable mirror are failing, and no one on the team can figure out why. The ultimate solution, Beuzit says, may be to replace the entire mirror with a new one using different actuator technology. Even so, he is optimistic that SPHERE and GPI alike will each meet and exceed their goals. In the meantime, commissioning must go on—it concluded earlier this year, generating its own first batch of early science observations, producing images of several previously imaged planetary systems.

When I ask him about SPHERE's rivalry with GPI, Beuzit's first response is only to smile and sip his coffee. After a moment, he speaks carefully. "Once we both start discovering new planets, no one will remember who was first on-sky," Beuzit says. "I'm not saying that we won't compete and fight, us and the Americans. But Bruce Macintosh and I have known each other for 15 years, and we both know how hard this is. We celebrate our successes and share our difficulties to improve both of our systems, to prepare the way for the next generation of observatories and imagers."

"We are entering a new age as all these facilities come online at almost the same time," says Dimitri Mawet, a professor at the California Institute of Technology and at the time a SPHERE principal instrument scientist. "We're going to discover many wonderful things, but we're also going to significantly push the adaptive optics technology forward. That will be fundamental for the next generation of telescopes, which will require these kinds of controls just to keep their huge mirrors aligned."

One of those new telescopes is being planned just 20 kilometers to the northeast of SPHERE, on the 3,000-meter peak of Cerro Armazones. Shortly after my visit, explosives blast off the peak's top, clearing ground for the construction of the European Extremely Large Telescope, one of three supersized observatories slated to debut in about a decade. Paired with the unprecedented light-gathering power of such an observatory's gargantuan 30- or 40-meter mirror, a system similar to SPHERE or GPI would be able to image not only self-luminous Jupiters but also cooler, 1,000 times fainter, potentially habitable planets orbiting the sun's nearest neighboring stars. A dedicated direct-imaging mission in space could then probe them even further, seeking signs of life. Provided, that is, such worlds are even there to see. The prospect of getting those images, glimpsing alien Earths, is what motivates many of the people behind projects such as GPI and SPHERE.

Macintosh had said as much during our conversations at Gemini South: "I see everything we're doing now as steps along the road toward a picture of another Earth. Someday we will have that picture. If we finally get results on the fraction of small, rocky planets that include really relevant things—which ones have oceans, atmospheric oxygen, and so on—and that number turns out to be very tiny, well, that's probably pretty important. It may make no practical difference to the progression of our civilization for a very long time, but philosophically, being able to say that 'ours is the only place like this within 1,000 light-years,' maybe that would cause us to try a little harder not to screw it up." ■

MORE TO EXPLORE

Exoplanet Detection Techniques. Debra Fischer et al. in *Protostars and Planets VI.* University of Arizona Press, 2014.

First Light of the Gemini Planet Imager. Bruce Macintosh et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 111, No. 35, pages 12,661–12,666; September 2, 2014.

SPHERE Science Verification. Bruno Leibundgut et al. in *Messenger,* No. 159, pages 2–5; March 2015.

FROM OUR ARCHIVES

Searching for Life on Other Planets. J. Roger P. Angel and Neville J. Woolf; April 1996.

The Dawn of Distant Skies. Michael D. Lemonick; July 2013.

scientificamerican.com/magazine/sa