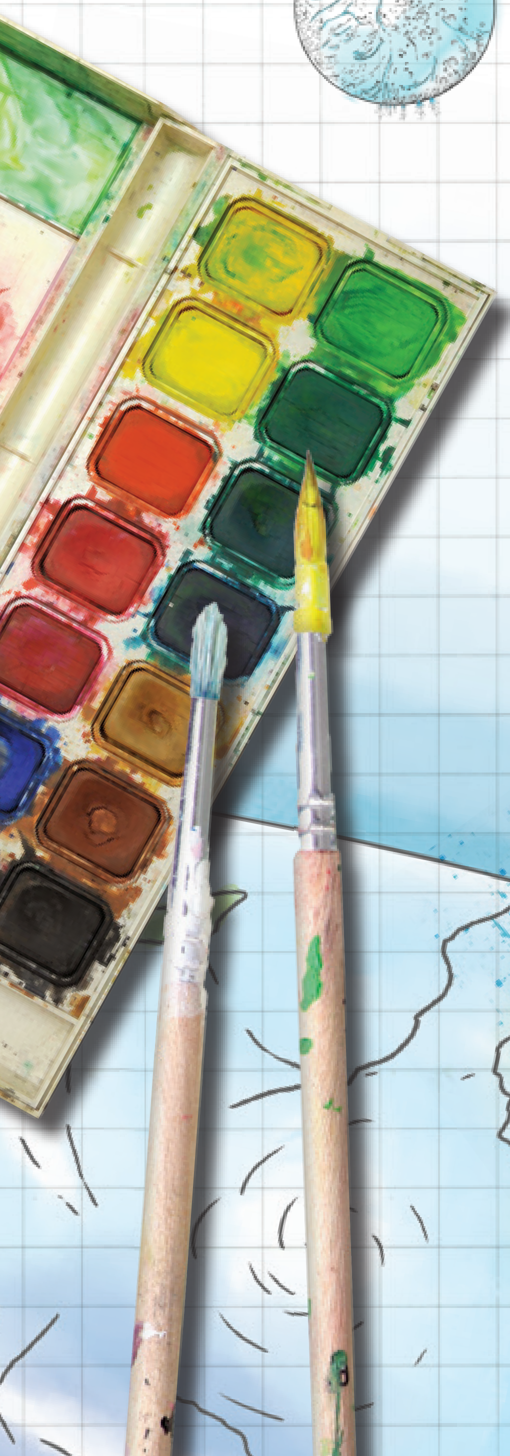
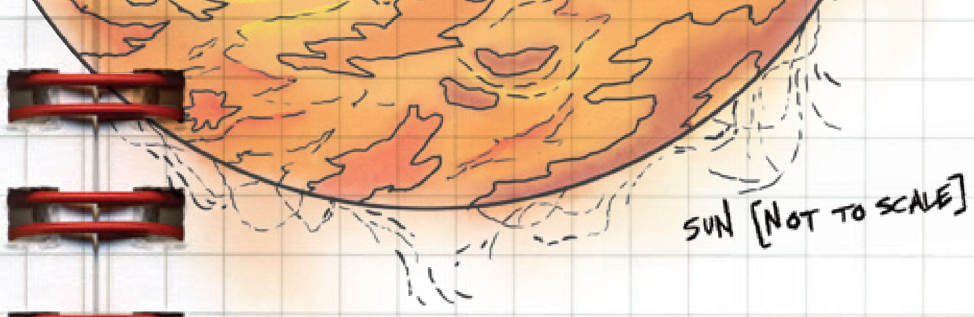
Worlds Together

The Caltech Center for Comparative Planetary Evolution (3CPE) unites astronomers, geologists, planetary scientists and others in one shared mission to understand what different planets can tell us about the evolution of the cosmos and the rise of life.

By Andrew Moseman

Illustrations by Lance Hayashida





Woody Fischer loves a problem with a bewitching name. Consider, for example, the "faint young sun paradox."

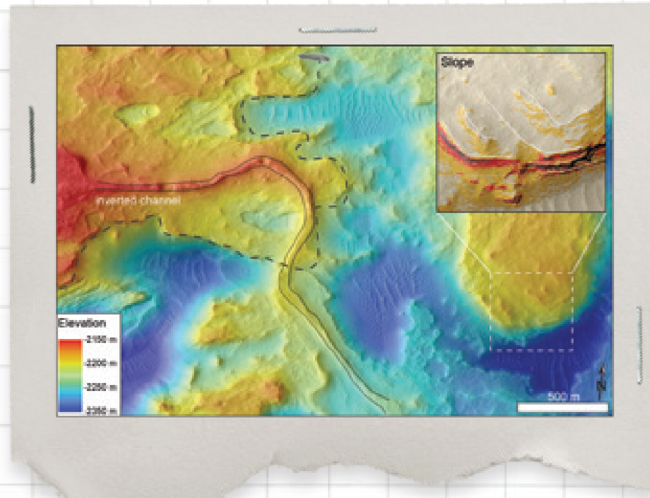
Fischer, a Caltech professor of geobiology, explains the problem this way: based on the well-understood physics of similar stars, the sun should have been 30 percent dimmer a few billion years ago. If our star were so dim, Fischer says, Earth would have been a ball of ice. Yet geologic evidence shows plenty of liquid water on the surface at that time, and we know life found a way.

In the 1970s, astronomers including Carl Sagan proposed a solution: Earth back then had more atmospheric greenhouse gases than researchers expected there would have been, which would have trapped enough sunlight to warm the planet. Their answer seemed to be satisfactory, until a new problem arose from the surface of another world. Data from the rovers and orbiters sent to Mars over the past several decades revealed that the Red Planet was warm and wet during the same period. But Mars is even farther from the sun than Earth is, and it would not have possessed enough atmosphere for Sagan's solution. Something else must have been going on, Fischer says.

"That's just an example of what you stand to learn when you get data from another planet and it shakes you out of your understanding," he says. "This thing I thought I understood that we all accepted, wrote up in the textbooks ... maybe this thing's not settled at all."

The new Caltech Center for Comparative Planetary Evolution (3CPE) is dedicated to such a premise: that comparing planets and moons to one another can lead to new insights and raise new questions. These scientists work to unite core topics for Caltech and the Jet Propulsion Laboratory (which Caltech manages for NASA), such as geochemistry, astronomy, and planetary science as part of an interdisciplinary effort that seeds collaborative research projects among these disciplines. Mike Brown, the Richard and Barbara Rosenberg Professor of Planetary Astronomy, holder of the Terence D. Barr Leadership Chair for 3CPE, and head of the new center, says the joint effort will deepen the understanding of our solar system, aid the hunt for new Earth-like worlds, and further the quest to understand the origin of life on this planet and the search for it elsewhere.

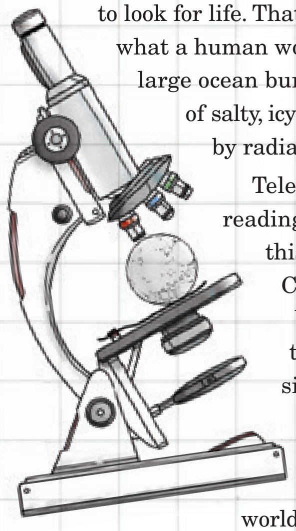
Woody Fischer



Ancient delta and mineral data suggest Mars was warm & wet — but what does that mean for early Earth and the rise of life?

"We're all really asking the same questions about how planets and planetary systems evolve," Brown says. "But, typically, we tend to ask these questions from within our own areas of expertise while perhaps missing some of the bigger picture and accumulated knowledge around us. There are real reasons for geochemists to talk to astronomers and vice versa. If you want to try to understand how an atmosphere of a planet evolves, for example, you need those conversations to happen."

A MOON IN A LAB



Jupiter's moon Europa is one of the most promising places to look for life. That does not mean its environment is what a human would call hospitable. The moon has a large ocean buried beneath a cracked surface made of salty, icy material that is constantly bombarded by radiation.

Telescopes have taken spectroscopy readings to understand the makeup of this strange world, and the Europa Clipper NASA mission, led by JPL, will launch in 2024 to fly by the moon, study it, and scout sites for a potential future Europa lander. "This is a big push over the next decade or so," Brown says. "NASA is going to these ocean worlds, these icy locations, and this is kind of the beginning of that exploration."

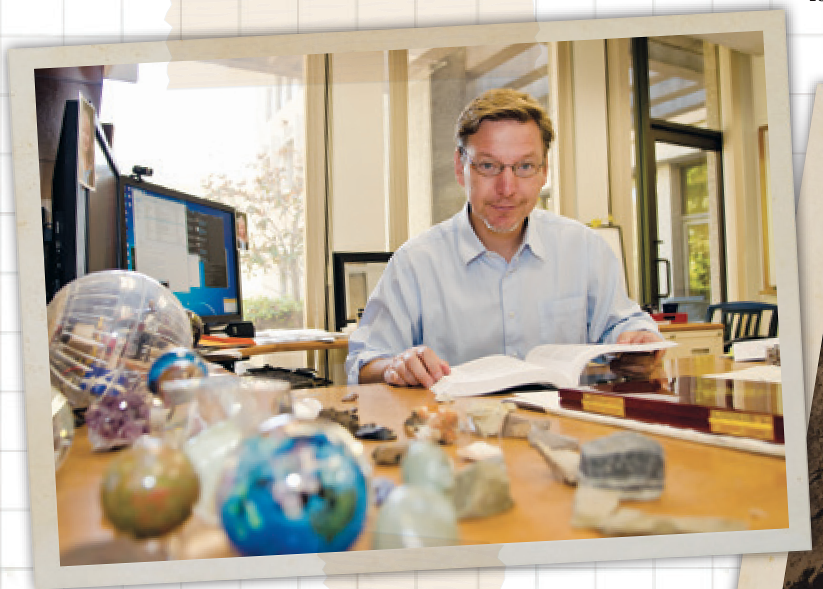
CAN'T WAIT!

Still, so much about this promising moon remains a mystery. For instance, Brown says, "What is it that you would see that would tell you something has been alive?" Geochemists have dedicated decades to deepening their understanding of how organic materials degrade and are preserved on Earth, but no place like Europa exists on this planet. That is why Brown and Caltech collaborators including Alex Sessions, professor of geobiology, and Victoria J. Orphan, the James Irvine Professor of Environmental Science and Geobiology, have begun to recreate the surface of Europa.

To simulate the moon's chemical interactions, the team repurposed a cesium-137 irradiator previously used for cancer research to bombard rock samples embedded in ice with gamma rays. A second instrument, nicknamed Sputnik, employs a vacuum chamber that can mimic the temperatures and atmosphere present on Europa to measure how water ice and other basic molecules react to such conditions. The project could determine what materials should be present on Europa's surface and, by extension, which materials would be an interesting aberration, and perhaps a sign of life, if found.

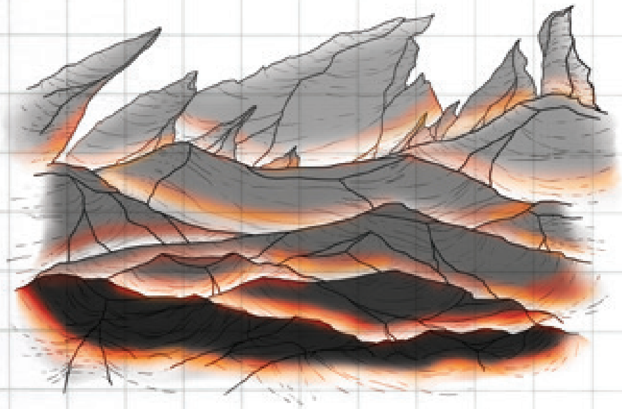
Jupiter's moons tell a story not only of ice but of fire. The most volcanically active body in the solar system, Jupiter's moon Io, is a pockmarked hellscape of lava lakes and liquid rock. Formerly volcanic places, such as Mercury and Earth's moon, wear their history on their surfaces, as their craters and lava plains testify to long-ago impacts and ancient eruptions that solidified as they cooled. Not so Io, where lava paves over the past.

Katherine de Kleer, Caltech assistant professor of planetary science and astronomy, seeks to rediscover Io's hidden history. Celestial mechanics can explain the reason why the moon is so volcanic. Io is locked in an orbital resonance with Europa and with Jupiter's moon Ganymede, and the various gravitational pulls create tidal heating within Io. But researchers do not know how long the moon has been volcanically active.



MIKE BROWN

KATHERINE DE KLEER (ON EARTH)



SURFACE OF IO?

One of the few ways to elucidate the billion-year history of Io, says de Kleer, is by focusing on sulfur, as her lab is now doing. The element abounds on Io: sulfur dioxide frost coats the surface, while sulfur-dioxide and sulfur-monoxide gases are found in the atmosphere. Some of these gases will escape into space while the rest freeze onto the surface and are recycled into the moon's interior. Sulfur exists in nature primarily as sulfur-32, which contains 16 protons and 16 neutrons, but Io also contains a smaller amount of the isotope sulfur-34, which carries two additional neutrons. Each time the sulfur cycles from the atmosphere back to the moon's interior, the two kinds of sulfur are lost at different rates and the ratio between the two isotopes changes. At Io's current resurfacing rate, its entire mantle would have been recycled about 50 times during its history; de Kleer's lab is trying to use Io's sulfur isotopes to prove it.

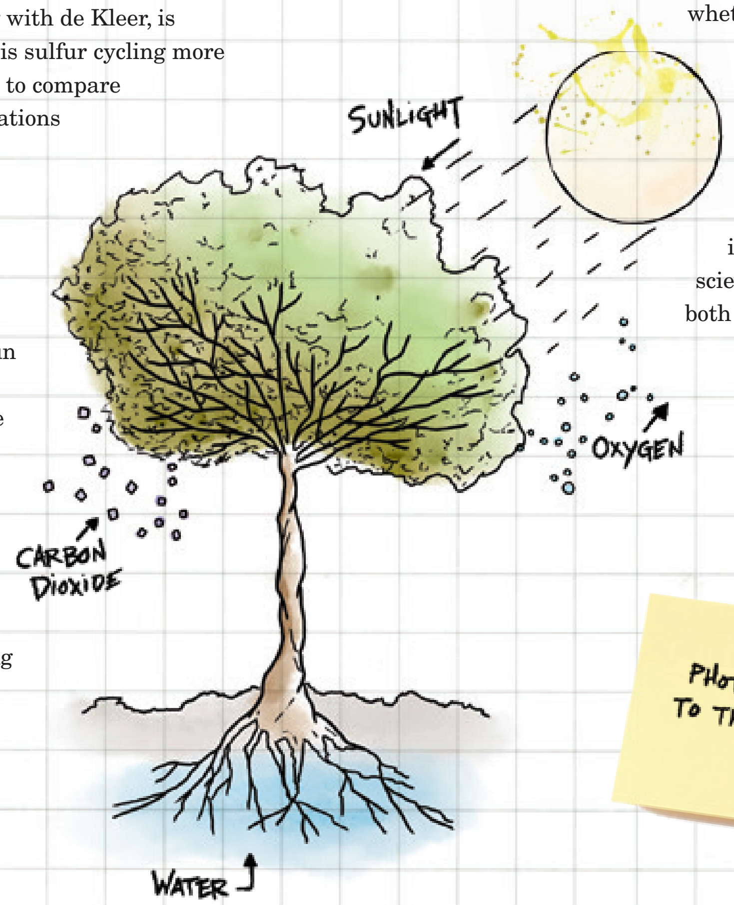
Ery Hughes, a postdoc working with de Kleer, is building a model to understand this sulfur cycling more completely. She and de Kleer hope to compare those predictions with real observations of sulfur isotopes from the Atacama Large Millimeter/submillimeter Array, or ALMA. (The ALMA isotope data for this study were supposed to arrive in March 2020 but have been delayed because of the COVID-19 pandemic.) "If we run that for the history of Io," Hughes says, "would we be able to recreate the isotope ratio we see today?" If so, that would indicate Io has been about as active as it is now throughout its history; if not, then the moon could have become volcanic more recently.

The scientists aren't just learning about Io for Io's sake, however. "It gives us an opportunity to better understand this process that is driving geological activity on moons all over the solar system as well as on exoplanets," de Kleer says. (An exoplanet is a planet that orbits a star outside our solar system.) Active geology also hints at the possibility of life existing on Saturn's moon Enceladus, which is another prime candidate for scientists in the search for life because of its geysers and warm subsurface ocean. Scientists have already modeled potential tidal heating in the TRAPPIST-1 system, composed of seven terrestrial planets discovered in 2017 and lying around 40 light-years from the sun.

TWO WORLDS ARE BETTER THAN ONE

It may be that Earth is a lonely outlier, perhaps the only world in the Milky Way that abounds with liquid water and life. Or it could be ordinary, just one of countless worlds that orbit in the habitable "Goldilocks" zones around their stars and contain the right stuff for life. Or the truth could lie somewhere in the middle. Science cannot begin to unravel this puzzle just by studying conditions on Earth, Fischer says. Researchers must learn more about other planets, be they neighbors within our solar system or distant newfound exoplanets.

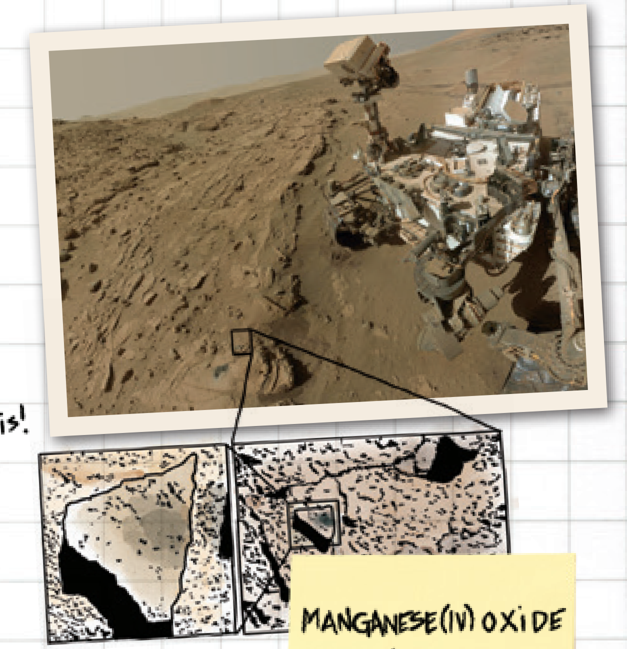
Earth history tells Fischer a tidy story: The planet becomes warm and wet. Life arises, creating a biosphere without much atmospheric oxygen. The arrival of photosynthesis pumps up the oxygen supply, allowing for multicellular complexity and, eventually, intelligent life. However, what Earth history cannot tell scientists is whether other planets follow the same sequence, and new data from Earth's most similar sibling, Mars, have thrown a wrench into how planetary scientists understand both it and Earth.



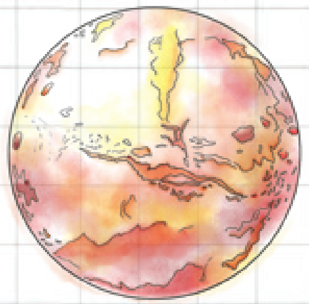
"One of the biggest breakthroughs in planetary science in the last 20 or 30 years is the recognition that Mars has a geologic record," Fischer says. "Just that discovery means that you're not stuck with what Mars looks like today, but you can ask questions about what it looked like in the past and how it came to be."

One example involves the manganese oxides the Mars *Curiosity* rover found near Gale crater in 2016. "Mars wasn't supposed to have these materials," Fischer says. That is because the manganese oxides on Earth postdate the rise of photosynthesis and the oxygenated atmosphere. One possible explanation for this difference is that Mars once had life; another less-explosive hypothesis is that there are ways for planets to make manganese oxides other than the biologically driven process found on Earth. Either way, Fischer says, surprises from the Red Planet not only change the perception of Mars but also raise new questions about how well we know our home world.

MARS WASN'T SUPPOSED TO HAVE THIS!



"Being able to take a discovery like that and flip it back on Earth is amazing," he says.



Other 3CPE researchers are refining techniques that could aid in the search for conditions friendly to life, including on Mars. Ilya Bobrovskiy, Texaco Postdoctoral Scholar Research Associate in Geobiology, focuses on life from the Precambrian eon, the vast period that predates the arrival of hard-shelled creatures 541 million years ago and makes up the bulk of Earth's history. Bobrovskiy takes samples from rock layers that have not been substantially changed since that time and studies the ratios of certain carbon isotopes (carbon-13 and carbon-12) to illuminate what happened in an environment that allowed more complex multicellular life to appear on the scene.

"In terms of comparative planetary evolution, the question I'm asking is, What does it take for a planet to create complex life?" Bobrovskiy says. That question will become increasingly important as scientists look for biosignatures around the solar system and beyond.

BEYOND THE SOLAR SYSTEM

Over the past quarter century, the catalog of known exoplanets has grown from a handful to several thousand. That explosion was driven largely by the Kepler space telescope, which operated from 2009 to 2018, finding planets by detecting a telltale dip in a star's brightness as a planet passed in front of it. But a telescope like Kepler is limited because of its restricted observing time and point of view. Consider this: if the Kepler telescope had studied our solar system from the other side of the galaxy, it could have possibly found only Venus and Earth and missed the other six planets, either because they are too small or because their orbits take too long for Kepler to have seen them during its mission.

This startling fact reveals just how much remains to be discovered, says Heather Knutson, Caltech professor of planetary science and 3CPE faculty member. Even so, she says, the barrage of newfound worlds has already told scientists something important about the universe. "The number one thing we learn from exoplanets is that when we make predictions based on our solar system, those predictions often turn out to be incorrect, or at least not representative of planetary systems as a whole. Exoplanets keep surprising us in all the ways that they are different from the planets in our solar system."

Our solar system contains four small rocky planets, four outer gas giants, and nothing in between. Not so with other star systems. When astronomers found their first big hauls of smaller planets, the most common type they turned up was one falling between gas giant Neptune and small rocky Earth in size, as Knutson described in a recent paper. "You have to ask, Why are these planets so incredibly common around other stars," she says, "and, given that, why don't we have one in this solar system?"

Knutson focuses on understanding the atmospheres of faraway worlds, which requires extrapolating from Earth, using what scientists have learned from weather patterns and climate models to predict conditions on an alien world with a different atmospheric makeup. Sometimes planets surprise her and do not fit the pattern, which she says is the best part.

"Then there's a neat chance to go back and improve those models to incorporate new physics and new chemistry that we had never thought about before," she notes. "Some of those improvements actually may help us to better understand the planets in this solar system."

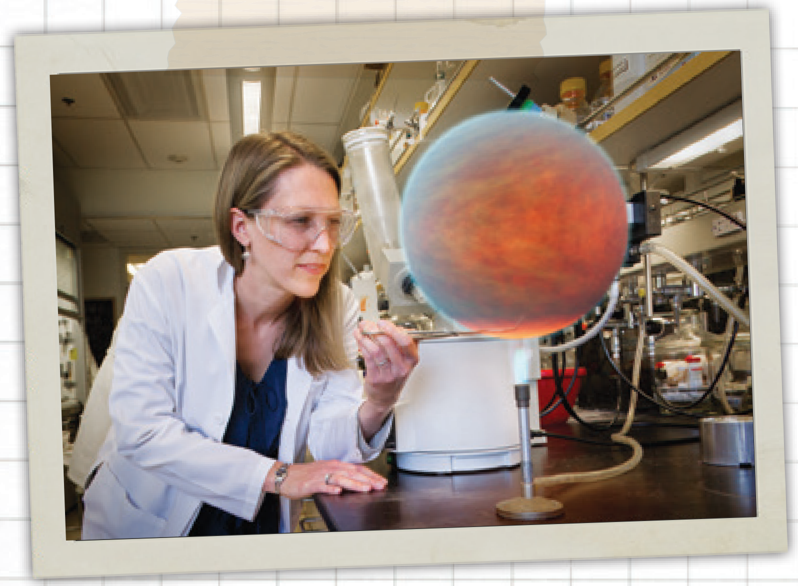
The next generation of telescopes will further that understanding. Knutson is one of many researchers who are now vying for observing time on the James Webb Space Telescope, scheduled to begin operation in 2021 as the most powerful space telescope ever launched. Yet even the James Webb may not be able to tell researchers much about the atmospheres of small, terrestrial exoplanets, Knutson says. "It's a big leap over what we have now, but you need another equivalently big leap in sensitivity to do terrestrial planets well."

That work is underway at Caltech. Inside the Cahill Center for Astronomy and Astrophysics, Professor of Astronomy Andrew Howard is building a next-generation spectrometer called the Keck Planet Finder, an instrument that will upgrade the Caltech-operated W. M. Keck Observatory in Hawaii. "It's going to be the most capable instrument for measuring the masses of planets anywhere in the world," Mike Brown says. Meanwhile, Dimitri Mawet, professor of astronomy and JPL research scientist, is focusing on the instrumentation and techniques that would be needed to directly image small exoplanets: a tall order, because it means separating their light from the overpowering light of their stars.

ANDREW HOWARD GAZING INTO THE FAR REACHES OF THE UNIVERSE

The 3CPE initiative depends upon and also promotes such breakthroughs in instrumentation. But above all, it is meant to inspire new and unlikely collaborations. Jennifer Jackson, the William E. Leonhard Professor of Mineral Physics, researches how minerals behave under extreme pressures within the earth; she has partnered with Victoria Orphan to investigate whether life can survive in hostile environments such as the interior of Mars. Konstantin Batygin (MS '10, PhD '12) and Phil Hopkins, astrophysicists from different sides of the field who say they would not have collaborated if not for their 3CPE project, are working together to predict the formation of moons around giant planets.

These collaborations are not happenstance. They are part of a concerted effort within 3CPE to unite scientists from across campus and across disciplines to find new ways to illuminate our world and others. "Our rule," Brown says, "is that it can't be a collaboration that exists. You have to find someone out there that you have not collaborated with, and you have to come up with a big idea. All of these projects are getting at this whole idea of how a planet evolves chemically, physically, and biologically. And getting all these people together and learning each other's common language is the way forward." C



HEATHER KNUTSON COOKS UP A PLANET

Donors whose support helped to launch the 3CPE initiative include Jose (BS '79) and Katie Helu; Leigh Engen (BS '99); L.E. Simmons; Caltech senior trustee Charlie Trimble (BS '63, MS '64); and the Melza M. and Frank Theodore Barr Foundation.