

Direct imaging reveals exoplanets in orbital motion

If a planet orbiting another star is young enough, the afterglow from its heat of formation may be adequate for imaging.

Most of the more than 300 exoplanets found thus far have been detected by the periodic Doppler shifting of the host star's spectrum as an orbiting planet tugs it to and fro. A few have revealed themselves by periodically dimming a star's perceived brightness as they transit across its face. And gravitational microlensing has uncovered a handful (see *PHYSICS TODAY*, April 2006, page 22). But none of those techniques is practical for planets that orbit their stars at distances larger than about 5 astronomical units. (1 AU is the mean distance between Earth and the Sun.)

There is, however, a search technique that gets easier with increasing distance between star and planet—namely, direct imaging. A planet less than about 10 AU (the orbital radius of Saturn) from its star is lost in the star's glare. And beyond 10 AU, reflected starlight would generally be too dim for imaging. But young Jovian planets less than a few hundred million years old are expected to retain enough of their heat of formation to glow quite brightly in the IR. That glow not only makes imaging feasible; its photometric and spectral details also promise to reveal much about a planet's makeup.

Therefore astronomers have in recent years been imaging the environs of nearby young stars at near-IR wavelengths in search of planets. The task is made difficult by the enormous brightness contrast between a star and a warm planet separated by only about an arc-second. But now in back-to-back papers, two groups have reported the imaging of Jovian planets orbiting stars in our local neighborhood.^{1,2} Both groups, having recorded images several years apart, present evidence that the planet candidates are indeed gravitationally bound objects in Keplerian orbits.

A three-planet system

Availing themselves of the adaptive-optics systems of two of the world's largest telescopes, atop Hawaii's Mauna Kea, a group led by Christian Marois of

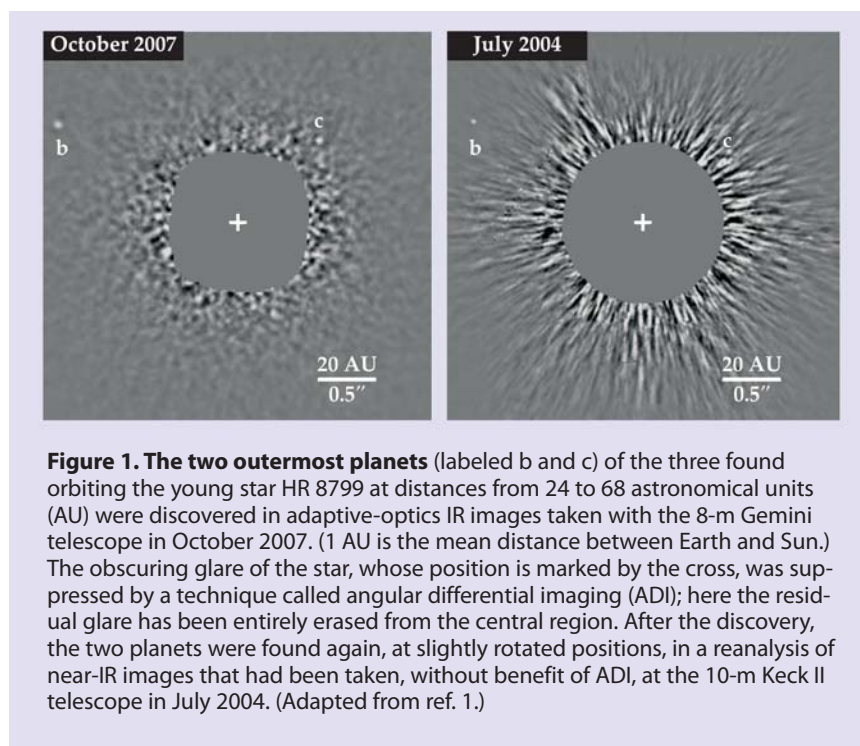


Figure 1. The two outermost planets (labeled b and c) of the three found orbiting the young star HR 8799 at distances from 24 to 68 astronomical units (AU) were discovered in adaptive-optics IR images taken with the 8-m Gemini telescope in October 2007. (1 AU is the mean distance between Earth and Sun.) The obscuring glare of the star, whose position is marked by the cross, was suppressed by a technique called angular differential imaging (ADI); here the residual glare has been entirely erased from the central region. After the discovery, the two planets were found again, at slightly rotated positions, in a reanalysis of near-IR images that had been taken, without benefit of ADI, at the 10-m Keck II telescope in July 2004. (Adapted from ref. 1.)

Canada's Herzberg Institute of Astrophysics has produced images over a range of near-IR wavelengths of three planets orbiting a luminous young star, HR 8799, about 130 light-years from our solar system.¹

From the counterclockwise displacements of the planet images from July 2004 to September 2008, the group concludes that it is seeing almost circular orbits roughly face-on, with orbital radii of about 24, 38, and 68 AU (see figures 1 and 2). At those radii, the observed displacements of the three planets over four years are consistent with Keplerian revolution around the star, whose mass is known to be about 1.5 solar masses $M_{\odot}$.

HR 8799 is an A-type star, hotter and about five times more luminous than the G-type Sun. That exacerbates the problem of brightness contrast. But IR planet searches of several hundred nearby young stars no more luminous

than the Sun had found nothing. "So we had to start looking at A stars," says Marois. "And this is what we found after looking at just a handful." The obvious conclusion is that at separations larger than 20 AU, Jovian planets are far more common around young A stars than around smaller, cooler sun-like stars of the same age.

The outermost two planets of the system were discovered in IR images taken at the 8-meter Gemini telescope on Mauna Kea in October 2007 (left panel of figure 1). The blurring due to atmospheric turbulence was dealt with by an adaptive-optics system that continually adjusted the shape of a small mirror in response to observed distortion of the central star's image. But then the star's image, broadened by diffraction, had to be minimized to render planets visible. To that end, Marois and company used a trick called angular differential imaging (ADI). Keeping the

telescope centered on the star, they allowed the camera's field of view to rotate around the star with the telescope's changing orientation during the night. Then they minimized nonplanetary features by subtracting from repeated exposures those features that didn't rotate with the field of view: the star itself, diffraction artifacts related to structural elements of the telescope, and speckles due to imperfections in the primary mirror or other optical components.

Having discovered the two planets at the Gemini telescope, the group found them also in a reanalysis of IR pictures they had taken of the same star in 2004 with the Keck II 10-meter telescope up the road (right panel of figure 1). The group found the innermost of the three planets with Keck II in July 2008. Figure 2 shows the most sensitive ADI image of the system, acquired two months later at Keck II in three near-IR bands. To indicate how well ADI reduces the star's obscuring image, the residual stellar image is left unscrubbed in the figure.

Weighing the planets

Unlike the Doppler method, which straightforwardly yields a lower mass limit for the discovered planet, direct imaging has to rely on cooling models and estimates of the planet's age and temperature to determine its mass with only modest precision. And that can become an issue of contention: A mass threshold of $13.6 M_J$ (Jupiter masses) separates large gas planets from brown dwarfs—semistellar bodies massive enough to support deuterium fusion but not the hydrogen fusion that marks a true star (see *PHYSICS TODAY*, June 2008, page 70).

Imaging a brown dwarf is regarded as less of an accomplishment than imaging a true exoplanet. Given its size and internal heat source, a brown dwarf is likely to glow more brightly in the IR than a planet, and it generally sits further from any stellar companion. Indeed several brown dwarfs have in recent years been imaged in orbit around stars. But it's not clear how instructive such pairings are about the formation of actual planetary systems.

From the luminosities of the planet candidates at wavelengths from 1 to $4 \mu\text{m}$, the group's best mass estimates are $7 M_J$ for the outermost planet and $10 M_J$ for the other two. "But," cautions planet hunter Geoffrey Marcy (University of California, Berkeley), "those masses depend sensitively on the host star's assumed age." The older the planet, the greater is its mass for a given

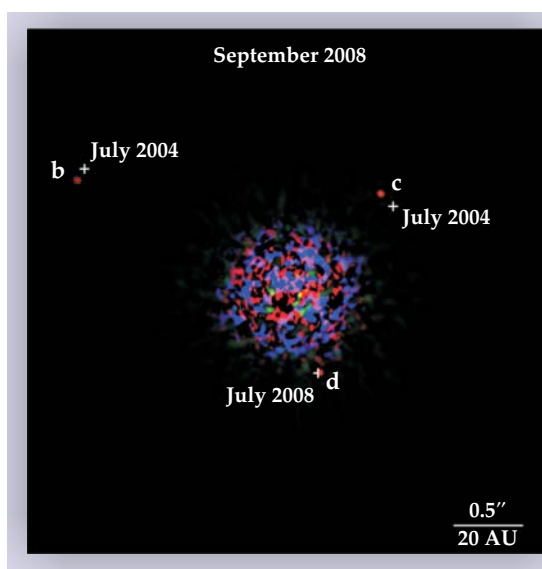


Figure 2. HR 8799's third planet (labeled d), only 24 AU from the star, was revealed in follow-up observations with the Keck II telescope in July 2008. In this composite image, which superposes observations at various near-IR wavelengths (shown in false colors) with Keck II in September 2008, the residual stellar glare that survives the angular differential imaging has not been erased. The dated crosses indicate how each planet has moved since it was first imaged. All three displacements are consistent with circular Keplerian orbits seen face-on. (Adapted from ref. 1.)

present temperature. That's primarily because more heat is generated in the formation of heavier bodies.

So an upper age limit corresponds to an upper mass limit. From HR 8799's color, luminosity, unusually massive debris disk, and stellar associates in its galactic neighborhood, Marois and company estimate the star's age to be about 60 Myr, with a very conservative upper limit of 160 Myr. Comparably conservative models of planetary cooling then yield upper limits of $13 M_J$ for the two heavier planets—just below the threshold for brown dwarfs. "Besides," says Marois, "these are three objects revolving in the same direction in essentially coplanar orbits around a star. No one has ever seen two or more brown dwarfs in such a system."

The system looks something like a scaled-up version of our own outermost planets girdled by a belt of dust and debris like our Kuiper belt. Planet formation can depend on the local intensity of stellar heating. For example, the radius of the so-called snow line—beyond which ice can accumulate on rocky material to form a growing core that might eventually accrete a giant envelope of gas—scales like the square root of the star's luminosity. Thus scaled down to the Sun's luminosity, the temperature equivalents of the three HR 8799 orbital radii are 11, 17, and 31 AU, much like the 10, 19, and 30 AU orbits of Saturn, Uranus, and Neptune.

But temperature is not the only issue. "Beyond 30 AU, protoplanetary gas disks are so rarified that the formation of gas giants by such core accretion becomes impossibly slow," says theorist Alan Boss of the Carnegie Institution of Washington. If the HR 8799

planets were indeed born near where they now orbit, he prefers the idea that they were formed far more abruptly by gravitational instabilities in the protoplanetary disk.

Orbiting Fomalhaut

Led by Paul Kalas of the University of California, Berkeley, the other group reports² the successful imaging of a planet orbiting the star Fomalhaut, familiar to stargazers. (The name is Arabic for whale mouth.) A young A-type star 16 times as luminous as the Sun and only 25 light-years away, Fomalhaut is one of the brightest stars in the equatorial night sky.

Like HR 8799 and the Sun, Fomalhaut is ringed by a belt of debris and dust. Despite the fact that the belt stands off from Fomalhaut by some 130 AU, the star's enormous glare makes it difficult to image. But in October 2004 Kalas and coworkers produced the first images of the belt at visible wavelengths in reflected starlight by means of the *Hubble Space Telescope's* advanced camera for surveys fitted with a coronagraph that minimized Fomalhaut's glare.

The images revealed several provocative features. First of all, the inner margin of the belt was sharply delineated, as if it had been sculpted by a planet orbiting nearby. The inner edge of the Kuiper belt is similarly sculpted by the nearby orbit of Neptune. Also suggestive of planetary influence is the 15-AU offset between the star and the geometric center of the belt. Furthermore Kalas and company found several faint pointlike images that might have been planets.

Because Fomalhaut is so close by, the

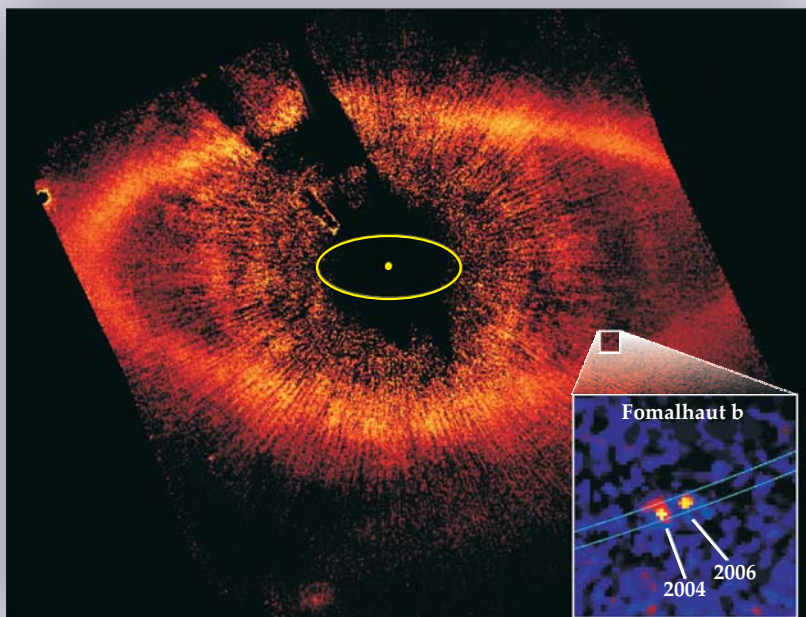


Figure 3. The belt of dust and debris ringing Fomalhaut, one of the brightest stars in the night sky, is seen here as a yellow band imaged in reflected starlight at visible wavelengths by a *Hubble Space Telescope* camera fitted with a coronagraphic occulting disk that masks the star's glare. The belt's eccentricity is only about 10%, but its plane is tilted 66° from the line of sight. Its sharply delineated inner edge has a semimajor axis of 133 AU. (Neptune's orbit is inscribed for scale.) About 20 AU starward of the belt's inner edge, the inset shows images of the planet candidate Fomalhaut b, recorded by the coronagraphic camera in 2004 and 2006. The displacement of Fom b in the 21 months between exposures is consistent with a Keplerian orbit nested inside the belt's inner edge. The curves flanking the Fom b images are segments of nested ellipses with semimajor axes of 114 and 116 AU. (Adapted from ref. 2.)

star's motion relative to the Sun makes it fairly easy to distinguish a planet from a background imposter by parallax. Just look again a year or two later. In the interval, Fomalhaut's motion will have taken it well away from any distant imposter's line of sight. And if you're lucky, the true planet will have advanced a perceptible distance along an appropriate Keplerian orbit.

The *Hubble's* hints of planetary images had come at wavelengths of 0.6 and $0.8\ \mu\text{m}$ in the visible, where one would not have expected to see them. But because Fomalhaut is only about 200 Myr old, a sufficiently large planet might well reveal itself by its IR glow. So in the summer and fall of 2005, Kalas and company repeatedly imaged Fomalhaut at near-IR wavelengths with Keck II—and found nothing.

But then in July 2006 they pointed the *Hubble* at Fomalhaut once again. Figure 3 shows the result of the group's comprehensive search of its 2004 and 2006 *Hubble* observations for planets at visible wavelengths. The star's light having been coronagraphically masked out, one sees the almost circular belt tilted at an angle of about 66° from the plane of the sky. The belt dwarfs the orbit of Neptune, inscribed for comparison.

Just short of the belt's inner edge, the group found images, 21 months apart, of what appears to be a planet circling Fomalhaut at a distance of 119 AU in a 900-year orbit appropriate to the star's $2M_\odot$ mass. They named the planet candidate Fomalhaut b. In September 2008 they followed up the discovery with

another attempt to find Fom b at near-IR wavelengths—this time with the Gemini telescope. But again they saw nothing.

The absence of any detections of Fom b in the infrared sets an upper limit of about 400 K on its effective temperature. Given the parent star's age, that translates into an upper mass limit of about $3 M_J$. What about the *Hubble* observations at 0.6 and $0.8\ \mu\text{m}$ in the visible? At those wavelengths, even a much warmer planet wouldn't show up. But the object does show up, a hundred times brighter than can be accounted for by starlight reflected off a planet not much bigger than Jupiter.

Suppose, however, that Fom b is adorned with a ring as reflective as Saturn's, but much wider. Kalas and company calculate that starlight reflecting off a circumplanetary ring extending out to about 30 Jupiter radii could account for the planet's brightness in the visible. That width is comparable to the orbital range of Jupiter's Galilean moons. So the group speculates that they might be seeing something like the young Jupiter before its moons formed from a protolunar ring.

With no thermal emission detected as yet, the group looked elsewhere for an independent mass estimate: the sculpted inner edge of the dust belt. That edge lies 15 or 20 AU beyond Fom b. In 2006 University of Rochester astronomer Alice Quillen predicted the presence of a planet near the edge.³ She argued that gravitational perturbation by a planet orbiting close to the belt

would sweep out a gap with such a sculpted edge.

The width of the gap would depend on the planet's mass. So, once Fom b had been found, one could use the observed width to estimate its mass. Led by Berkeley theorist Eugene Chiang, the Kalas group incorporated the observations into a detailed model calculation of the sweeping mechanism.^{2,4} The gap's width and the absence of obvious disruption of the belt beyond its edge yielded an upper mass limit of $3 M_J$ for Fom b, reassuringly close to what the IR null results imply.

"Our best guess," says Chiang, "is that its mass is about half of Jupiter's. The belt is probably what remains of the disk material that went into building Fom b. While we don't know whether the planet is largely rocky or has a significant hydrogen envelope, we think that Fom b formed near the record-breaking distance from the star at which we see it now."

The group hopes to get its first IR images of Fom b with the now dormant NICMOS camera aboard *Hubble* after the servicing mission scheduled to fly to the orbiting telescope in May.

Bertram Schwarzschild

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