Astronomers spot a 'highly eccentric' planet on its way to becoming a hot Jupiter

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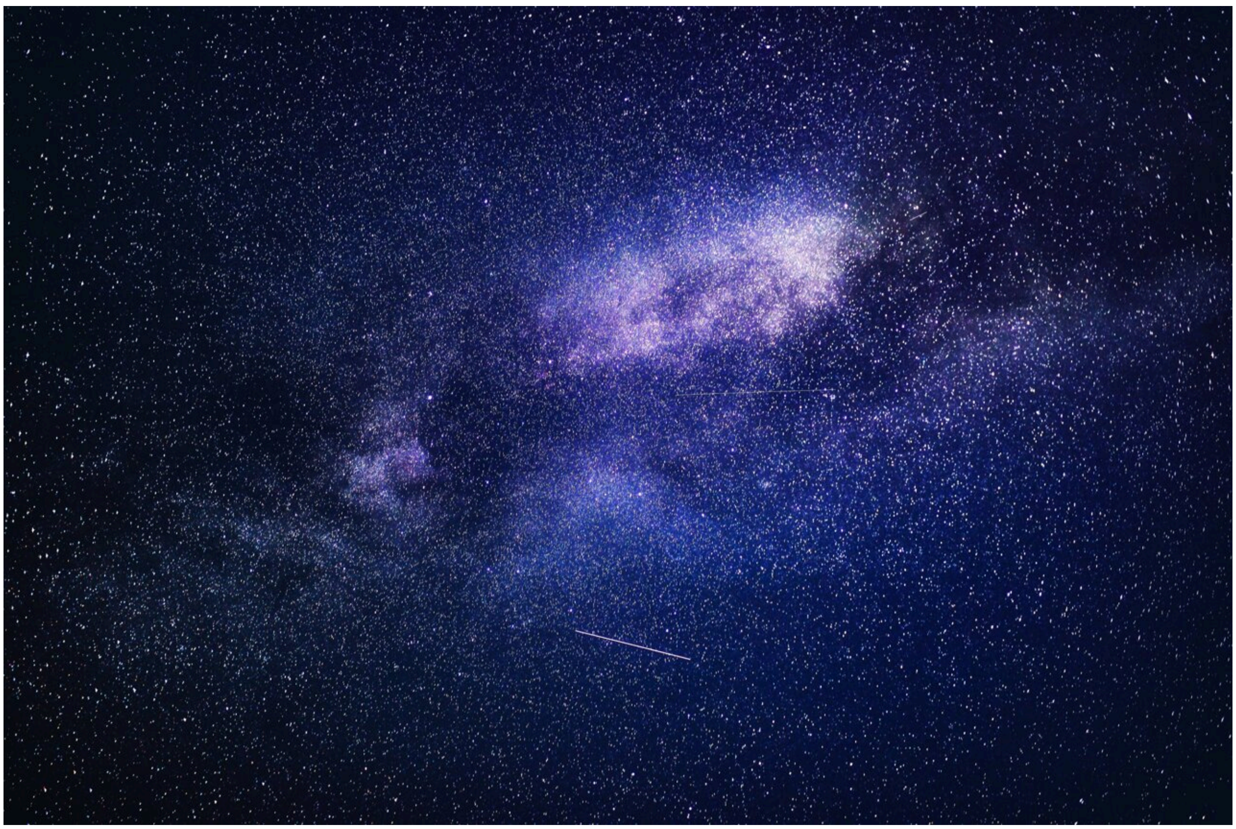

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Hot Jupiters are some of the most extreme planets in the galaxy. These scorching worlds are as massive as Jupiter, and they swing wildly close to their star, whirling around in a few days compared to our own gas giant's leisurely 4,000-day orbit around the sun.

Scientists suspect, though, that hot Jupiters weren't always so hot and in fact may have formed as "cold Jupiters," in more frigid, distant environs. But how they evolved to be the star-hugging gas giants that astronomers observe today is a big unknown.

Now, astronomers at MIT, Penn State University, and elsewhere have discovered a hot Jupiter "progenitor"—a sort of juvenile planet that is in the midst of becoming a hot Jupiter. And its orbit is providing some answers to how hot Jupiters evolve. The findings are published in the journal *Nature*.

Co-authors include MIT undergraduate Haedam Im, lead author Arvind Gupta of Penn State University and NSF NOIRLab, and collaborators at multiple other universities, institutions, and observatories.

The new planet, which astronomers labeled TIC 241249530 b, orbits a star that is about 1,100 light years from Earth. The planet circles its star in a highly "eccentric" orbit, meaning that it comes extremely close to the star before slinging far out, then doubling back, in a narrow, elliptical circuit.

If the planet was part of our solar system, it would come ten times closer to the sun than Mercury, before hurtling out, just past Earth, then back around. By the scientists' estimates, the planet's stretched-out orbit has the highest eccentricity of any planet detected to date.

The new planet's orbit is also unique in its "retrograde" orientation. Unlike the Earth and other planets in the solar system, which orbit in the same direction as the sun spins, the new planet travels in a direction that is counter to its star's rotation.

The team ran simulations of orbital dynamics and found that the planet's highly eccentric and retrograde orbit are signs that it is likely evolving into a hot Jupiter, through "high-eccentricity migration"—a process by which a planet's orbit wobbles and progressively shrinks as it interacts with another star or planet on a much wider orbit.

In the case of TIC 241249530 b, the researchers determined that the planet orbits around a primary star that itself orbits around a secondary star, as part of a stellar binary system. The interactions between the two orbits—of the planet and its star—have caused the planet to gradually migrate closer to its star over time.

The planet's orbit is currently elliptical in shape, and the planet takes about 167 days to complete a lap around its star. The researchers predict that in 1 billion years, the planet will migrate into a much tighter, circular orbit, when it will then circle its star every few days. At that point, the planet will have fully evolved into a hot Jupiter.

"This new planet supports the theory that high eccentricity migration should account for some fraction of hot Jupiters," says Sarah Millholland, assistant professor of physics in MIT's Kavli Institute for Astrophysics and Space Research.

"We think that when this planet formed, it would have been a frigid world. And because of the dramatic orbital dynamics, it will become a hot Jupiter in about a billion years, with temperatures of several thousand kelvin. So it's a huge shift from where it started."

'Radical seasons'

The new planet was first spotted in data taken by NASA's Transiting Exoplanet Survey Satellite (TESS), an MIT-led mission that monitors the brightness of nearby stars for "transits," or brief dips in starlight that could signal the presence of a planet passing in front of, and temporarily blocking, a star's light.

On Jan. 12, 2020, TESS picked up a possible transit of the star TIC 241249530. Gupta and his colleagues at Penn State determined that the transit was consistent with a Jupiter-sized planet crossing in front of the star. They then acquired measurements from other observatories of the star's radial velocity, which estimates a star's wobble, or the degree to which it moves back and forth, in response to other nearby objects that might gravitationally tug on the star.

Those measurements confirmed that a Jupiter-sized planet was orbiting the star and that its orbit was highly eccentric, bringing the planet extremely close to the star before flinging it far out.

Prior to this detection, astronomers had known of only one other planet, HD 80606 b, that was thought to be an early hot Jupiter. That planet, discovered in 2001, held the record for having the highest eccentricity, until now.

"This new planet experiences really dramatic changes in starlight throughout its orbit," Millholland says. "There must be really radical seasons and an absolutely scorched atmosphere every time it passes close to the star."

'Dance of orbits'

How could a planet have fallen into such an extreme orbit? And how might its eccentricity evolve over time? For answers, Im and Millholland ran simulations of planetary orbital dynamics to model how the planet may have evolved throughout its history and how it might carry on over hundreds of millions of years.

The team modeled the gravitational interactions between the planet, its star, and the second nearby star. Gupta and his colleagues had observed that the two stars orbit each other in a binary system, while the planet is simultaneously orbiting the closer star. The configuration of the two orbits is somewhat like a circus performer twirling a hula hoop around her waist, while spinning a second hula hoop around her wrist.

Millholland and Im ran multiple simulations, each with a different set of starting conditions, to see which condition, when run forward over several billions of years, produced the configuration of planetary and stellar orbits that Gupta's team observed in the present day. They then ran the best match even further into the future to predict how the system will evolve over the next several billion years.

These simulations revealed that the new planet is likely in the midst of evolving into a hot Jupiter: Several billion years ago, the planet formed as a cold Jupiter, far from its star, in a region cold enough to condense and take shape. Newly formed, the planet likely orbited the star in a circular path. This conventional orbit, however, gradually stretched and grew eccentric, as it experienced gravitational forces from the star's misaligned orbit with its second, binary star.

"It's a pretty extreme process in that the changes to the planet's orbit are massive," Millholland says. "It's a big dance of orbits that's happening over billions of years, and the planet's just going along for the ride."

In another billion years, the simulations show that the planet's orbit will stabilize in a close-in, circular path around its star.

"Then, the planet will fully become a hot Jupiter," Millholland says.

The team's observations, along with their simulations of the planet's evolution, support the theory that hot Jupiters can form through high eccentricity migration, a process by which a planet gradually moves into place via extreme changes to its orbit over time.

"It's clear not only from this, but other statistical studies too, that high eccentricity migration should account for some fraction of hot Jupiters," Millholland notes.

"This system highlights how incredibly diverse exoplanets can be. They are mysterious other worlds that can have wild orbits that tell a story of how they got that way and where they're going. For this planet, it's not quite finished its journey yet."

More information: Arvind Gupta, A hot-Jupiter progenitor on a super-eccentric retrograde orbit, *Nature* (2024). DOI: 10.1038/s41586-024-07688-3.
www.nature.com/articles/s41586-024-07688-3