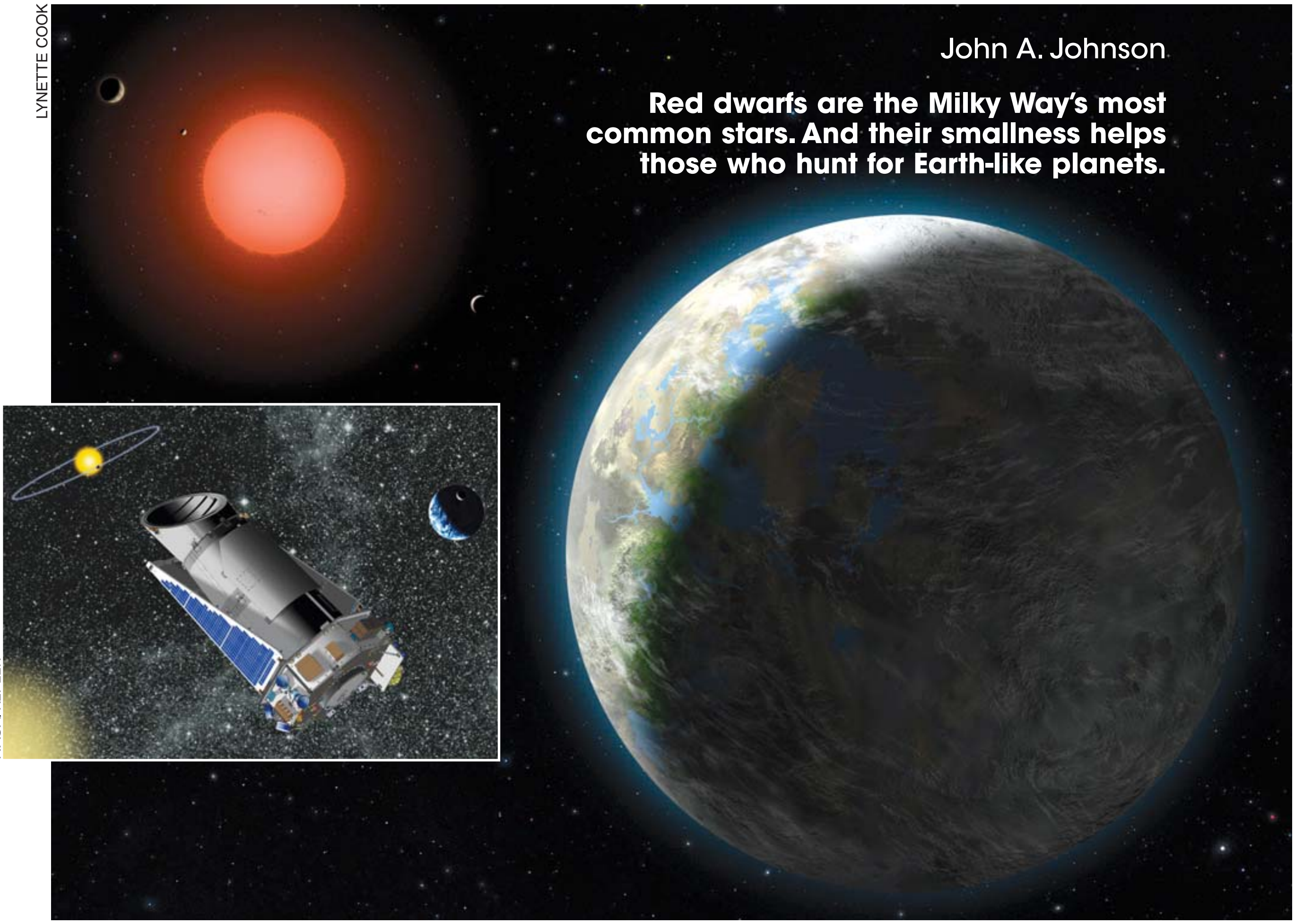
Warm planets orbiting cool stars

John A. Johnson

Red dwarfs are the Milky Way's most common stars. And their smallness helps those who hunt for Earth-like planets.



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By taking a naked-eye inventory of the night sky, one might conclude that our galaxy is inhabited mostly by stars whose masses range from about one to two solar masses $M_\odot$. But that's highly misleading. The eye's wavelength range of light sensitivity—approximately 0.4–0.6 µm—makes us miss out on the galaxy's most numerous class of stars. With eyes sensitive to longer wavelengths in the near-IR, we'd see an entirely different type of star filling the night sky: the red dwarfs.

The masses M of red-dwarf stars range from 0.1 to 0.5 $M_\odot$, and their radii are roughly proportional to M. Their surface temperatures are about half the Sun's 6000 K. But the process of radiative diffusion, by which the energy generated in the stellar core works its way to the surface, and the requirement of hydrostatic equilibrium dictate that the radiant power output of a star (its luminosity L) scales like M^4. Thus a red dwarf with a quarter of the Sun's mass will have only about 0.5% of its luminosity. So red dwarfs are extremely faint, and therefore easily overlooked.

Stars, in general, can be well approximated as blackbodies. The peak wavelength of a blackbody's emission spectrum is inversely proportional to its temperature. The Sun's peak output is near 0.5 µm in the yellow. Red dwarfs, shining brightest near 1 µm in the IR, represent about 70% of the stars in the Milky Way (see figure 1). Those faint dwarf stars might be called the galaxy's "silent majority."

As the most numerous stars in the galaxy, red dwarfs might also be the most common hosts of exoplanets. But Sun-like stars have received the lion's share of planet hunters' attention over the past two decades in the rapidly growing field of exoplanetary

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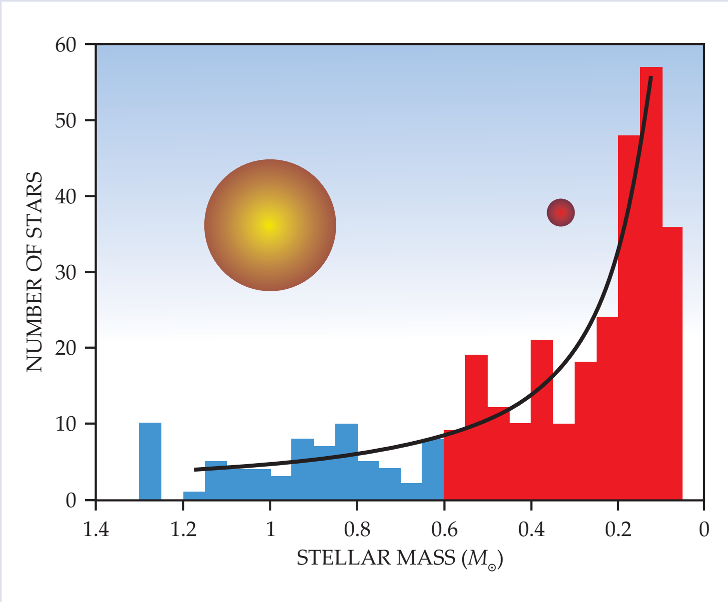


Figure 1. The mass distribution of all stars within 30 light-years of the Sun is plotted in units of the Sun's mass $M_\odot$. The red-dwarf stars, lighter than $0.6M_\odot$, are much more numerous than all heavier stellar types (blue). The distribution rises steeply toward smaller masses. The illustrative stellar disks show the relative sizes of the Sun and a typical red dwarf.

science (see PHYSICS TODAY, January 2014, page 10). It's not just solar-system chauvinism. Astronomical observation depends on photons, and hot solar-mass stars put out orders of magnitude more of them than do red dwarfs.

Of course, chauvinism does play a justifiable role. We're interested in finding planets like our own. Until a few years ago, the conventional wisdom among astronomers was that Earth-like planets should be found in planetary systems with Sun-like stars. But that conclusion was based on a sample of one. Our solar system is not a paradigm for planetary systems in the galaxy. One goal of exoplanetary science is to gain a better understanding of planet formation. Among other things, we need to understand the nature of planetary systems orbiting red dwarfs.

Early discoveries

On 19 April 1963, a *New York Times* story bore the headline "Another solar system is found 36 trillion miles from the Sun." It was based on an announcement at the annual meeting of the American Astronomical Society by astronomer Peter Van de Kamp of Swarthmore College. He and his students had spent two and a half decades making painstaking measurements of the position of a red dwarf named Barnard's Star. At a distance of only 6 light-years, it's our second nearest stellar neighbor. (The nearest, at 4.4 light-years, is the much brighter triple-star system Alpha Centauri.)

The proximity of Barnard's Star gives it a conspicuous "proper motion" across the background of more distant stars. That's what drew the attention of its discoverer, Vanderbilt University astronomer Edward E. Barnard, in the early 1900s. Van de Kamp's astrometric measurements of the diminutive star's motion suggested that it was wobbling back and forth in a dual-frequency oscillation, which he attributed to the gravitational tugs of two unseen planets.

Alas, subsequent astrometric measurements did not detect Van de Kamp's wobbles. They appear to have been due to systematic errors in the position measurements. But in addition to the projection of its motion on the plane of the sky—which is the only thing astrometry measures—a star orbited by a planet can have an oscillating "radial" velocity component V_R along our line of sight, detectable by a periodic Doppler shifting of spectral lines.[1]

However, a recent analysis of Doppler measurements of Barnard's Star's V_R going back to 1987 showed no evidence of V_R variations down to a sensitivity limit of 2 m/s. So, within the current precision limits on stellar velocity measurement by astrometry and Doppler monitoring, Barnard's Star harbors no detectable planets. (See the article by Jonathan Lunine, Bruce Macintosh, and Stanton Peale, PHYSICS TODAY, May 2009, page 46.)

The first planet discovered orbiting a red-dwarf star was not securely detected until 1999, about four years after the first exoplanet was detected around a Sun-like star. The Lick Observatory planet survey, begun in 1987, had monitored the radial velocities of 120 bright stars in the northern sky. One of the few red dwarfs bright enough to be included in that survey was star number 876 in the Gliese Catalog of Nearby Stars. Known therefore as Gl 876, the star is 15 light-years away in the constellation Aquarius. Its mass is about 0.3 $M_\odot$.

In 1998, two independent teams monitoring Gl 876 for periodic Doppler shifts announced the detection of V_R variation with an amplitude of 240 m/s and a period of 60 days. That oscillation along the line of sight indicated a gas-giant planet, designated Gl 876b, orbiting the star at a distance of 0.2 astronomical units (1 AU is Earth's distance from the Sun). It has about twice Jupiter's mass M_J.

Continued Doppler monitoring revealed a second planet, Gl 876c, in 2001. Its mass is 0.7 M_J and its orbital period is about 30 days. The two orbits are so close to each other that they're not Keplerian. In fact, dynamical analyses show that they're locked in a mean-motion resonance, with a period ratio of 2:1. That resonant arrangement has provided theorists with a rich dynamical playground for testing models of planet formation and orbital evolution.

The architecture of the Gl 876 system—two gas giants with periods less than 100 days—is very unusual.[2] Radial-velocity surveys of larger samples have found that only about 2% of red dwarfs harbor even one gas-giant planet within 2.5 AU of the star. By contrast, about 7% of stars with masses similar to the Sun's have giant planets, and the occurrence rate increases to about 20% for stars significantly heavier than the Sun.

The scarcity of giant planets like Jupiter and Saturn around red dwarfs is probably related to the less massive protoplanetary disks found around young, low-mass stars.[3] Gas giants close to their host stars are widely thought to originate from the collisional buildup of Earth-sized, rocky cores. Once formed, the cores rapidly accumulate gas to form thick atmospheres of hydrogen and helium. They end up with only a small fraction of the planet's mass in its heavy-element core. Low-mass disks generally have less of the heavy-element building blocks required for the formation of rocky cores. Furthermore, the collisional accretion of material is suppressed by the lower orbital speeds of planetesimals at a given distance from the star.

Because theorists were so excited about Gl 876's resonant pair of short-period gas giants, Doppler observers continued to accumulate V_R measurements. In addition to revealing additional details about the two gas giants, the data uncovered a new periodic variation that implied the presence of a third planet, Gl 876d. It's quite different from its heavier brethren. Its mass is only about 7 Earth masses $M_\oplus$, and its orbital period is just two days.

Such planets have no obvious solar-system analogs; they're often called "super Earths." But recent studies suggest they should be thought of as miniature versions of the lesser gas giant Neptune (17 $M_\oplus$), with large atmospheres rich in heavy volatiles and no well-defined, solid surface.[4]

Short-period middleweights like Gl 876d are found frequently around red dwarfs. In part, that abundance reflects the overall mass distribution of planets. Doppler V_R surveys have demonstrated that the abundance of exoplanets increases steeply toward lower planet masses. But another reason why low-mass planets are discovered more frequently around red dwarfs than around larger stars is an observational bias: Planets are much easier to detect around smaller stars. In the V_R technique, a planet of a given mass will cause a lighter host star to oscillate with larger amplitude than a heavier star. The same bias also holds for searches of planets transiting the faces of their host stars.

Microlensing

Another way of finding exoplanets is to exploit an optical prediction of the general theory of relativity: Light from a distant star is gravitationally bent when it passes sufficiently close to another star along the line of sight. In effect, a passing foreground star can act as a transient magnifying lens.[5]

Such stellar magnification, called microlensing to distinguish it from the showier gravitational-lensing effects of galaxy clusters, is observable only when the foreground lensing star passes our line of sight to the background star at a distance less than the system's Einstein-ring radius. That's the angular radius of the ring into which the background star's image would be distorted if the alignment were perfect (see PHYSICS TODAY, March 2012, page 19). In a typical microlensing situation, the Einstein radius corresponds to 2 or 3 AU at the foreground star.

A foreground lensing star unaccompanied by planets causes a characteristic symmetrical waxing and waning of the background star's apparent brightness over several weeks as it moves past the line of sight. But if a planet orbits the foreground star at a few AU, chance alignment may place it briefly near the Einstein ring radius. In that lucky case, the planet gets in on the lensing act, as witnessed by a brightness blip, perhaps a day long, on top of the brightening curve caused by the foreground star itself. (See figure 2.)

Even though there's often no light detected from the foreground star, one can estimate the characteristics of its planetary system with remarkable precision from the detailed shape of the background star's perceived brightness variation during the foreground system's passage.

Red dwarfs feature prominently in microlensing planet surveys. Such surveys have provided valuable statistics about low-mass planets in wide orbits around red dwarfs.[6] Those results are complementary to the detections made by Doppler surveys, because the Doppler V_R signal decreases with increasing orbit size. The microlensing technique is most sensitive right where low-mass planets become difficult to detect with the Doppler technique.

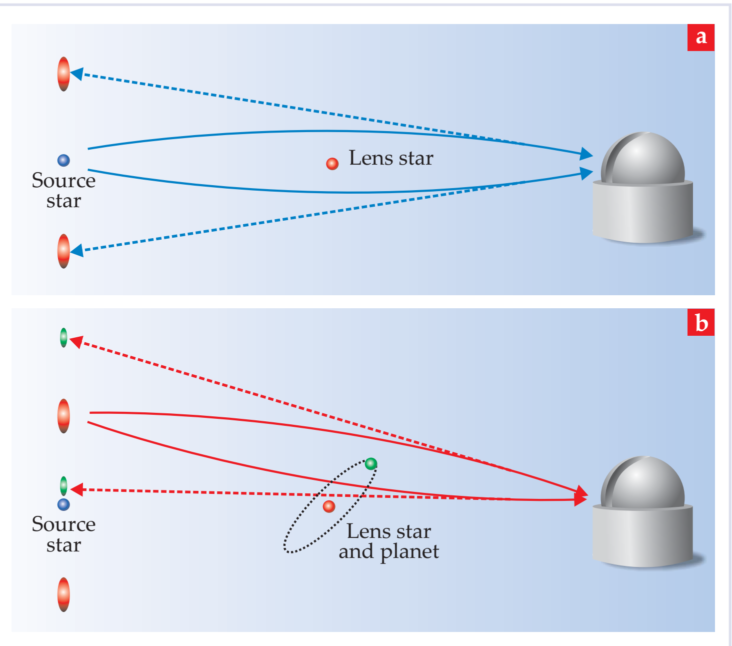


Figure 2. Microlensing searches exploit the gravitational bending of light to find exoplanets. **(a)** When a foreground star passes close to our line of sight to a more distant star, the foreground star can act as a lens, brightening the background source star by creating displaced and distorted (but unresolvable) images (dashed lines). **(b)** If a planet in a felicitous orbit accompanies the lensing star, it can lens one of the displaced source-star images and thus add a telltale blip to the brightening and waning curve caused by the passage of the lensing star itself.

Heavyweight gas giants around red-dwarf stars are relatively rare. Doppler surveys suggest that only about 2% of red dwarfs harbor any at orbital distances less than 2.5 AU. But microlensing surveys find that Neptune-mass planets are more common. If the mass distribution of planets in wide orbits around red dwarfs follows that of the close-in planets detected by Doppler surveys—namely, that abundance increases with decreasing mass—the galaxy must be teeming with Earth-mass planets.

Thus the giant planets found around red dwarfs are probably just the tip of the proverbial iceberg. Finding small planets orbiting those small stars requires pushing search techniques to higher precision and detection efficiency.

Transiting exoplanets

Atop Mount Hopkins in the Arizona desert are the eight small, robotic telescopes of the MEarth (pronounced "mirth") survey. MEarth seeks Earth-sized planets orbiting red dwarfs (also called M dwarfs) through the transient stellar dimming perceived by an observer from whose vantage point a planet transits across a distant star's face. Founded in 2008 by Harvard University astronomer David Charbonneau, the survey automatically monitors the brightnesses of several thousand red dwarfs for periodic brief dimming due to planetary transits.

In 2009 MEarth discovered a super-Earth transiting GJ 1214, a local red dwarf with about 20% of the Sun's mass and diameter.[7] The diameter of the super-Earth GJ 1214b is about 2.7 times Earth's, and its mass is 6 $M_\oplus$. Because GJ 1214 is only 39 light-years away, it's relatively bright, particularly at near-IR wavelengths. So GJ 1214b has become an object of intense study.

From right next door, we can see the twice-per-century transit of Venus across the Sun's face in exciting detail. But from a transit in another stellar system, we see only a transient dimming of that star's light by the tiny ratio $(R_p/R_*)^2$ of planetary and stellar disk areas. The transit of a Jupiter-sized planet across a Sun-sized star would show up as a 1% dip in the star's brightness. The transit signal for an Earth-sized planet orbiting such a star would be a hundred times weaker.

Here again, small stars offer a bonus in planet detectability. The fractional dip in a star's light curve due to a planet of given size scales like $1/R_*^2$. So, as illustrated in figure 3, an Earth-sized planet transiting a red dwarf with a quarter of the Sun's radius will cause a dimming signal 16 times that of a same-sized planet transiting a Sun-like star.

Furthermore, the lower luminosities and temperatures of red dwarfs shrink the orbital radius that corresponds to a given planet-surface temperature. Planets in "habitable zones"—where equilibrium temperatures would allow liquid surface water—will reside much closer than 1 AU to a red dwarf. That closer-in zone gives any planetary inhabitant a greater transit probability. Just by geometry, the tighter the orbit, the more likely is a transit from the viewpoint of a randomly placed observer. Furthermore, the tighter habitable orbits around red dwarfs have periods significantly shorter than a year, which makes it easier to spot the periodic repetitions that signal transits. Figure 4 compares the habitable zone of GJ 1214 with that of a Sun-like star.

Thus, targeting smaller stars gives searchers a significant boost in the detectability of rocky planets that might have liquid surface water. The remaining question is whether red dwarfs harbor planets at a rate comparable to that of Sun-like stars.

Kepler's red-dwarf census

One advantage of the MEarth survey is that it uses small telescopes and thereby provides a method of surveying the sky on the cheap.[8] But the downside for any ground-based telescope is that photometric precision is hampered by the vacillating transparency of Earth's atmosphere. A ground-based telescope also misses transit events because its observing cycle is interrupted by the Sun. Transit surveys are best conducted with spacecraft.

Over the past four years, NASA's *Kepler* mission has dramatically demonstrated the advantages of searching for planets from space. The *Kepler* space telescope is a beautifully simple instrument designed for one purpose: detecting the transits of Earth-sized planets. Until its precision pointing system failed last year, *Kepler* stared unflinchingly at a single 10° × 10° field of stars near the constellation Lyra.[9] In that field, 150 000 target stars were selected (mostly on the basis of apparent brightness) for continual monitoring. Starlight entering the telescope's 1-m aperture passed through several optical elements that focused it onto an array of 42 CCD detectors, each with 8 million pixels.

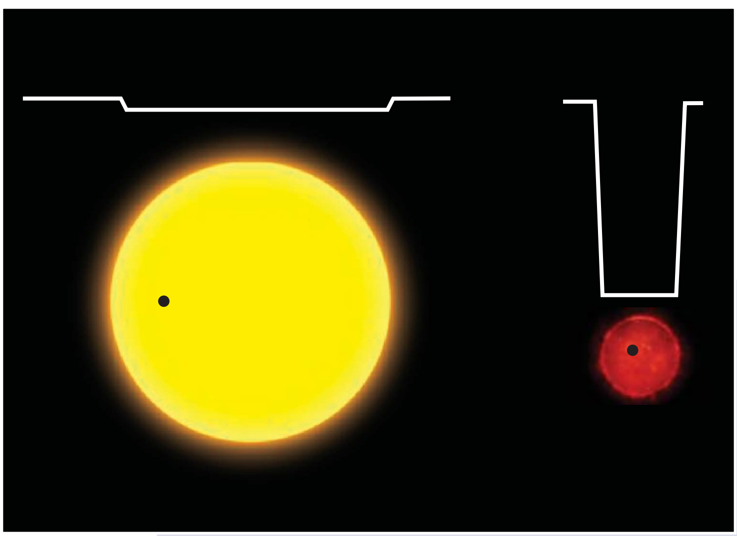
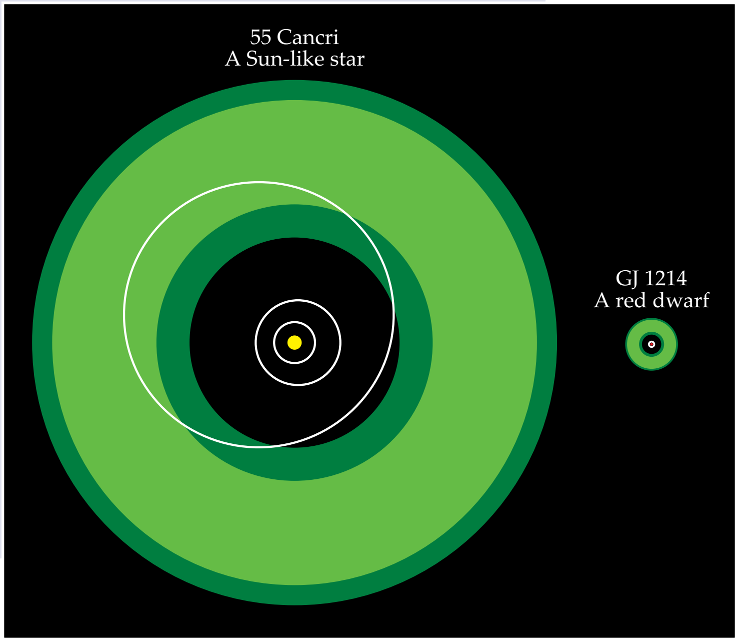


Figure 3. As a planet transits across the face of its host star, a distant observer sees the star's brightness very slightly dimmed by the squared ratio $(R_p/R_*)^2$ of their radii. Thus a planet transiting a red-dwarf star with a radius only 25% that of the Sun will produce a fractional dimming signal 16 times deeper than would a planet of the same size transiting a Sun-sized star.

Figure 4. Comparing habitable zones around big and little stars, where planets could have liquid surface water. Light and dark green shadings indicate conservative and permissive habitability criteria. White circles show planet orbits. One of the planets of the Sun-like star 55 Cancri, with an eccentric orbit averaging 80% of Earth's orbital radius, spends some of its time in the heart of its star's capacious habitable zone. The red dwarf GJ 1214, with a luminosity less than 1% of 55 Cancri's, has a habitable zone that's much smaller and closer in. That makes it easier to detect a habitable-zone planet orbiting the smaller star, for two reasons: Close orbits are geometrically more likely to exhibit transit, and their shorter periods yield more frequent transits. Nonetheless, the orbital radius of GJ 1214's one known planet is too small even for the dwarf star's snug habitable zone. (Courtesy of the Habitable Zone Gallery, http://www.hzgallery.org.)



The numbers of photons collected by the CCD array for each of the *Kepler* field's target stars were totaled up every half hour, with a precision of about 10 parts per million for the brightest stars and 100 ppm for stars of typical brightness. The best precision obtained with ground-based telescopes has been a factor of 4 or 5 worse—and that only for a few hours at a time under ideal weather conditions.

The *Kepler* mission primarily sought to conduct a galactic census of planets of Earth-like mass and orbital radius around Sun-like stars. Of the 150 000 target stars, 90% have masses within 20% of $M_\odot$. But just like our naked-eye view of the night sky, that sample is not representative of the galaxy's stellar population. Happily, a small subset (about 3000) turned out to be red dwarfs.

Despite the planet-detection advantages they offer, red dwarfs come with a major drawback: Their stellar radii R_* are hard to determine accurately. And one needs R_* to determine a planet's size from the transit dimming. For Sun-like stars, models of stellar interiors and atmospheres are well calibrated by studies of the Sun. But red dwarfs have very different internal structures, which makes it hard to deduce their sizes from observable properties.

Stellar spectra

A further complication is the great differences between the spectra of red dwarfs and Sun-like stars. The Sun's spectrum has many discrete absorption lines from which one can, with stellar models, deduce temperature, surface gravity, chemical composition, and other properties. But the spectra of red dwarfs are crowded with molecular-absorption features that are not well understood.[10] So it's hard to extract the physical properties of a given red dwarf from its spectrum.

Directly modeling red-dwarf spectra has proven unfruitful. But broadband photometry does provide some useful empirical calibrations. One such correlation is the tight relationship observed between a red dwarf's IR luminosity and its mass. That correlation can be used to determine the mass of a relatively nearby red dwarf—if one knows its distance from parallax measurements.

Another key stellar parameter is "metallicity"—a star's abundance of elements heavier than hydrogen and helium (essentially the only two elements in the prestellar cosmos). The heavier elements, iron in particular, provide free electrons when they're ionized in stellar atmospheres. Therefore, they have a major effect on the diffusion of radiation out of the star's central fusion engine. That diffusion, in turn, governs the star's size. Stars with very absorbing atmospheres are bigger and puffier than the more freely radiating low-metallicity stars.

Stars also become larger in old age. For Sun-like stars, that bloating poses an ambiguity between metallicity and age. But red dwarfs have lifetimes that are orders of magnitude longer than the Sun's paltry 10^{10} years. In fact, just about every red dwarf ever formed in the Milky Way is still alive, and will still be alive long after the Sun dies! Therefore a middle-aged red dwarf of a given temperature has a radius determined by its metallicity alone. So measuring its temperature and metallicity suffices to yield its size.

In 2010, Bárbara Rojas-Ayala, then a graduate student at Cornell University, discovered features near 2 μm in red-dwarf IR spectra that can be calibrated to yield both a star's temperature and its metallicity. She and coworkers used that spectroscopic calibration to measure the radii of the host stars of planets found orbiting red dwarfs in the *Kepler* sample. Those stellar radii let them revise and refine the estimates of the planetary radii, thus opening a window of opportunity for the study of small planets orbiting *Kepler*'s coolest, smallest target stars.[11]

A miniature

The very smallest of *Kepler*'s planetary systems is small in several respects. The mass and radius of the

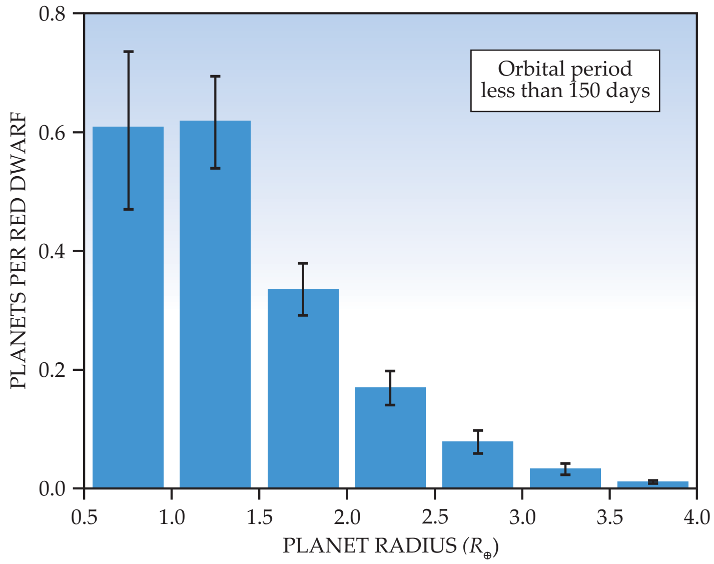


Figure 5. The size distribution of planets (in units of Earth radii) orbiting red-dwarf stars with periods less than 150 days, as found by NASA's *Kepler* telescope. Earth-sized planets far outnumber Neptune-sized planets (roughly 4 $R_\oplus$). (Adapted from ref. 12.)

host star, Kepler-42, are both less than 20% of the Sun's, and its luminosity is less than 1% of $L_\odot$. Its three planets all have tiny orbits, with periods less than 2 days. The planets themselves are all smaller than Earth. In scale, the system looks more like Jupiter and its Galilean moons than like any other known planetary system.

Based on an analysis of Kepler-42 and other red-dwarf systems found by the *Kepler* mission, my research team at Harvard University has concluded that there are, on average, about two planets per red dwarf throughout the galaxy. In addition to measuring the overall abundance of planets around red dwarfs, we can study the abundance as a function of planet size and orbital period. Figure 5 shows the size distribution of planets orbiting *Kepler*'s red dwarfs with periods less than 150 days, calculated by team members Tim Morton and Jon Swift.[12] Of the more than a hundred planetary systems discovered orbiting red dwarfs, only one contains a Jupiter-sized planet. The vast majority are comparable in size to Earth.

Harvard graduate student Courtney Dressing is particularly interested in Earth-sized planets that orbit red dwarfs in their habitable zones. From the *Kepler* red-dwarf data, she has measured the abundance of rocky, habitable-zone planets—having taken careful account of detection efficiencies. The result is remarkable: There are about 0.5 Earth-sized planets per red-dwarf habitable zone.[13]

From hunters to gatherers

Thanks to the red dwarfs, we're moving from an era of planet hunting to one of planet gathering—to be followed by detailed studies of individual exoplanets at the level of attention previously lavished only on solar-system planets. The next step is to develop instruments for finding and examining the Earth-like exoplanets we're now convinced must be right next door. Because the majority of them will be orbiting red dwarfs, the next-generation instruments will be optimized for sensitivity at near-IR wavelengths.

An example of the next generation of IR instruments includes the Habitable-Zone Planet Finder being developed for the large Hobby–Eberly Telescope in Texas. That high-resolution spectrometer is specifically designed to find Earth-mass planets orbiting red dwarfs. Such instruments will make surveys of the rocky planets orbiting the nearest red dwarfs possible. To find low-mass planets in wider orbits beyond 1–2 AU, the Korea Microlensing Telescope Network will use three wide-field, red-sensitive telescopes distributed across the Southern Hemisphere to search for microlensing events with unprecedented sensitivity and time coverage.

Next-generation transit missions such as NASA's *TESS* (Transiting Exoplanet Survey Satellite) and the European Space Agency's *PLATO* (Planetary Transits and stellar Oscillations) spacecraft will follow *Kepler* into space. But whereas *Kepler* stared continuously at a single field of view, *TESS* will search the entire sky for small planets transiting nearby bright stars. Included among its half million targets will be thousands of red dwarfs.

Once Earth-like planets are found orbiting nearby red dwarfs, those planetary systems will be prime targets for NASA's *James Webb Space Telescope*. The *JWST* will be able to measure a transiting planet's atmospheric absorption features imprinted on the stellar spectrum. Such transmission-spectroscopy measurements will let astronomers search for telltale gasses that might be signs of life beyond the solar system.

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