A conversation with astronomer Dimitri Mawet

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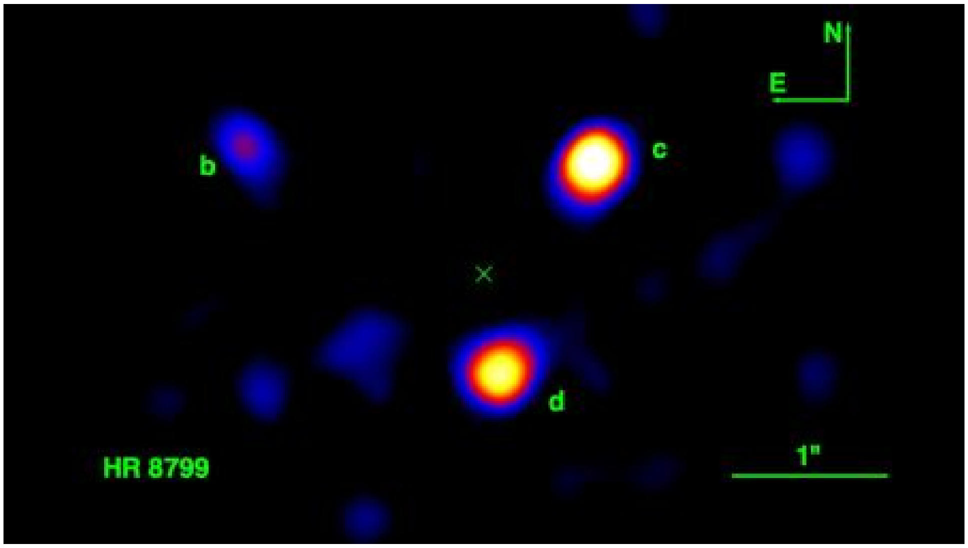

The star HR 8799 has three planets (b, c, and d) that can be seen with the vortex coronagraph. The 'X' marks the nulled-out star's position. Credit: E. Serabyn, D. Mawet, and R. Burrus/Caltech/JPL

Associate Professor of Astronomy Dimitri Mawet has joined Caltech from the Paranal Observatory in Chile, where he was a staff astronomer for the Very Large Telescope. After earning his PhD at the University of Liège, Belgium, in 2006, he was at JPL from 2007 to 2011—first as a NASA postdoctoral scholar and then as a research scientist.

Q: What do you do?

A: I study exoplanets, which are planets orbiting other stars. In particular, I'm developing technologies to view exoplanets directly and analyze their atmospheres. We're hunting for small, Earth-like planets where life might exist—in other words, planets that get just the right amount of heat to maintain water in its liquid state—but we're not there yet. For an exoplanet to be imaged right now, it has to be really big and really bright, which means it's very hot.

In order to be seen in the glare of its star, the planet has to be beyond a minimum angular separation called the inner working angle. Separations can also be expressed in astronomical units, or AUs, where one AU is the mean distance between the sun and Earth. Right now we can get down to about two AU—but only for giant planets. For example, we recently imaged Beta Pictoris and HR 8799. We didn't find anything at two AU in either star system, but we found that Beta Pictoris harbors a planet about eight times more massive than Jupiter orbiting at 9 AU. And we see a family of four planets in the five- to seven-Jupiters range that orbit from 14 to 68 AU around HR 8799. For comparison, Saturn is 9.5 AU from the sun, and Neptune is 30 AU.

Q: How can we narrow the working angle?

A: You either build an interferometer, which blends the light from two or more telescopes and "nulls out" the star, or you build a coronagraph, which blots out the star's light. Most coronagraphs block the star's image by putting a physical mask in the optical path. The laws of physics say their inner working angles can't be less than the so-called diffraction limit, and most coronagraphs work at three to five times that. However, when I was a grad student, I invented a coronagraph that works at the diffraction limit.

The key is that we don't use a physical mask. Instead, we create an "optical vortex" that expels the star's light from the instrument. Some of our vortex masks are made from liquid-crystal polymers, similar to your smartphone's display, except that the molecules are "frozen" into orientations that force light waves passing through the center of the mask to emerge in different phase states simultaneously. This is not something nature allows, so the light's energy is nulled out, creating a "dark hole."

If we point the telescope so the star's image lands exactly on the vortex, its light will be filtered out, but any light that's not perfectly centered on the vortex—such as light from the planets, or from a dust disk around the star—will be slightly off-axis and will go on through to the detector.

We're also pushing to overcome the enormous contrast ratio between the very bright star and the much dimmer planet. Getting down to the Earth-like regime requires a contrast ratio of 10 billion to 1, which is really huge. The best contrast ratios achieved on ground-based telescopes today are more like 1,000,000 to 1. So we need to pump it up by another factor of 10,000.

Even so, we can do a lot of comparative exoplanetology, studying any and all kinds of planets in as many star systems as we can. The variety of objects around other stars—and within our own solar system—is mind-boggling. We are discovering totally unexpected things.

Q: Such as?

A: Twenty years ago, people were surprised to discover hot Jupiters, which are huge, gaseous planets that orbit extremely close to their stars—as close as 0.04 AU, or one-tenth the distance between the sun and Mercury. We have nothing like them in our solar system. They were discovered indirectly, by the wobble they imparted to their star or the dimming of their star's light as the planet passed across the line of sight. But now, with high-contrast imaging, we can actually see—directly—systems of equally massive planets that orbit tens or even hundreds of AU's away from their stars, which is baffling.

Planets form within circumstellar disks of dust and gas, but these disks get very tenuous as you go farther from the star. So how did these planets form? One hypothesis is that they formed where we see them, and thus represent failed attempts to become multiple star systems. Another hypothesis is that they formed close to the star, where the disk is more massive, and eventually expelled one another by gravitational interactions.

We're trying to answer that question by starting at the outskirts of these planetary systems, looking for massive, hot planets in the early stages of formation, and then grind our way into the inner reaches of older planetary systems as we learn to reduce the working angle and deal with ever more daunting contrast ratios. Eventually, we will be able to trace the complete history of planetary formation.

Q: How can you figure out the history?

Once we see the planet, once we have its signal in our hands, so to speak, we can do all kinds of very cool measurements. We can measure its position, that's called astrometry; we can measure its brightness, which is photometry; and, if we have enough signal, we can sort the light into its wavelengths and do spectroscopy.

As you repeat the astrometry measurements over time, you resolve the planet's orbit by following its motion around its star. You can work out masses, calculate the system's stability. If you add the time axis to spectrophotometry, you can begin to track atmospheric features and measure the planet's rotation, which is even more amazing.

Soon we'll be able to do what we call Doppler imaging, which will allow us to actually map the surface of the planet. We'll be able to resolve planetary weather phenomena. That's already been done for brown dwarfs, which are easier to observe than exoplanets. The next generation of adaptive optics on really big telescopes like the Thirty Meter Telescope should get us down to planetary-mass objects.

That's why I'm so excited about high-contrast imaging, even though it's so very, very hard to do. Most of what we know about exoplanets has been inferred. Direct imaging will tell us so much more about exoplanets—what they are made out of and how they form, evolve, and interact with their surroundings.

Q: Growing up, did you always want to be an astronomer?

A: No. I wanted to get into space sciences—rockets, satellite testing, things like that. I grew up in Belgium and studied engineering at the University of Liège, which runs the European Space Agency's biggest testing facility, the Space Center of Liège. I had planned to do my master's thesis there, but there were no openings the year I got my diploma.

I was not considering a thesis in astronomy, but I nevertheless went back to campus, to the astrophysics department. I knew some of the professors because I had taken courses with them. One of them, Jean Surdej, suggested that I work on a concept called the Four-Quadrant Phase-Mask (FQPM) coronagraph, which had been invented by French astronomer Daniel Rouan. I had been a bit hopeless, thinking I would not find a project I would like, but Surdej changed my life that day.

The FQPM was one of the first coronagraphs designed for very-small-working-angle imaging of extrasolar planets. These devices performed well in the lab, but had not yet been adapted for use on telescopes. Jean, and later on Daniel, asked me to help build two FQPMs—one for the "planet finder" on the European Southern Observatory's Very Large Telescope, or VLT, in Chile; and one for the Mid-Infrared Instrument that will fly on the James Webb Space Telescope, which is being built to replace the Hubble Space Telescope.

I spent many hours in Liège's Hololab, their holographic laboratory, playing with photoresists and lasers. It really forged my sense of what the technology could do. And along the way, I came up with the idea for the optical vortex.

Then I went to JPL as a NASA postdoc with Eugene Serabyn. I still spent my time in the lab, but now I was testing things in the High Contrast Imaging Testbed, which is the ultimate facility anywhere in the world for testing coronagraphs. It has a vacuum tank, six feet in diameter and eight feet long, and inside the tank is an optical table with a state-of-the-art deformable mirror. I got a few bruises crawling around in the tank setting up the vortex masks and installing and aligning the optics.

The first vortex coronagraph actually used on the night sky was the one we installed on the 200-inch Hale Telescope down at Palomar Observatory. The Hale's adaptive optics enabled us to image the planets around HR 8799, as well as brown dwarfs, circumstellar disks, and binary star systems. That was a fantastic and fun learning experience.

So I developed my physics and manufacturing intuition in Liège, my experimental and observational skills at JPL, and then I went to Paranal where I actually applied my research. I spent about 400 nights observing at the VLT; I installed two new vortex coronagraphs with my Liège collaborators; and I became the instrument scientist for SPHERE, to which I had contributed 10 years before when it was called the planet finder. And I learned how a major observatory operates—the ins and outs of scheduling, and all the vital jobs that are performed by huge teams of engineers. They far outnumber the astronomers, and nothing would function without them.

And now I am super excited to be here. Caltech and JPL have so many divisions and departments and satellites—like Caltech's Division of Physics, Mathematics and Astronomy and JPL's Science Division, both my new professional homes, but also Caltech's Division of Geology and Planetary Sciences, the NASA Exoplanet Science Institute, the Infrared Processing and Analysis Center, etc. We are well-connected to the University of California. There are so many bridges to build between all these places, and synergies to benefit from. This is really a central place for innovation. I think, for me, that this is definitely the center of the world.

Provided by California Institute of Technology

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