

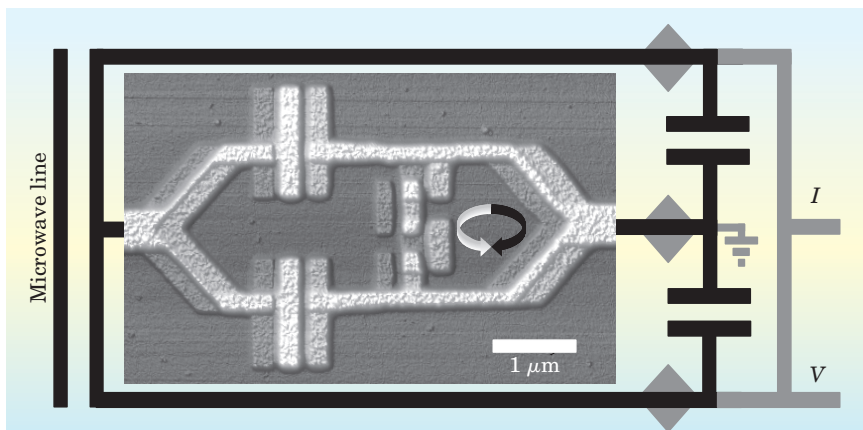


Figure 3. This AFM image shows a superconducting quantum interference device (SQUID) circuit (the large hexagonal loop) coupled to a magnetic flux qubit (the smaller loop), whose current directions, clockwise or counterclockwise, correspond to its states. Microwave pulses manipulate the qubit state into the ground or excited state, which the SQUID reads. But the SQUID also serves as a harmonic oscillator with its own set of quantum levels, which can coherently couple to the qubit. (Adapted from ref. 5.)

herent transitions in the qubit with the SQUID in the ground or excited state. The asymmetry in the levels enabled them to then resolve transitions among the different qubit and SQUID states. Time-resolved spectroscopy of the qubit–oscillator system—fixing the state of the qubit and then scanning over pulse length as a function of microwave power—confirmed the dynamics.

Mooij plans to hitch another SQUID to the circuit to serve as a high- Q (low-attenuation) oscillator to avoid the resistive attenuation that currently damps their SQUID.

Designing the future

Both groups are optimistic that the flexibility built into their circuit designs brings the coherent interaction of multiqubit systems on a chip

within reach. Qubits may behave like atoms, but each one differs subtly from the others, cautions Schoelkopf. So the ability to tune each qubit in situ may be important in any architecture that imagines entangled qubits connected to a common photon bus or SQUID oscillator. But such a device would represent a direct analog to the quantum computers now envisioned using ion traps.

Alternatively, the circuits could be adapted for a more immediate application: detecting single microwave photons.

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Three Newly Discovered Exoplanets Have Masses Comparable to Neptune's

Unlike Neptune and Uranus, the ice giants of our solar system, the new planets may be rocky “super-earths.”

In the past 10 years, some 120 planets have been discovered outside the solar system. With the exception of three lightweight oddballs orbiting a millisecond pulsar—the dead remnant of a supernova—all of these exoplanets have been at least two orders of magnitude heavier than Earth. Though observational biases clearly favor the discovery of such giants, astronomers couldn't help wondering whether, for some unknown reason, lighter exoplanets might in fact be much rarer than gas giants like our own Jupiter and Saturn.

Now the catalog of known exoplanets has suddenly become more diverse. Three teams of planet searchers recently announced the discovery of three exoplanets with masses on the order of Neptune's. The masses of Neptune and Uranus, the so-called ice giants of the solar sys-

tem, are 17.2 and 14.6 $M_{\oplus}$ (where $M_{\oplus}$ is Earth's mass). By contrast, the masses of Jupiter and Saturn are 318 and 95 $M_{\oplus}$.

The new neptunes

On 25 August, Nuno Santos (University of Lisbon) and collaborators in Switzerland, France, and Chile reported the discovery of a 14 $M_{\oplus}$ planet orbiting the Sunlike star μ Arae in the southern constellation Ara with a period of 9.5 days.¹ A week later at NASA headquarters, Paul Butler (Carnegie Institution of Washington) and Barbara McArthur (University of Texas) announced the discovery of two more planets with Neptune-like masses. McArthur's McDonald Observatory team had found an 18 $M_{\oplus}$ planet orbiting the Sunlike star ρ^1 Cancri with a period of only 2.8 days.² The planet found by the third

team, led by Butler and Geoff Marcy (University of California, Berkeley), executes an even shorter (2.6 day) and tighter orbit around Gliese 436, a cool red-dwarf star with a mass less than half the Sun's.³ For that planet, Butler and company can quote only a lower mass limit of 21 $M_{\oplus}$. But there's good statistical reason for believing that its true mass is less than twice that minimum.

Though the three new planets have acquired the nickname “neptunes,” their provenance and character remain open questions. Like their namesake, they may have cores of mixed ice and rock surrounded by modest gas envelopes (see the article by Tristan Guillot in *PHYSICS TODAY*, April 2004, page 63). Or they might be overgrown earths, composed almost entirely of rock. Least likely, say the theorists, is that they are stunted gas giants, consisting largely of hydrogen and helium like Jupiter, but somehow prematurely stalled in their

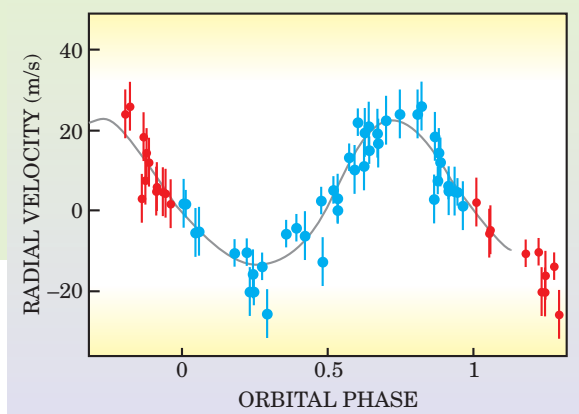


Figure 1. Periodic Doppler shift of light from the red dwarf star Gliese 436 indicates that the line-of-sight component of its velocity is oscillating in response to a planet with an orbital period of 2.64 days, which implies an orbital radius of 0.028 astronomical units. The data, taken over many periods, are folded with that periodicity. (Red dots indicate repeated data points.) The curve is the best Keplerian fit to the data. Its amplitude yields a planet of 21 Earth masses, if the orbit is being observed edge-on. (Adapted from ref. 3.)

accumulation of gas from the protostellar disk.

Like almost all the heavier exoplanets discovered before them, the three new neptunes were revealed by the tiny, periodically varying Doppler shift imposed on the light of the parent star as it's gravitationally tugged to and fro by the orbiting planet. Depending as it does on oscillation of the star's velocity component along the observer's line of sight, the so-called radial-velocity method favors the discovery of planets whose orbital planes are seen edge-on. In the absence of supplemental information, the method yields only a planet's minimum mass $M \sin i$, where M is the unknown true mass and i is the inclination angle of the orbital plane's normal relative to the line of sight.

All the exoplanets discovered thus far by the radial-velocity method are within 100 light-years of us. To the extent that the parent star's mass is known from its spectrum and luminosity, the periodicity of the Doppler signal yields the planetary orbit's semimajor axis a . With their spectacularly short periods, each of the three new neptunes orbits within less than 0.1 astronomical unit of its star, (1 AU, the mean distance of Earth from the Sun, is about 1.5×10^8 km).

Many of the Jupiter-mass exoplanets were also found in such infernally tight orbits. Those "hot jupiters," like the new neptunes, are presumed to have formed much farther out and then migrated inward by tidal interaction with the protostellar disk in the few million years before it dissipated. There is, however, an observational bias in favor of small orbits, just as there is in favor of large masses. The amplitude of the telltale Doppler oscillation is proportional to $(M \sin i) / a^{1/2}$.

Orbiting a red dwarf

In contrast to the many exoplanets found around Sunlike stars, the new

neptune orbiting Gliese 436 is only the second planet found around a red dwarf, even though these stellar light-weights are much more common in our neighborhood than Sunlike stars. Red dwarfs are far less luminous than the Sun, "and the protostellar disks that surround them in infancy are also smaller," says Marcy. "That's probably why they have fewer planets massive enough for us to have found."

Orbiting only 0.028 AU from the red dwarf, the planet is so close that tidal coupling may well have locked its rotational period to its orbit. That is, like our Moon, it may always be showing its parent the same face. But because the red dwarf is 40 times dimmer than the Sun, the temperature of the planet's perpetually illuminated face is estimated to be only a modest 620 K, not hot enough to melt most metals or rocks. The tidal locking raises an intriguing possibility: There could be a narrow band at the fixed margin between the illuminated and dark faces that's clement enough to sustain liquid water—and perhaps life.

The Butler-Marcy team studied Gliese 436 with the 10-m Keck Telescope on Mauna Kea as part of a systematic survey of red dwarfs. In some respects, searching for planets around red dwarfs is harder than around heavier, hotter stars. But in one respect it's easier. It's harder because the star's low surface temperature permits the survival of molecular species whose crowded spectra tend to obfuscate the atomic spectral lines from which one determines the Doppler shift; and cooler stars generally have fainter spectra. On the other hand, red dwarfs, with typical masses less than half the Sun's, acquire more wobble, and therefore a larger oscillating Doppler amplitude, from a planet of given mass and distance.

The radial velocity of Gliese 436 oscillates with an amplitude of 18 m/s in response to its 2.6-day planet (see figure 1). By contrast, the 14- $M_{\oplus}$ planet orbiting μ Arae is more than three times farther away from a star

more than twice as massive. Therefore, the amplitude of the radial velocity oscillation it produces is only about 4 m/s (see figure 2). With decreasing oscillation amplitude, it becomes increasingly difficult to ferret out a periodic planetary signal in the presence of various noise sources that produce random fluctuations in a star's apparent radial velocity.

A purpose-built spectrograph

"Using the first spectrograph designed and optimized specifically for planet searches, we can now find velocity oscillations smaller than 1 m/s," says Didier Queloz, who, with his Geneva Observatory colleague Michel Mayor, leads the collaboration that found the new μ Arae planet. The resolution of the general-purpose telescope spectrographs used by the other planet hunters is limited to about 3 m/s.

Last year, Queloz and company installed their new high-precision spectrograph, called HARPS, on the European Southern Observatory's 3.6-m telescope in the Chilean Andes. "The initial successes of HARPS lead us to hope that it can find planets as light as 3 $M_{\oplus}$," says Queloz. Still, a faithful Earth analog—a 1 $M_{\oplus}$ planet orbiting a Sunlike star at 1 AU—would produce a Doppler amplitude of only 0.1 m/s.

The new μ Arae neptune shares the star with two jovian giants discovered by Butler and company in 2001. Sitting much farther out than the new neptune, they take years to orbit the star. Therefore the 9.5-day oscillation produced by the smaller inner planet is superimposed on what looks—over several months of observation—like a steady linear change in radial velocity.

The HARPS group's paper argues that the inclination angle of the new planet's orbit is close to 90°, so that the 14 $M_{\oplus}$ minimum mass derived from the Doppler data is close to its true mass. The crux of the argument is that the projection, along the line of sight, of the star's surface rotation velocity, as measured by the Doppler widths of its spectral lines, is very close to the full surface velocity one

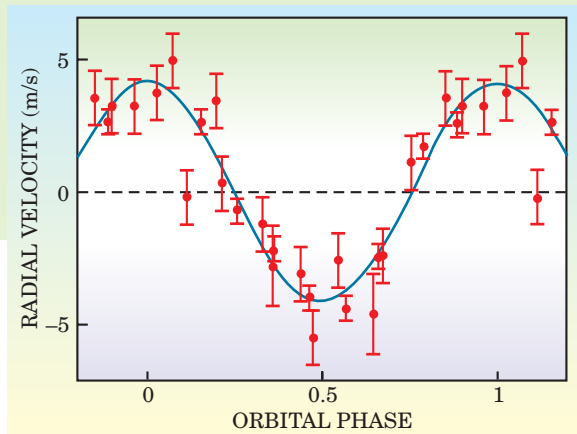


Figure 2. The 9.5-day oscillation of the Doppler shift of light from the Sunlike star μ Arae implies a 14-Earth-mass planet orbiting at a distance of 0.09 astronomical units from the star. The monotonic effect of two much heavier, long-period planets has been subtracted off. The mass estimate takes account of astrophysical evidence that the star's rotation axis, and therefore presumably the axis of the planet's orbit, is roughly perpendicular to the line of sight. (Adapted from ref. 1.)

deduces from spectral characteristics that probe the star's rotation rate by way of its magnetic field. The assumption is that planetary orbits line up roughly with the parent star's axial rotation.

An astrometric assist

There's also supplementary information about the orbital inclination of the third new neptune—the one orbiting ρ^1 Cancri with a 2.8-day period. The new planet is, in fact, the innermost of four known to circle the star. The first three, discovered by Butler and company between 1997 and 2002, range outward from a Jupiter-mass planet with a 15-day period to a lumbering superjupiter that takes about 14 years to circle the system's outer reaches.

To study this unusually rich exoplanetary system in greater detail, McArthur and her McDonald Observatory colleagues last year mounted a two-pronged assault. With the observatory's 9-m Hobby–Eberly telescope in the mountains of west Texas, they made precise new observations of ρ^1 Cancri's complex, multiperiodic Doppler oscillation. And, to get a handle on the planetary system's inclination angle i , they combed through existing astrometric data on the star from the *Hubble Space Telescope*.

Astrometry—the precise measurement of two-dimensional stellar positions on the celestial sphere—complements the radial-velocity method in the study of exoplanets. Very precise astrometric measurements would show the centroid of a star executing an ellipse on the sky over the full period of a planet with sufficient pull. From that ellipse one can, in principle, determine the inclination of the planet's orbital plane.

Astrometry has not yet reached a precision sufficient to find new planets on its own. That will probably have to await the launch of the *Space*

telescope. The McDonald Observatory team also augmented its new Hobby–Eberly Doppler data with longer-term observations of ρ^1 Cancri by the Butler and Queloz groups. Attempting to fit all these radial-velocity data to Keplerian orbits for the system's three known planets, they uncovered a robust residual oscillatory signal with a periodicity of 2.8 days and an amplitude of 6 m/s. That translated into a new innermost planet with a mass of about $18 M_{\oplus}$, orbiting the star at a distance of 0.04 AU.

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Speculation

Such a four-planet system is a valuable find that invites speculation. Presumably, says McArthur, the evolution of the three inner planets is closely linked. The most massive of these, the jovian 15-day planet, might have swept its inner neighbor prematurely inward before the smaller planet could reach the critical core mass necessary for the accumulation of a jovian gas envelope. Alternatively, McDonald team's paper speculates, the newly discovered neptune might once have been a gas giant—before it migrated so close to the star that tidal heating stripped it of most of its gas.

What do planetary theorists make of the three new neptunes at first glance? That seems to depend on which of two competing scenarios they favor for the formation of gas giants in general. Douglas Lin (University of California, Santa Cruz) is a champion of the core-accretion theory. This scenario proposes that a jovian gas giant forms when, by gradual accretion of rock or ice, a solid planetary core has reached a critical mass of perhaps $10 M_{\oplus}$. Then the core rapidly starts enveloping itself in gas it captures gravitationally from

the circumstellar disk.

“Many incipient gas giants won't make it to jovian mass before the disk dissipates after a few million years,” says Lin. “So we can expect lots of failed jupiters to show up as neptunes.” But last year, before the three neptunes had been found, Lin predicted, on the basis of the core-accretion theory, that such intermediate-weight planets would be quite rare at distances closer than 3 AU to a Sunlike star.⁴ “The surprising discovery of such new planets,” admits Lin, “has much to teach us about planetary migration mechanisms.”

Theorist Alan Boss (Carnegie Institution of Washington) favors a less gradual scenario. He attributes gas-giant formation to the abrupt appearance of gravitational instabilities in the circumstellar gas disk. This sudden creation of full-grown jupiters would leave no unfinished middleweights behind. Boss argues that our own Neptune and Uranus began life as gas giants that were thermally stripped of their envelopes by UV radiation from nearby massive young stars in an early epoch of intense star formation. Jupiter and Saturn didn't share that fate, he says, because they are far enough in for the Sun's gravity to prevent such stripping.

Similarly, the new neptunes orbiting close to ρ^1 Cancri and μ Arae could not have been formed by thermal stripping. “We know from their long-period outer companions that inward migration was very limited in those two systems,” explains Boss. “I think the newly discovered hot neptunes may be rocky super-earths formed relatively close to their stars. They could be the tip of an iceberg of Earthlike planets waiting to be found in the next few years.” **Bertram Schwarzschild**

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