Discovering New Worlds

As a kid, John Johnson wasn't interested in astronomy—or even science for that matter. But now, as an associate professor of astronomy, he's discovering entirely new worlds. In this interview, he talks about the search for planets and the rapidly evolving field of exoplanet astronomy.

In high school, John Johnson wanted to be a fighter pilot. But when he learned that sinus problems would prevent him from flying planes, he declined his admission to the Air Force Academy and enrolled at the Missouri University of Science and Technology to study engineering. "I figured I'd build planes if I couldn't fly them," he says. There, he discovered a passion for science, and graduated with a degree in physics in 1999. That summer, he did a Summer Undergraduate Research Fellowship (SURF) at Caltech, working on the Laser Interferometer Gravitational-Wave Observatory (LIGO) project. He was admitted to UC Berkeley's graduate school in astronomy, and when he visited the campus, he learned about exoplanets—planets that orbit other stars—and fell in love. In fact, he had only just read about them in Astronomy magazine the day before his visit, in an article of which Berkeley astronomer Geoff Marcy was a coauthor. Marcy, as he would soon find out, is a pioneer in the study of exoplanets, and has discovered more planets than anyone in the world. "Over those two days, I learned what exoplanets were," Johnson says. "I guess I had heard about them, but it dawned on me that there were 33 of them—and that was amazing." And when he realized that the field was so young that even third-year graduate students were writing significant papers, he was sold. "This is what I want to do," he says. "I want to make big discoveries. I want to find something new."

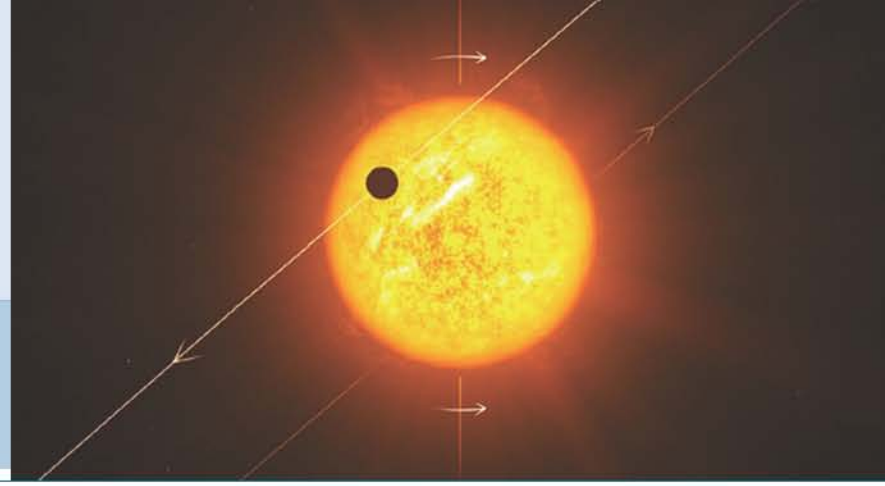
Working with Marcy, he became an expert planet hunter, earning his MA and PhD in 2002 and 2007, respectively. After a stop at the Institute for Astronomy at the University of Hawaii as a National Science Foundation Astronomy and Astrophysics Postdoctoral Fellow, he came to Caltech as an assistant professor of astronomy in September 2009. In the following interview, he discusses the search for planets and the rapidly evolving field of exoplanet astronomy. Today, mainly by measuring the slight wobble of stars caused by the gravitational tugs of their planets, astronomers have discovered more than 430 exoplanets—and the number is rising every week.

What's the focus of your research?

Broadly speaking, we want to find new planets around other stars, which are commonly referred to as exoplanets. We're building up a huge statistical sample. When you have a large number of planets, you can start looking for patterns, trends, and hints

Left: John Johnson in front of the 200-inch Hale Telescope at Caltech's Palomar Observatory.
Right: This artist's conception shows a planet in a highly tilted orbit around its star.

By Marcus Y. Woo



about the planet-formation process. The primary goal of my search for planets is to understand planet formation and therefore to understand the origins of the solar system. My characterization work is focused on individual systems of planets or the planets themselves. We're trying to learn about their physical characteristics, such as their radii, masses, average densities, and atmospheric properties. For systems of planets, we're interested in how planets interact gravitationally with one another. The exact nature of those gravitational interactions gives us hints about how planetary orbits evolve after they form. And that probably has a lot to do with how architectures of planetary systems eventually come to be.

What are some of the current big questions that you guys are trying to tackle?

We're interested in how the solar system formed. We're interested in our immediate environment and describing its origins. And beyond that, we're interested in general in how planetary systems formed. There are some very specific questions that arise at every turn. There are so many surprises in this field—almost nothing is turning out as we expected. There are Jupiter-mass planets in three-day orbits. There are planets with masses that are between those of the terrestrial planets in our solar system and the gas giants in the outer part of our solar system. There are Jupiter-mass planets with hugely inflated radii—at densities far lower than what we thought were possible for a gas-giant planet. There are giant planets with gigantic solid cores that defy models of planet formation, which say there shouldn't be enough solids available in a protoplanetary disk to form a planet that dense. There are planets with tilted orbits. There are planets that orbit the poles of their stars, in so-called circumpolar orbits. There are planets that orbit retrograde—that is, they orbit in the opposite direction of their star's rotation. There are systems of planets that are in configurations that are hard to describe given our understanding of planet formation. For instance, some planets are much too close to one another.

But a lot of those surprises have to do with the fact that we have only one example of a planetary system—our solar system—to base everything on, right?

What's interesting is that we've found very little that resembles our example.

What sort of planets are we finding often?

There are classes of planets that are unexpected—the so-called hot Jupiters, for example. That's a class of planet that's received a great deal of attention; I call them the bonus planets. To detect Jupiter-mass planets, you would've expected to have to wait about 12 years to see a complete orbit. But suddenly there were these Jupiter-mass planets with orbits of only a few days, making them easy to detect. You can fully characterize one of these planets with a week's worth of observations. Those planets weren't supposed to be accessible to us, but suddenly they are. So people are doing things like measuring their spectra, measuring their temperatures directly, and getting a handle on their atmospheric properties.

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How do we think hot Jupiters form?

It's generally thought that they formed much farther out from their star, probably at a distance similar to where Jupiter is in our solar system. Then, they somehow migrated inward. They can migrate through a number of different mechanisms. One of the areas of my research is to understand what mechanism or mechanisms are largely responsible for the population of hot Jupiters.

Do astronomers have a favored mechanism?

Up until two years ago, the favored one was that the planet hitches a ride with the disk material. As the planetary system is forming, the disk material around a star starts to spiral inward. You can think of it as a bathtub draining, and the planet gets dragged along for that ride, and somehow gets stranded right next to the star. That theory was favored until about 2008 because most of the planets we found were well aligned. The star was spinning one way and the planet basically tracked the star's equator. It went parallel to the equator in the same direction as the star. That's what you would expect. The star got its angular momentum from the disk, the planet was formed in the disk, so they should still share that angular momentum vector today. But then we started finding tilted planets, and polar planets, and retrograde planets, and that theory has now gone into the dustbin. We're scrambling to find a new way of de-

To learn more and to watch a video demonstrating how astronomers detect exoplanets, go to John Johnson's website.

scribing how these gas giants can move in that also causes their orbits to be tilted.

Could it be that planets actually do spiral inward, but some other object comes into the picture and interacts with the system and tilts the orbit?

Personally, I'm not ready to give up on the old theory. I'm just reflecting what most exoplanet scientists think these days. I think we're getting fooled by a combination of selection biases. I have a grad student, Tim Morton, working on that right now, trying to understand what conclusions we can draw from the current sample; it's not as easy as you might think. It's analogous to trying to measure the average height of human beings by standing in the middle of a basketball court. Where you are and how you make that measurement really matters. You want to broadly sample a population—you don't want a myopic view of that population. If you stood in the middle of a Lakers game, you might report that the average height of a human being is six foot eight. We know that's not true. We have to be out in the stands.

How much has the field changed since you entered it as a graduate student 10 years ago?

I'm a specialist in measuring precise radial velocities or measuring Doppler shifts of stars as they move in response to their planet's gravitational tug. We've increased our precision in measuring those shifts by a factor of three, so we're able to see much smaller planets than we could back then. Overall, we've moved away from the era of stamp collecting, when it was really cool to find a planet, and a discovery immediately warranted a paper. Now we've moved to a regime where we have tons of detections and it's hard to get around to publishing them all because each exoplanet has relatively little impact. It just adds to the statistical sample. Nowadays, people have to stretch to find the defining characteristic of a given planet that they're announcing.

> I couldn't go back to sleep. I was bone-tired, but I was excited and hyped up, so I got up and started working on the paper.

My own research has shifted to studying the statistics of large numbers of planets rather than any one planet.

You're studying the whole population rather than specific systems.

Yeah, I think that's where one of the frontiers is. That's where I'm trying to put my own research. For instance, we just published a new result based on the statistics of planets showing that the more massive a star is, the more likely it is to have a Jupiter-mass planet. That's telling us something very important about planet formation. A more massive star should have a more massive disk, and the more massive disk should have more raw materials for planet building. There's a competing theory of planet formation that says it shouldn't really matter how much mass you have in the disk. There should be other factors that govern whether that disk is going to turn into planets. So we were actually able to pit those two theories against one another, conduct this experiment, and test those predictions. I feel like we were able to make a pretty clear conclusion that it really does matter how much raw material you have in a disk for planet building.

Was that unexpected?

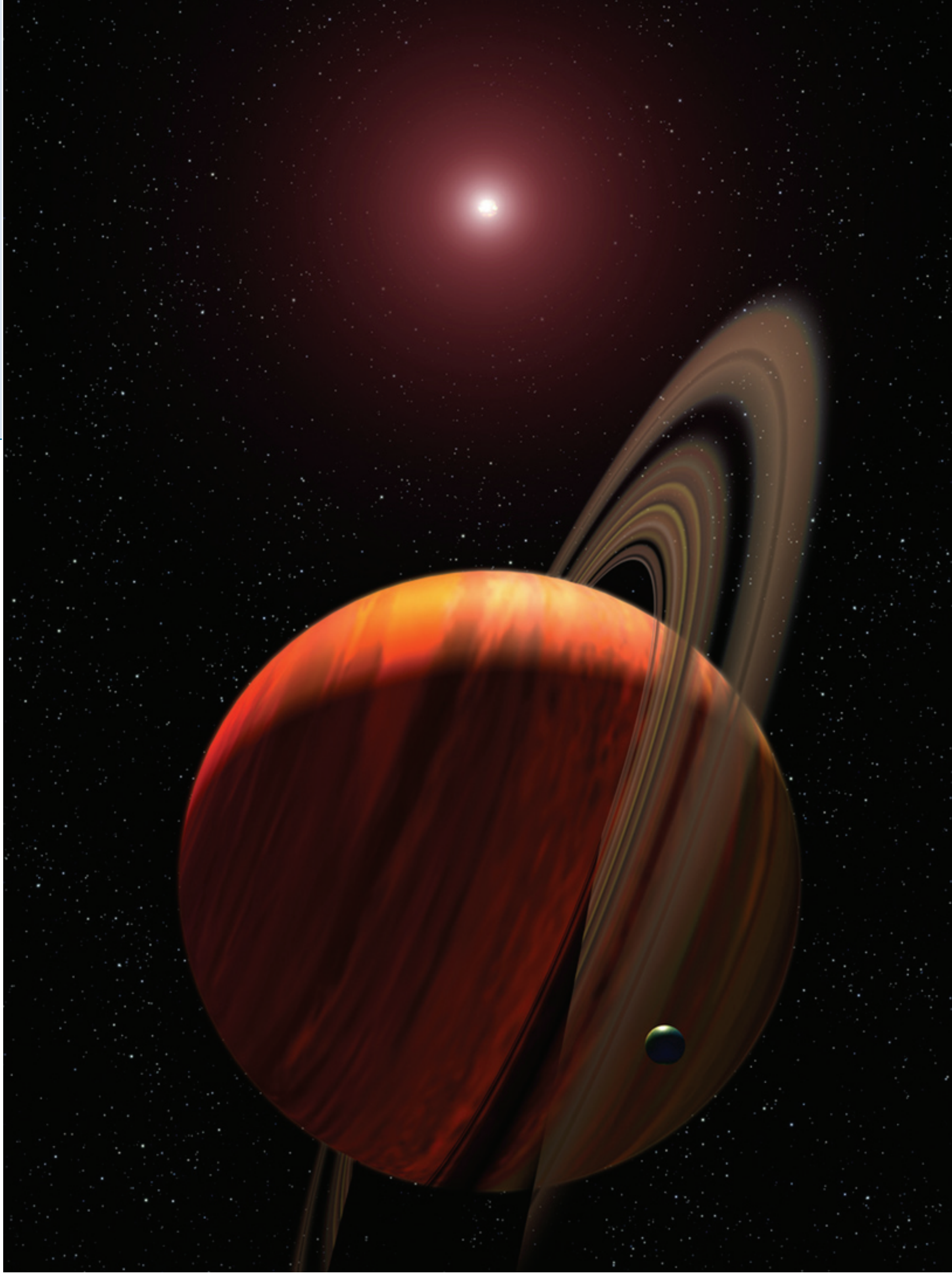
That was the theory of planet formation before we knew of exoplanets. Then when we found exoplanets, it was thought we might need a better theory. This old-fashioned theory has actually won out against the newfangled one.

What is the old-fashioned theory of planet formation?

The old-fashioned idea is the nebular hypothesis of Pierre-Simon Laplace (1749–1827) and Immanuel Kant (1724–1804). When a star forms, it's surrounded by a spinning disk of gas and dust, and planets form within the disk. Because the disk is largely circular, planets end up in circular orbits. Because there's more raw material for planet building in the more distant reaches of the disk, where things like water ice can condense and give you the building blocks of planets, gas-giant planets should be farther away from the star. Where there are fewer volatiles that condense, where there are heavier elements like silicon and iron, is where you should get terrestrial planets. After about 10 million years, the sun burns off what's left of the gas disk. And that's why the solar system is the way it is.

That's the old-fashioned way of looking at things. Nowadays, it's still basically that—just version 2.0. We can take the original

An artist's rendering of a gas-giant exoplanet orbiting a so-called subgiant star. The imagined planet has a ring and moon system similar to Saturn and Jupiter. As techniques improve in the future, astronomers may soon be able to detect rings and moons around exoplanets.



story up until the gas disk goes away. Maybe the planets start off in those nice circular orbits. But then they begin to gravitationally interact, tossing each other about, causing each other to undergo weird oscillations and inclinations. After that whole dance is done, the survivors are left on tilted, eccentric orbits that sometimes bring them very close to their star. There's much to that story that's yet to be understood, but I'm really excited about that. I'm glad that this is not a closed case, because I'm really enjoying this research. It's more fun when there are more open questions—at least for an observer. If you're a theorist it's not so much fun.

What about this field is exciting?

It gets me out of bed every morning. I literally can't wait to see the latest data. It happened to me just yesterday. I was observing remotely in the basement of Cahill until my collaborators relieved me at about 3 a.m., since I had a full workday the next day and needed to sleep. I went to bed at about 3:30, expecting to sleep until 10:30. But I woke up at 7:30 and started thinking, you know, we just observed this new system we found and it's really wacky. It's a hot Jupiter around a type of star that's not supposed to have any hot Jupiters. If this next observation falls on the predicted curve, and it's likely going to be very real, then I'm going to have to think about how to share this with everybody. I couldn't go back to sleep. I was bone-tired, but I was excited and hyped up, so I got up and started working on the paper.

I don't know if I would get that level of excitement if I were doing cosmology or if I were studying galaxies—not to say that those fields are not immensely important and have exciting results. I just see new things every day that nobody on Earth has ever seen. It's just really fun being in a field of astronomy that's in its infancy—and being in a place like Caltech where we have Keck access once a month and we can actually watch all this happen.

It's like you're a field biologist observing some sort of new species.

Yeah. What this reminds me of is when people started exploring the deep sea in submersibles, and they would go into these tiny little things with one-foot Plexiglas walls and a tiny viewing window, and descend three miles down and look out into the dark with the light and all of a sudden, there's some octopus-looking thing that nobody's ever seen before, or some angler fish that's totally unexpected. I remember watching a documentary recently where they went down to the bottom of the ocean and they found an undersea lake. It was just a lake of heavier, denser water sitting at the bottom of an ocean. No one expected that. I imagine those marine biologists are similar to me. After doing one of those runs where they go deep under the water, they come back up and try to go to sleep that night. They probably wake up early thinking, oh my God, I want to look at that sample again—that's amazing. I feel like we're doing the same thing out in space. We're going out into the solar neighborhood, where there are things that we thought were just familiar, things that we thought we understood. But just the wackiest stuff comes up—and it's sure keeping me busy.

Once we find more planets like our own, it'll further define our place and give us a better universal context for what it means to be human.

Can you give us a sense of how wacky these planets are?

In 2005, my collaborator, Josh Winn, and I started measuring the degree of alignment of planets, using an ancient technique now applied to the brand-new field of exoplanets. We didn't really know what to expect, but Josh would say to me every time we'd go to the telescope, "Tonight's the night we find a retrograde planet." I would chuckle and say, that would be awesome. But it would also be awesome to find a new car in front of my house. Finding a retrograde planet would be awesome and wonderful, and I wouldn't give it back if we happened to find one. But I didn't in my heart of hearts expect we would do it. Then, four years later, I was on my way up to use the eight-meter Subaru telescope to measure the spin-orbit angle of a planetary system. He wasn't able to join us on the run, but he sent me an email, and at the bottom he wrote, "Tonight's the night we find a retrograde planet." As usual, I said that'd be great. And that was the night we found a retrograde planet. That was another one of those weeks where I wasn't getting much sleep because this was amazing—absolutely amazing.

It's like going out on safari and saying today's the day we're going to find a blue lion. And then you do find one, and you go, what is this? It must be a joke! That might be the level of wackiness I would attach to it. There might be some visionaries out there who totally expected a retrograde planet. But to actually find one—that was just weird.

What got you interested in science in general?

Stephen Hawking. *A Brief History of Time*—it changed my life. It's kind of clichéd. Half of all physicists are in physics because of that book. That's definitely what got me. Other popular-physics books after that sealed the deal. I was an engineer when I started off as an undergrad, doing aerospace and mechanical engineering. But it wasn't as interesting as discovering things about the universe.

But it all started in college. I can't say that I was one of those kids who begged their dad to buy them a telescope and then used it in their backyards. I had zero interest in astronomy until late in my college career. I was the kid who stayed inside and played with his Legos instead of the kid who went outside and explored under rocks. I was an engineer.

Were there any "aha!" moments during your career?

I remember more of the moments when I realized I wasn't cut out for engineering. In college, I did an internship with John Deere in Iowa. I realized that my crowning achievement for that summer internship was developing a new ladder for a front-end loader for the operator to climb up on. I just thought, "There's got to be more to this." If I was going to be sitting around figuring out very complicated things, then I wanted something that's more meaningful outside the company where I work. Some people are fine with that. I'm glad there are tons of people making bridges and building airplanes for us. But it wasn't for me.

Has there been a highlight in your scientific career so far?

Yeah, definitely. When I found my first planet.

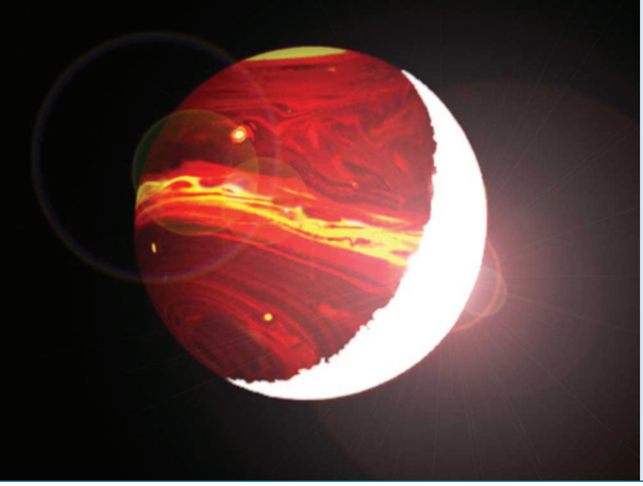
What was that like?

I couldn't sleep for a week. I had a whole bunch of data for my thesis, but I had not yet perfected the analysis software. There were some bugs that were making it very difficult for me to see signals clearly. When I finally got my code to work—that was an "aha!" moment. That was great. It was one of the first major analysis undertakings that I had done as a student. So suddenly I was able to see things clearly in my data. I went back to all the stars I had been observing for the past year and there was just a really clear signal that popped up for one of the stars. I looked at the velocities and fit a model to it, and there it was: my first planet. That was HD185269b. That was a real rush. It was the result of all the effort I put into it. That was the antimoment to that summer internship. That was the moment I realized, oh my God, I can do some really amazing stuff.

Where were you?

Lick Observatory, on a mountaintop. I had been observing for three or four days straight. It was great. I fixed the code, and immediately turned the telescope to get the star, which was in the process of setting. It was going to set in a few weeks after that. I remember that my friend was going to be on the telescope a week after I was, and I sent him detailed instructions about how to reach the star so he could grab a few more data points for me because it was going to be another three or four months before we could get more data. It all worked out great—great weather and everything.

I was using the smallest telescope, one that nobody wanted to use. I was also using a very old instrument that nobody else wanted to use either. So I had as much time as I wanted on the telescope—and I used a lot of time. Every night I'd go to dinner, walk from the diner to the telescope, open up the telescope, and do the calibration. Then I'd wait for the sun to dip down 12 degrees below the horizon and I'd get to the first target, and I'd walk across the sky observing one star after the next. Each observation yielded a velocity measurement, and those velocities



An artistic rendering of a so-called hot Jupiter on a three-day orbit around a Sun-like star. This image was based on atmospheric models of gas giants being bombarded by heat and radiation from its star.

over time gave the accelerations that those stars were experiencing. I would do that and repeat for four days straight.

Where do you see your work at Caltech in the near future?

Being here at Caltech is great. We have access to the world's largest optical telescope and a very high-precision radial velocity instrument—and they're giving me lots of time on them. I'm going to put it all to use. I have about four major projects going on. The sky's the limit at Caltech. I cannot do this anywhere else. I have these four projects to work on and see to completion in the next three years, probably. From there, it's exploring the two frontiers of exoplanets. The first consists of long-period planets, which you find by waiting. The longer we wait, the longer we observe a given star, the longer period we're able to detect. The other frontier is with low-mass planets. Those have very low Doppler amplitudes, so we have to push the precision of existing instruments and then build new instruments. My collaborators at Yale and Penn State and I have put a proposal to the NSF to build a new instrument at Palomar to use the five-meter telescope there. Once we get that project funded, that's going to keep people busy for the next 10 years. That'll be at the very frontier of this field—finding Earth-like planets, two or three Earth masses in the habitable zone of stars, where they could potentially have liquid water. That's going to be a major undertaking. It's going to require another factor-of-three increase in precision. It's going to require a lot of nights on the telescope, and it's going to take me right back to my thesis. But it's going to be great. I really enjoy it.

Is there any way to anticipate what we'll find?

Kepler, the space mission we're flying right now, is going to tell us what we're going to find. It's going to get the first view of what exists out there for the low-mass planets and longer-period orbits that we know today. It's blazing the trail, but it's doing it for stars that are very distant. We're going to be doing it for stars that are right next door. The first hints that are emerging from that mission are very promising.

Why should we care about finding exoplanets? They don't plug up oil spills.

Every astronomer goes through that existential crisis. You have to understand that our society as we know it today is shaped largely through a lot of different astrophysical discoveries. The fact that we know Earth orbits the sun came from astronomers 450 years ago. The work that we're doing today is going to impact our culture and our understanding of our place in the universe forever. It's going to happen slowly, but that's what we're in the business of doing. Exoplanets are really good for that because we live on a planet, and we are finding other planets. We're trying to understand the planet we live on—where did it come from? It's the ultimate origin story. We are coming out of the darkness from a couple hundred years ago and we're rubbing our eyes today, realizing that we are on a really small planet around a really average star in an unspectacular part of the galaxy, and we're learning our place in this whole universe. Once we find more planets like our own, it'll further define our place and give us a better universal context for what it means to be human. E&S

From top to bottom: graduate student Tim Morton, Johnson, postdoc Justin Crepp, and telescope operator Kajsa Peffer, in the control room of Palomar's Hale Telescope.