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Exoplanets—Seeing Is Believing

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Direct observations have been made of the infrared and optical signatures of planets orbiting distant stars.

The bonanza of extrasolar planet discoveries, more than 300 at last count, has been enabled mainly by two indirect methods—radial-velocity surveys, which detect the motion of the star induced by its orbiting partner, and searches for planets that transit their primary stars. Both methods can reveal the architecture of planetary systems (masses and orbits), and the transiting planets also yield a second harvest (radii, densities, and atmospheric properties inferred partly from absorption of the star's light). Transit characterization methods depend upon proximity of the target planet to the primary star and so far tell us nothing about planets at large orbital separations. The holy grail in planet detection has thus been direct imaging because any planet spatially separated from its primary star is amenable to follow-up characterization. Although there have been previous claims of such detections (*1*, *2*), we ultimately know a planetary system when we see it. Thanks to two papers in this week's *Science* Express—by Kalas *et al*. (*3*) and Marois *et al*. (*4*)—we now have compelling images of the infrared glow of faint planetary companions—not only adjacent to but clearly orbiting stars. Kalas *et al.* present Hubble Space Telescope images of what is likely to be a planet with a mass a few times that of Jupiter orbiting the famous bright A star Fomalhaut. Marois *et al.* present a series of infrared images of three giant planets orbiting the A-type star HR 8799 in the constellation Pegasus. The planets (see the figure) are seen in nearly face-on, circular orbits spaced not unlike those of the solar system's giants at larger scale.

Direct imaging of planets is eminently challenging, particularly for ground-based telescopes observing through the blurring effects of the atmosphere, as faint planets are lost in the scattered and diffracted glare of their primary stars. The tools required for planet-imaging searches include adaptive optics techniques, which correct for the blurring of the atmosphere, and coronagraphs, which block out most of the star's light (a technique developed to study the Sun's corona).

Earlier mileposts on the road to images of planets orbiting stars have included the brown dwarf Gliese 229 B (*5*), which orbits an M star, and the several–Jupiter-mass object 2MASS 1207 B (*1*), which orbits a brown dwarf (see the figure). Neither of these low-mass objects nor other contenders fits the planet profile. Gliese 299 B is massive enough to fuse deuterium, which requires a mass greater than about 13 times Jupiter's mass ($M_{\rm Jup}$) (*6*), and the object that 2MASS 1207 B orbits is not a star—its mass is less than ~75 $M_{\rm Jup}$, the minimum required to permit fusion of hydrogen to helium (*7*).

The systems studied by Marois *et al.* and by Kalas *et al.* are notable for their similarities. Dusty debris disks, presumably arising from collisions of planetesimals, and perhaps shepherded by the new planets, surround both stars. A similar disk is likely present in our own solar system (*8*). The primary stars in both systems are younger, brighter, warmer, and more massive than the Sun. Although main-sequence A stars are generally not amenable to radial-velocity planet searches, more than a dozen giant planets have been detected by such surveys around evolved A-type stars, and trends suggest that the likelihood of a giant planetary companion increases with stellar mass (*9*).

Although images of faint companions orbiting their primary stars are captivating, their masses must be inferred from their brightness. Unlike stars, giant planets fade as they radiate away the heat of their formation. Thus, estimates of the masses of these planets depend upon how bright and how old they are. Marois *et al.* constrain the total luminosity of each companion to HR 8799 by combining images taken in several different spectral bandpasses, each of which covers a limited range of wavelengths in the infrared. They then compare the luminosities with theoretical models for giant-planet evolution assuming an estimated stellar age of 30 to 160 million years, and conclude that all three objects have masses well below the ~13 $M_{\rm Jup}$ planet threshold. However, the evolution models at these ages can be sensitive to assumed initial conditions (*10*). Higher-resolution near-infrared spectra of the planets and long-term astrometric measurements of their orbits will ultimately refine their masses. Nevertheless the multiple objects, faint luminosities, young ages, small companion-to-primary mass ratios, circular, well-spaced orbits, and associated dust disk recount a compelling story.

For Fomalhaut's companion, the plot is more complex: Apparently, planetary thermal emission is detected in only a single spectral bandpass. Kalas *et al.* must rely upon spectra from model atmosphere calculations that have never been validated in this temperature regime and upper limits from nondetections at other wavelengths for their mass estimate. The lack of gravitational disruption to this system's dust belt places an independent (but still model dependent) constraint on the planet's mass (<3 M_{Jup}). Together, the available data imply a very cool atmospheric temperature (400 K or less) and possibly a bright circumplanetary ring. If confirmed, this object will be the coolest and lowest-mass body imaged outside of the solar system.

The difficult path to ascertaining masses of these planets foreshadows the challenges that will be faced if space-based coronagraphic telescopes, such as NASA's proposed Terrestrial Planet Finder, directly image extrasolar terrestrial planets in reflected starlight. For such mature objects, there will be no connection between stellar age and planet mass; thus, the mass of planets detected only by imaging will be uncertain. Images of dots—even pale blue ones that recall Earth—orbiting other stars will be ultimately unsatisfying without knowledge of their mass. Partly for this reason, the NASA-NSF Exoplanet Task Force (*11*) advocated an astrometric planet-finding space mission that could measure masses of even terrestrial planets around nearby stars. Lacking such direct measures, the masses of future planetary discoveries will continue to hinge on the veracity of theory.

However, for the two systems now in hand, the prospects are bright. Spectroscopic and photometric observations should determine how the atmospheric composition of the planets compares to that of their primary stars, a key test of planet-formation models. In our own solar system, the atmospheric abundance of heavy elements in giant planets exceeds that of the Sun, increases with orbital distance, and is smallest in the most massive planet. It will be fascinating to see if similar trends are found elsewhere. We can further expect a race to the bottom as portraits of smaller, colder, and older giant planets, found ever closer to their parent stars, are teased out from the glare of those stars by increasingly sophisticated techniques.

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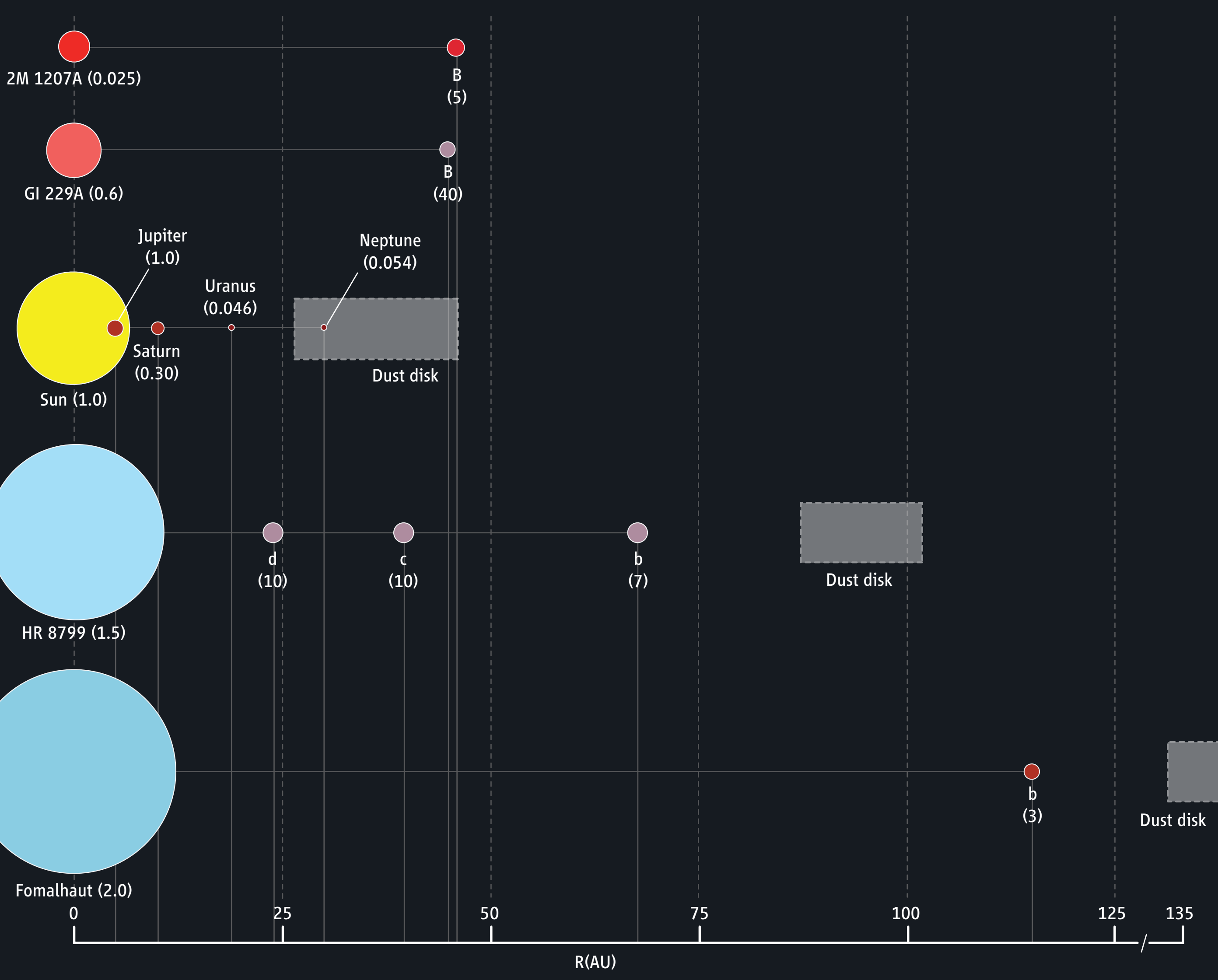
Distant stellar systems. This schematic diagram compares the directly imaged Fomalhaut and HR 8799 systems to the solar system and two other well-known binary systems. All companions are plotted at the correct projected orbital distance *R* from their primaries. Sizes and distances are shown on consistent—but separate—linear scales. The approximate locations of the known dust disk around Fomalhaut, as well as the disks inferred to be present around HR 8799 and the Sun, are also shown. Numbers in parentheses below each object are masses, for the primaries in units of the Sun's mass and for the companions in units of Jupiter's mass. Masses for all of the companions beyond the solar system are uncertain, in some cases (including Gl 229 B and 2M1207 B) by at least 50%. Stellar colors are suggestive; companions with similar (arbitrary) colors have comparable atmospheric temperature.


2M 1207A (0.025)
B
(5)
GI 229A (0.6)
B
(40)
Jupiter
(1.0)
Neptune
(0.054)
Uranus
(0.046)
Saturn
(0.30)
Dust disk
Sun (1.0)
d
(10)
c
(10)
b
(7)
Dust disk
HR 8799 (1.5)
b
(3)
Dust disk
Fomalhaut (2.0)
0
25
50
75
100
125
135
R(AU)