A Black Widow's Best Friend?
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ASTRONOMY

A Black Widow's Best Friend?

Observations reveal an exotic planetary companion to a millisecond pulsar.

Frederic A. Rasio

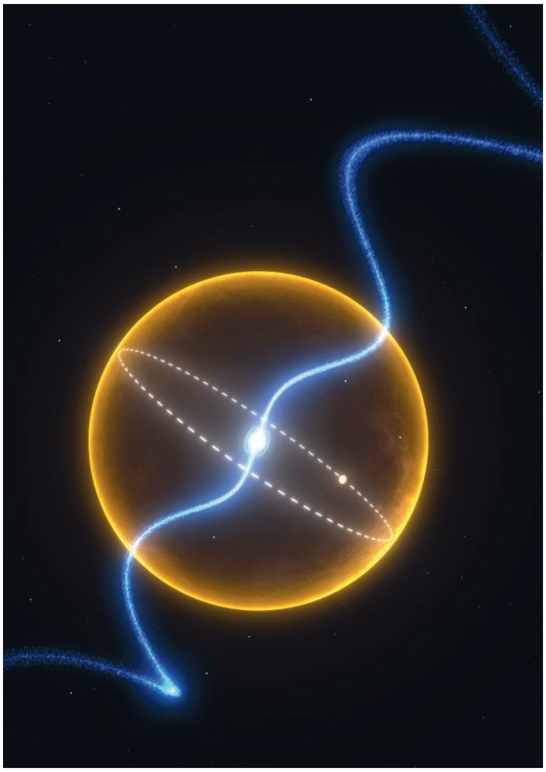
The question "what is a planet?" revisited in 2006 by the International Astronomical Union (IAU) led to the controversial downgrading of Pluto to dwarf planet status (*1*). In practice, astronomers will happily assign "planet" to any object of planetary mass, or size. Indeed, for the vast majority of the 1000 or so planets known outside our solar system, or exoplanets, the object's mass or diameter (rarely both) is its only measured property (*2*). On page 1717 of this issue, Bailes *et al*. (*3*) report the discovery of a Jupiter-mass companion orbiting the millisecond pulsar PSR J1719−1438, forcing us to further rethink the very meaning of what constitutes a planet.

The 2006 IAU definition of a planet is limited to objects within our solar system. This definition may naturally be extended to objects of planetary mass orbiting other stars like the Sun. But what if the central star is nothing like our Sun?

Pulsars are neutron stars, the collapsed remnants of massive progenitors, initially about 10 to 20 times more massive than our Sun, that have run out of nuclear fuel to burn. These progenitors explode as supernovae, leaving behind a superdense core supported against gravity by the degeneracy pressure of pure nucleon matter. Their enormous densities, exceeding those inside atomic nuclei, and correspondingly high gravities, allow neutron stars to spin absurdly fast without being ripped apart by centrifugal forces. The fastest, so-called millisecond pulsars (*4*), are nearly perfect spheres roughly 20 km across, more massive than the Sun, and rotate at hundreds of times per second.

The name "pulsar" refers to the way we detect these neutron stars, through their pulsed radio or x-ray emission. Their electromagnetic radiation, concentrated into two beams that emanate from near the magnetic poles and sweep around as the star spins, is observed as regular periodic flashes. This periodic emission makes pulsars fantastic clocks. By some measures, millisecond pulsars, which can be timed with high precision, are better clocks than the best atomic clocks. This also makes them exquisitely sensitive probes of their environments. For example, anything placed in orbit around them causes periodic Doppler shifts in their pulses' arrival times on Earth, which can then be analyzed to reveal the presence of the companion and, with enough data, provide precise measurements of the orbit and the object's mass. The technique is so sensitive that even objects as small as asteroids can be detected if they happen to orbit a millisecond pulsar (*5*).

Planets around pulsars have a long history. The first confirmed exoplanets (*6*, *7*), discovered several years before the first detections of exoplanets around "normal" solar-like stars, were found in orbit around a millisecond pulsar, PSR B1257+12 (the numbers following the acronym PSR correspond to the coordinates of the source on the sky). Although many astronomers discounted them as "not real planets" because of the strange nature of their host star, the PSR B1257+12 planets remained for many years the only Earth-mass objects known outside our solar system. And one of them, with an even smaller mass, comparable to that of our Moon, is still today the smallest-mass object known beyond the solar system.



A black widow's companion. Artist's view of PSR J1719–1438 and its planet. The millisecond pulsar is at the center, and the orbit of the planet is shown by the dashed line, with, for comparison, the size of the Sun shown as the yellow sphere.

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It is often argued that the definition of a planet should incorporate knowledge about the object's formation process. The planets in our solar system are thought to have formed through a coagulation process occurring early in the protostellar disk that surrounded the Sun for the first 10 million years or so of its existence (*8*). In contrast, the PSR B1257+12 planets likely formed out of the debris of a destroyed companion star that used to orbit the pulsar (*9*). In PSR J1719−1438, the planet most likely *is* the companion, or, rather, what's left of it after being almost entirely blasted away by the extreme irradiation from the nearby pulsar. The orbital radius is about the radius of the Sun (see the figure). Many other millisecond pulsars are known to have such companions with very low masses. They are known as "black widow" pulsars (*10*), as they appear to be slowly eating away their companion.

The companion of PSR J1719−1438 has simply been ablated down to an even smaller mass, close to that of Jupiter. The next lowest-mass companion of a "black widow" pulsar is about 20 times more massive, comparable to the mass of a brown dwarf. The possibility that a pulsar's companion might be evaporated down to such small mass as to become a planet was proposed almost 20 years ago (*11*).

Do we really know how any planets were formed? Even for the solar system, alternatives to the standard formation model exist, such as those based on gravitational instabilities (*12*). Moreover, the predictions made by theoretical models of solar system formation, when confronted with observations of exoplanets, fail rather spectacularly. Planetary systems that formed in disks should have all their planets orbiting close to the same plane, and on very nearly circular orbits. Instead, the vast majority of detected exoplanets have highly eccentric orbits, and many of them

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are now also known to be highly inclined (*2*). Some are even retrograde, orbiting in a direction counter to the spin of their host star, implying complex formation and dynamical histories (*13*).

What about chemical composition? Through careful modeling of their data, Bailes *et al*. conclude that the companion of PSR J1719−1438 has a mean density at least 20 times or so higher than Jupiter's, and that it is most likely made of elements heavier than helium. One possibility is carbon, which would be expected if the original companion was a moderately massive white dwarf (*14*). Carbon at such high densities and pressures would be in a crystallized form, leading to the nickname "diamond planet." Carbon-rich planets, including the possibility of pure diamond layers, had been discussed previously as theoretical possibilities (*15*).

Should such an extreme object, orbiting such an exotic star, with such an unusual formation path, really be called a planet? The lesson here is perhaps that, as our rapidly improving astronomical instruments make it possible to detect objects of smaller and smaller mass in distant and, sometimes, very exotic environments, any narrow definition of planet will soon become obsolete.

References

1. IAU 2006 Resolutions 5A and 6A, www.iau.org/public_press/news/detail/iau0603/.
2. Extrasolar Planets Catalog, http://exoplanet.eu/catalog.php.
3. M. Bailes *et al*., *Science* **333**, 1717 (2011); 10.1126/science.1208890.
4. J. W. T. Hessels *et al*., *Science* **311**, 1901 (2006).
5. S. E. Thorsett, J. A. Phillips, *Astrophys. J.* **387**, L69 (1992).
6. A. Wolszczan, D. A. Frail, *Nature* **355**, 145 (1992).
7. A. Wolszczan, *Science* **264**, 538 (1994).
8. P. Bodenheimer, D. N. C. Lin, *Annu. Rev. Earth Planet. Sci.* **30**, 113 (2002).
9. M. Tavani, L. Brookshaw, *Nature* **356**, 320 (1992).
10. D. Eichler, *Nature* **336**, 557 (1988).
11. F. A. Rasio *et al*., *Astron. Astrophys.* **256**, L35 (1992).
12. R. H. Durisen *et al*., in *Protostars and Planets V*, B. Reipurth *et al.*, Eds. (Univ. of Arizona Press, Tucson, 2007), pp. 607–622.
13. S. Naoz *et al*., *Nature* **473**, 187 (2011).
14. C. J. Deloye, L. Bildsten, *Astrophys. J.* **598**, 1217 (2003).
15. M. J. Kuchner, S. Seager, http://arxiv.org/pdf/astro-ph/0504214v2 (2005).

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MICROBIOLOGY

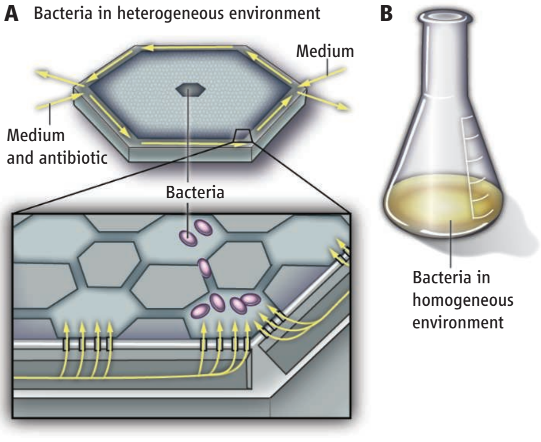
Antibiotic Resistance, Not Shaken or Stirred

Microdevices for microbial culture may better capture the evolution of antibiotic resistance in real-world environments.

Ryan L. Frisch and Susan M. Rosenberg

James Bond preferred vodka martinis shaken, not stirred, displaying impressive discriminatory power. Bacteria may be similarly discerning. Zhang *et al*. (*1*) abandoned the standard lab practice of growing bacteria in shaking homogeneous liquid cultures in favor of fabricated microenvironments and report, on page 1764 of this issue, that bacteria can tell the difference. They evolve antibiotic resistance far more rapidly in the structured environment. Evolution seems to work differently in the microenvironment, and perhaps more like evolution in the real world.

In the human body, bacteria encounter heterogeneous environments full of transient chemical and nutrient gradients. Antibiotic gradients can arise when a patient begins and ends therapies, or forgets doses. They might form across spatial heterogeneities as well. For example, the concentration of an antibiotic may be high in blood but low in less permeable dense bacterial clumps or biofilms. To simulate real-world conditions, Zhang *et al.* built a microfluidic device of tiny chambers to create gradients of both a specific chemical and nutrients. The authors then assessed the effect of the microenvironments generated within these chambers on bacterial populations grown in them. This approach may more accurately reflect encounters of microorganisms with chemicals and nutrients in the heterogeneous range of niches they encounter in the real world, such as in soil or within an animal's body. They found that when bacteria (*Escherichia coli*) are grown in a heterogeneous environment that includes a steep concentration gradient of the antibiotic ciprofloxacin (cipro), they show surprisingly rapid and repeatable acquisition and fixation of cipro-resistance mutations compared with bacteria in homogeneous environments.



Microenvironment for bacterial evolution. Fabricated microenvironments, such as the microfluidic device described by Zhang *et al.* (**A**), may provide a relevant approach to understanding microbial evolution in real-world environments that are spatially complex and full of chemical and nutrient gradients, and so differ from homogeneous liquid cultures (**B**).

The microenvironments devised by Zhang *et al*. are chambers within a device (1200 hexagonal wells etched in a silicon wafer) that are interconnected by channels and imbued with nutrient medium through nanoslits (see the figure). Medium flows into the array from two sides of the device: one side with and the other without cipro, thus creating an antibiotic gradient from bottom to top of the device. Inoculated in the center of the device, the bacteria deplete the nutrients locally and then move toward the nutrient-rich periphery through the channels and chambers. Bacteria grow at the periphery of the device but only where the cipro concentration falls below inhibitory levels.

Under these conditions, the steepest point in the cipro gradient is at the periphery where there is a convergence of flow between medium that contains and lacks cipro. The authors found this to be a "Goldilocks point"—a spot at which conditions are just right for de novo cipro-resistant mutants to become fixed in the population. This occurred repeatably, reflected by the accumulation of fluorescent-labeled cells at this point. The increased fitness of these antibiotic-adapted cells allows their growth in unoccupied niches with high cipro concentrations. In addition, the adaptation to cipro occurred rapidly (10 hours with an initial

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