feature article

The detection and characterization of exoplanets

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The variety of methods by which planets beyond our solar system can be found will lead to the detection and eventual characterization of Earth-size bodies orbiting their stars at hospitable distances.

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Since 1995, more than 340 planets around stars other than the Sun have been discovered.[1] After centuries of speculation as to whether our planetary system might be one of many, that's a remarkable achievement. The techniques that have been used to accomplish those discoveries and to study the properties of the exoplanets are based on physical phenomena ranging from the straightforwardly simple—planets tugging gravitationally at their host stars or blocking their light—to the subtle general-relativistic effect of gravitational microlensing. But conceptual simplicity doesn't make it any less difficult to detect the tiny periodic effect of an orbiting planet on its host's motion or apparent brightness.

The already discovered exoplanets in figure 1 range from bodies many times the mass of Jupiter to the presently detectable limit of a few Earth masses ($M_\oplus$), in close circular orbits or larger orbits sometimes eccentric enough to periodically bring the planet close to the parent star.

A handful of exoplanets have known masses and radii, so their mean densities are known. And in a few cases, some atmospheric parameters are known. In this article we highlight present-day and near-future techniques for detecting planets. We compare the sensitivities of the discovery techniques and discuss prospects for follow-up characterization with large space-based telescopes. Much of what is presented here is based on the recent report of the Exoplanet Task Force of the NASA–NSF Astronomy and Astrophysics Advisory Committee.[2]

Doppler spectroscopy

Thus far, the most successful technique for detecting exoplanets has relied on finding the periodic Doppler shifting of light from a star that is being gravitationally tugged to and fro by a planet orbiting close by (see PHYSICS TODAY, November 2004, page 27). Fully 90% of all the known planets outside our solar system have been found by that technique, which was pioneered in the mid-1990s by Michel Mayor and Didier Queloz in Switzerland and Geoff Marcy and Paul Butler in the US, revealing the first exoplanets orbiting ordinary main-sequence stars.[3] A few years earlier, several planets had been discovered in orbit around radio pulsars—neutron stars near which one wouldn't want to live—by periodic anomalies in the pulsating radio signals.

Doppler-shift spectroscopy measures only the component of a star's to-and-fro motion along the line of sight. The star and planet orbit around the system's center of mass. For a planetary system oriented at any angle other than face-on to Earth, the "radial" component of the star's motion toward and away from the observer creates an oscillating Doppler shift in the star's spectrum. Atomic and molecular spectral lines are shifted slightly toward the blue and then the red. At present, telescopes appropriately outfitted with precise spectrometers can discern radial velocities as slow as a few meters per second (see figure 2). That walking speed creates a Doppler shift of a part in 10^8 of the spectral line's wavelength.

The amplitude of the Doppler oscillation caused by a planet of given mass and orbital radius depends on the orientation of its orbital plane relative to the observer, which is not generally known. Looking edge-on, one sees the strongest Doppler signal; face-on one sees none. Therefore the technique generally yields only a lower limit to the perturbing planet's mass. But when other techniques—for example, observing planetary transits across the star's face—establish the orbit's inclination, one can determine the planet's mass without the orientational ambiguity.

A key requirement for Doppler detection is observation of the star for at least one full orbit period. That's why the earliest discoveries were of giant planets in very close proximity to their parent stars. But as time has gone by, the method has unveiled planets of lesser mass and greater orbital distance. By now, the statistics for stars scrutinized in Doppler surveys show that at least 15% of Sun-like stars have gas-giant planets with orbital periods shorter than 10 years, and about 1% of Sun-like stars have very close-in gas giants—referred to as hot Jupiters.[4]

The challenge for Doppler spectroscopy is to push to higher precision so one can detect the tugs of ever smaller planets in larger orbits.[5] Discoveries to date indicate that the actual number of planets rises steeply with decreasing planet mass. Both the duration and precision of Doppler measurements have steadily increased, overcoming noise sources such as turbulence in the photospheres of the parent stars. Planets as small as $5M_\oplus$ in close orbits have already been detected, as have 33 multiple-planet systems. In addition to solar-type stars, M-dwarf stars are common subjects of Doppler planet surveys. Those cool red stars with masses less

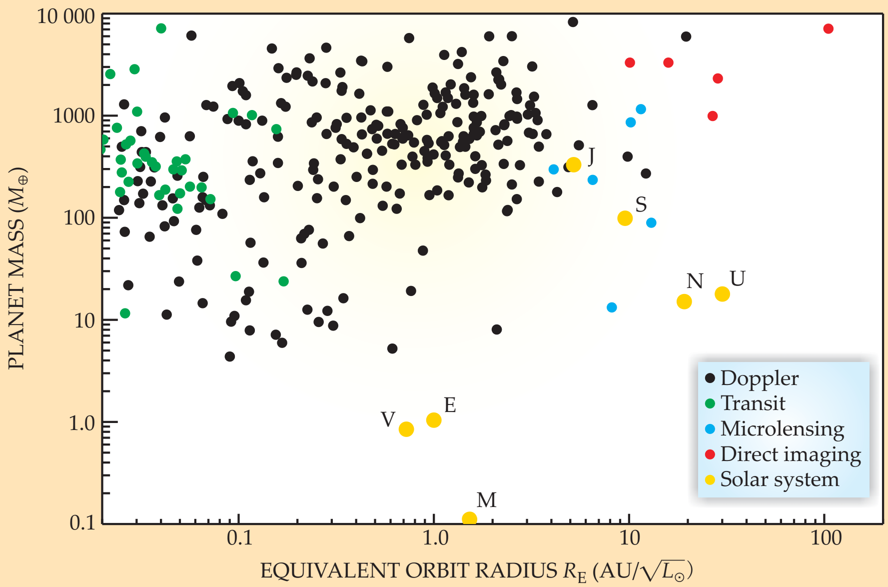

Figure 1. For more than 300 planets already discovered, mass (in units of Earth's mass $M_\oplus$) is plotted against R_E, a thermal-equivalent orbital radius given by $R/\sqrt{L}$, where R is the actual radius (in astronomical units) and L is the parent star's luminosity (in units of the Sun's luminosity $L_\odot$). So planets with the same R_E around very different stars experience the same intensity of stellar irradiation, and planets orbiting in the so-called habitable zone of Earth-like temperatures all have R_E near 1. Planets of our solar system are labeled by their initials. The exoplanets are colored according to the technique by which each was first detected.

than half that of the Sun are the dominant residents of our galactic neighborhood. Because their radiant flux peaks at near-IR wavelengths of 1–2 microns, IR Doppler spectroscopy has been proposed as a new technique to search for planets orbiting the lowest-mass stars.[6]

The current precision with IR spectrometers permits the detection of line-of-sight velocity components as slow as 80 m/s. That might be adequate for detecting gas giants orbiting such low-mass stars. But proposals for new IR spectrometers envision velocity precisions approaching those of the optical-wavelength techniques. With a Doppler precision of 1 m/s, one could detect Earth-mass planets around the smallest of the M dwarfs.

Microlensing

The deflection of light by gravity is a key feature of general relativity. The images of distant galaxies can be displaced, distorted, and even duplicated by massive foreground galaxy clusters acting as gravitational lenses. On a more modest scale, the microlensing that can reveal planets occurs when an intervening lens star harboring a planet passes almost directly between a more distant, bright source star and the observer, and the source star's light is gravitationally focused into two images on either side of the lens star (see PHYSICS TODAY, April 2006, page 22).

The angular separation of the microlensed images is typically only about 1 milliarcsecond, too small to resolve the two images. Instead the source star's image appears temporarily magnified, its brightness waxing and waning as the lens star traverses the line of sight (see figure 3). A planet belonging to the lensing star can reveal itself by perturbing the light curve when it passes through the line of sight to one of the stellar images. Observation of such a microlensing event can often be used to determine the mass of the planet and its projected separation from the star.

The theory of microlensing is rigorous, and the search technique is robust. With a space-based microlensing survey, it should ultimately be possible to determine the occurrence

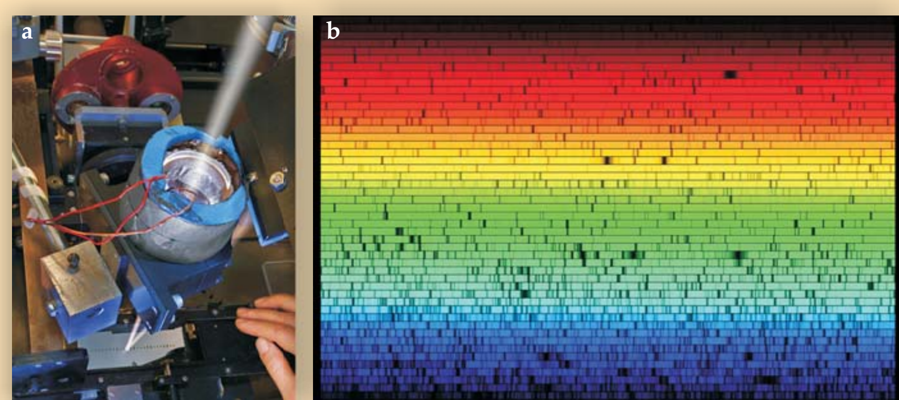

Figure 2. Doppler spectroscopy in search of exoplanets. **(a)** A reference iodine-absorption cell provides precise measurement of the oscillating positions of spectral lines from stars tugged to and fro by planets. The beam of starlight from the telescope enters the cell and passes on, imprinted with thousands of narrow iodine absorption lines, through the entrance slit into the spectrometer. The iodine lines fix both the wavelength scale and any instrumental peculiarities onto the oscillating stellar spectrum, providing Doppler velocity measurements accurate to 1 m/s. (© Laurie Hatch Photography, http://www.lauriehatch.com.) **(b)** Stellar absorption produced by such a system's echelle spectrometer is projected onto a CCD detector array in stacked horizontal bands covering the optical spectrum from red to violet. Over that wavelength range, thousands of absorption lines contribute to the final Doppler measurement. (Courtesy of Geoff Marcy.)

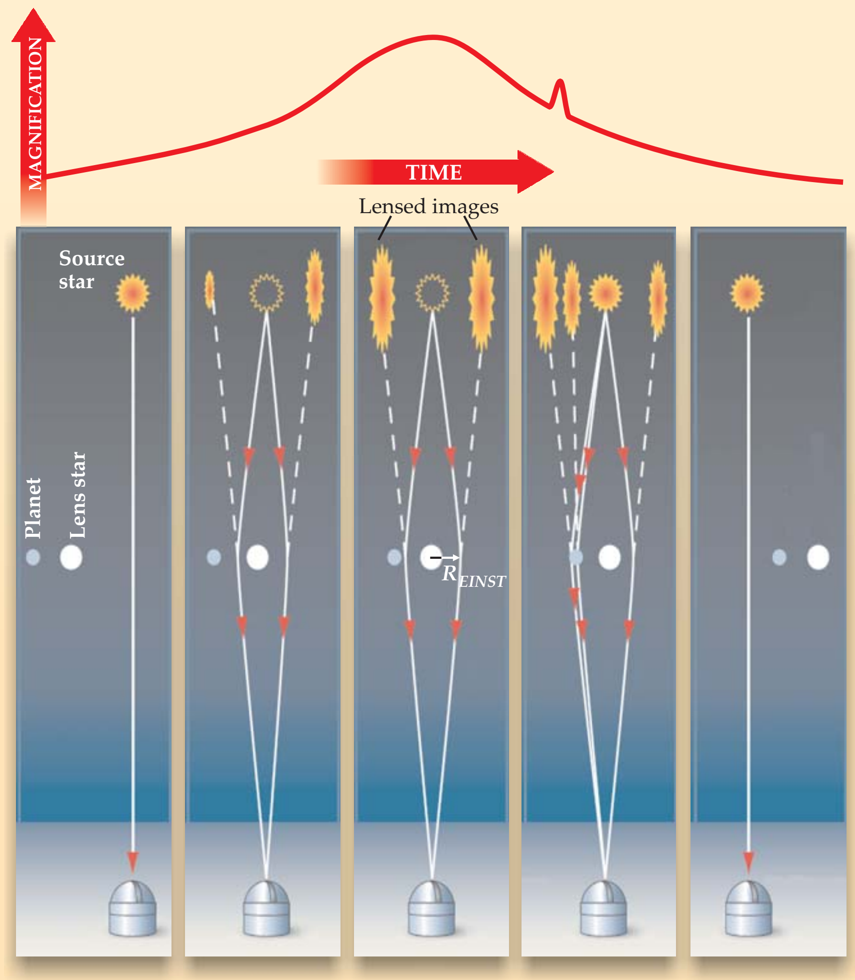

Figure 3. Microlensing can reveal exoplanets. By gravitational bending of light, a foreground lensing star passing near the sightline to a much brighter background source star displaces, distorts, and often duplicates the latter's image. If the Einstein radius R_{Einst}, the characteristic size parameter of the lensing event, subtends an angle too small for a telescope to resolve, the observer does not see multiple images of the source star but only an ephemeral brightening of its light curve (red curve, top) as the lens star passes by. A planet accompanying the lens star at a distance comparable to R_{Einst} can reveal itself as a bump on the light curve. (Adapted from David Bennett's website: http://www.nd.edu/~bennett/moa53-ogle235.)

of planets as a function of planet mass down to 0.1 $M_⊕$, host-star type, and planet–star separation from 0.5 to 15 astronomical units, where 1 AU is the Earth–Sun separation.[7] Planets at further separations from their stars would be hard to distinguish from free-floating planets.

So far there are 13 secure detections of planets by microlensing. Eight have been published: five Jovian, two somewhat smaller than Neptune, and one $3M_⊕$ planet. Two of the Jovian planets are members of the same planetary system, with a mass ratio and separation ratio comparable to those of Jupiter and Saturn. Some of the discoveries still undergoing analysis are also multiple-planet systems. The $3M_⊕$ planet orbits either a brown dwarf or a very cool ordinary star.[8] So the modest microlensing harvest to date has already told us that cold Neptunes are common and that solar-system analogs may well be common. Microlensing, by the way, is also the only way to detect free-floating planets.

The number of microlensing detections could be greatly enhanced by a Southern Hemisphere array of three 2-m-aperture telescopes with large fields of view.[9] Two of the telescopes already exist. A planet orbiting a lens star is most easily detected when the projected distance between them equals the radius R_{Einst} of the so-called Einstein ring that the source star's image would form if the two stars were perfectly aligned. For good Sun-like microlensing candidates, R_{Einst} is typically 2–4 AU. The circumstellar region near R_{Einst} is called the lensing zone.

The ground-based telescope array might find a significant number of Earth-like planets in the lensing zone. But it could detect essentially none in the habitable zone of 0.5–1.5 AU. More massive planets have a much higher discovery rate; more than 400 Jupiters would be found in a four-year survey if all the stars had a Jupiter in the lensing zone.

If a source star were in the Milky Way's central bulge, about 25 000 light-years away, and a lensing system identical to our solar system were halfway there along our line of sight, we would see its Jupiter in its Sun's lensing zone.

From space, microlensing observations could probe habitable zones for Earth-sized planets. Relative to ground-based telescopes, space telescopes would suffer much less blending of the source star's image with those of nearby stars, and the photometric signal-to-noise ratio is much better. The discovery rate for Earth-mass planets in the lensing zone would be about 40 times higher and, in the habitable zone, 600 times higher![1]

Transits

The passage of a planet in front of its parent star's disk, shown in figure 4, is called a transit. Because the transit temporarily blocks a small fraction of the star's light, one can hope to discover transiting planets by monitoring a large sample of stars, looking for periodic, short-lived dimming events. One may also seek transits of planets that have already been discovered by the Doppler technique but whose orbital inclinations are unknown. The combination of transit photometry and Doppler velocimetry reveals both planetary radius and mass. High-precision follow-up observations can reveal a wealth of information about the planet and its star that is not available for a nontransiting planet.

Some five dozen transiting planets are known. The ground-based photometric surveys have detected planets that dim the parent's starlight by as much as 3% and as little as 0.5%. With a few exceptions,[10] the parents are almost all ordinary stars with masses ranging from 0.5 to 1.4 times that of the Sun, and the planets are gas giants with radii comparable to Jupiter's. Their masses, however, tend to be smaller by 5–20% than one would expect for a Jovian planet of a given size. Part of the size excess is attributable to the fact that these transiting planets are generally very close to their stars and therefore very hot. (Seeing a transit becomes increasingly un-

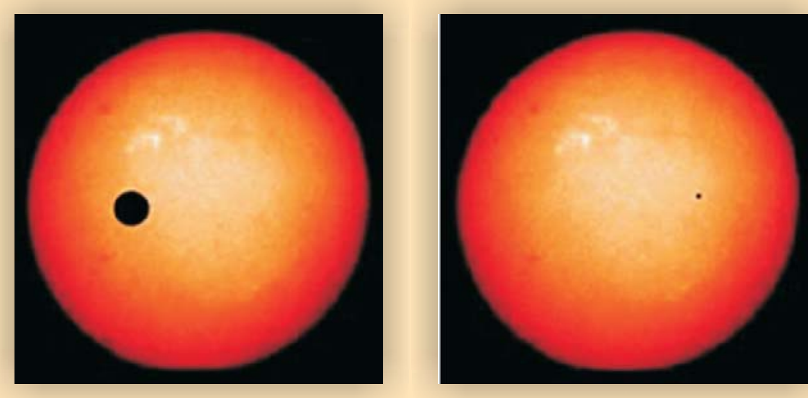

Figure 4. The transit of an exoplanet across the disk of its parent star is simulated by an image of the Sun and dark spots representing (left) a Jupiter-size and (right) an Earth-size planet. A transiting Jupiter would block about 1% of a Sun-like star's light. An Earth's dimming signal would be 100 times weaker. (Courtesy of NASA.)

likely with increasing orbital radius.) But that explanation by itself is insufficient to explain the most bloated of transiting planets; the question remains open.

A space-based transit survey is being conducted by the joint French–ESA (European Space Agency) satellite *Corot*, which has been in orbit since December 2006. Designed to do both stellar seismology and planet-transit searches, *Corot* has a 27-cm-diameter telescope with a field of view 3° wide. It has demonstrated photometric precision better than a part in 10^4, which is difficult to achieve from the ground, and has detected planets as small as two Earth diameters. Detecting the transit of Earth-size planets will require improving photometric accuracy by at least another order of magnitude. That's the goal of NASA's *Kepler* mission, launched on 7 March. With a 95-cm-diameter telescope, *Kepler*'s field of view is 10° wide. The 10^8-pixel focal-plane array is the largest camera ever flown by NASA.

Launched into an Earth-trailing heliocentric orbit, *Kepler* is to monitor about 100 000 Sun-like stars in a patch of the Milky Way, most of them between 600 and 3000 light-years away. Assuming a random distribution of orbit inclinations, about 1% of those stars with Earth-like planets in the habitable zone should show detectable transits. By 2012 *Kepler* should have accumulated enough observations to yield good statistics about the occurrence of Earth-size planets in the habitable zones of Sun-like stars.[11]

The stars *Kepler* will monitor are distant and therefore faint. So although the transits of Earth-like planets can be detected, it will be hard to characterize the planets thus discovered by Doppler or other follow-up techniques. Therefore it would be very useful to find transits of planets in the habitable zones of stars much closer by than those under *Kepler*'s surveillance. A follow-on mission has been proposed that would use arrays of small cameras, each with a small lens but a large field of view, to image huge swaths of the sky in search of the nearest transiting planets. Such a mission would be especially valuable in the study of transits around the ubiquitous M-dwarf stars. Follow-up IR Doppler measurements would allow precise measurements of planet mass and orbital properties, and the more massive planets could be characterized in detail with a large-aperture telescope such as the *James Webb Space Telescope*, to be launched in 2013.

The *JWST* is a cooled IR telescope with a segmented 6-m-diameter mirror. Its ability to observe planetary transits at various IR wavelengths should allow it to measure atmospheric properties of exoplanets as small as two Earth diameters orbiting M dwarfs. Because the *JWST* is not designed as a survey instrument, it will not search for exoplanets. Instead, the plan is for it to study those that have already been found by ground- and space-based surveys.

Astrometry

The same stellar reflex motion that gives the radial-velocity Doppler signatures also gives rise to astrometric signatures—looping motions across the celestial plane normal to the line of sight. Astrometry is the measurement of stellar positions on the celestial sphere. Conclusions from the astrometric data do not suffer the planet-mass ambiguity associated with Doppler oscillations. Combining astrometry with Doppler data yields unambiguous and precise orbital parameters that can confirm the presence of Earth-mass planets and something of their dynamical history.

There has, as yet, been no confirmed detection of a planet by astrometry. But the astrometric signature of Jupiter, as seen by an observer watching the solar system face-on from 30 light-years away, would be a 12-year solar loop 500 microarcseconds in angular diameter. Such a loop could easily be seen by an astrometric space mission such as ESA's *Gaia*, planned for launch in 2011. Because the amplitude of such loops around the system's center of mass increases with orbital radius, outer planets should be more easily found by astrometry than by most other methods. But the limited duration of a space mission will sharply cut off this improvement for planets whose orbital periods are very long. Astrometry should detect many giant planets; a large fraction of them will already have been found by Doppler surveys.

Finding Earth-mass planets by astrometry requires submicroarcsecond precision. A mission to search 100 nearby Sun-like stars for Earth-mass planets in Earth-like orbits would have to detect astrometric signatures as small as 0.22 μas, using hundreds of observations per star over the mission's life. Technology studies at the Jet Propulsion Laboratory are aiming toward the launch of such an astrometric system by the end of the next decade.[12] That mission could point out specific nearby planets for later direct-imaging missions to characterize more efficiently and cost-effectively than if the imaging missions had to do the searching themselves.

In the near term, astrometric accuracy from ground-based telescopes is expected to improve to better than 100 μas on large telescopes as the various sources of wavefront error are understood. At that level of precision, ground-based astrometry will concern itself chiefly with finding giant planets and determining their masses and orbits. The best ground-based astrometric work is expected from several facilities with large telescopes whose aperture diameters are 8 meters or more. The two 10-m Keck telescopes on Mauna Kea in Hawaii have a goal of 50- to 100-μas precision by the end of this year. Similar precision is predicted for the four-year-old Large Binocular Telescope in Arizona, with its twin 8.4-m mirrors. A more ambitious effort is planned for the European Southern Observatory's Very Large Telescope Interferometer array in Chile.

Direct detection

Ultimately, the ability to directly image an extrasolar planet—by the light it reflects or emits—offers the greatest prospect

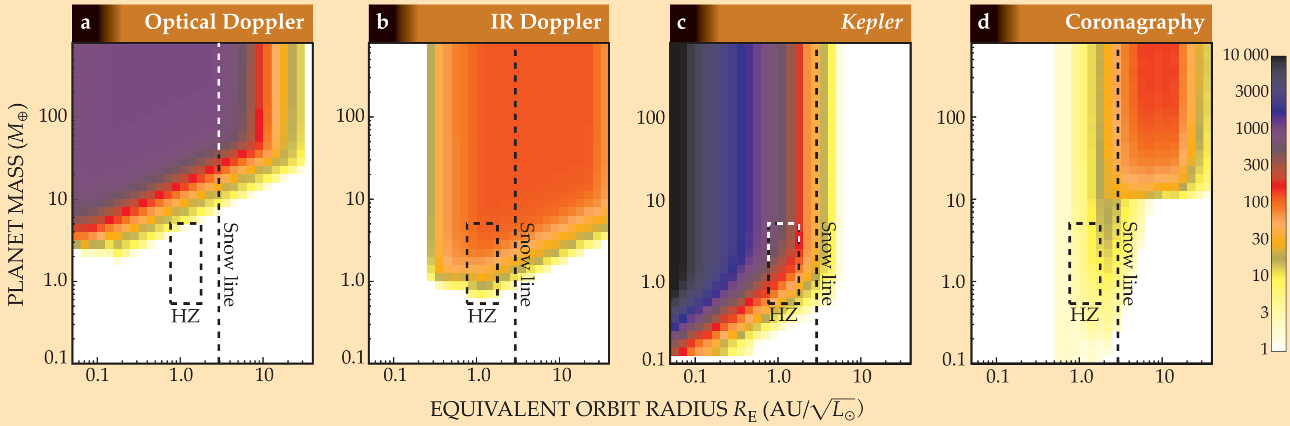

Figure 5. Depth-of-search plots compare the discovery potential of planet-search surveys of different sizes and techniques. Plotted are the distributions of a figure-of-merit function $S(M,R_E)$ over the masses M and thermal-equivalent orbital radii R_E (defined in the text) of exoplanets being looked for. At each point in the M,R_E plane, S is the sum, over all the survey's stars, of the probabilities of detecting such a planet if it were indeed orbiting that particular star. The dashed rectangle marks the habitable zone (HZ) of radii that allow liquid water and masses suitable for both substantial atmospheres and rocky surfaces. Beyond the marked snow line, icy material in the early stellar system was available for rapid formation of planetary cores. **(a)** A large-scale Doppler survey covering 1000 stars over 15 years at optical wavelengths. **(b)** A smaller Doppler survey covering 120 cool, low-mass stars over 5 years at IR wavelengths. **(c)** The recently launched *Kepler* mission searching for transiting exoplanets. *Kepler* can only detect a planet passing directly between it and the face of the host star. Therefore the detection probability drops from about 10% for orbits close to the star to much less than 0.1% for large orbits. *Kepler* will survey about 100 000 stars, so S drops from 10 000 to less than 100 with increasing orbital radius. **(d)** A proposed direct-imaging survey using an orbiting 2.5-m telescope operating with an advanced coronagraph and spectroscopic capability. The telescope's aperture would limit the mission's range to a few hundred nearby stars.

for characterizing that distant world (see PHYSICS TODAY, January 2009, page 11). In particular, direct imaging offers the possibility of determining the colors and spectra of planets far enough from their parent stars so that the star's glare can be suppressed by various means. Jupiter analogues would be relatively easy, but ultimately one hopes to image Earth analogues. Direct imaging may be the only means for establishing habitability or signs of life on any exoplanet. But the problems are formidable. As seen from outside our solar system, Jupiter's brightness at full phase is only a billionth that of the Sun, and Earth is an order of magnitude fainter still.

To combat stellar glare, two coronagraphic approaches have been proposed: An internal-occulter coronagraph blocks the starlight using optical elements within a telescope; an external-occulter coronagraph employs a separate, large starshade positioned in front of the telescope—usually tens of thousands of kilometers away. The chief advantage of internal coronagraphs is their packaging simplicity; all the hardware needed to detect an exoplanet is contained in a single spacecraft. The challenge of that approach remains achieving the requisite starlight suppression without losing the stability and light throughput necessary to detect an Earth-like planet.[13]

In the early 1960s Lyman Spitzer pioneered the study of external-occulter coronagraphs. Their appeal lies in their potential for circumventing many of the problems faced by internal coronagraphs. Instead, the offending starlight is blocked by a free-flying occulter located between 20 000 and 70 000 km from the telescope.[14] The precise distance involves a tradeoff between Fresnel and Fraunhofer diffraction.

Such a distant occulter would allow the use of a generic diffraction-limited visible-light telescope rather than one especially configured with an internal coronagraph. Early laboratory experiments have shown that this technique can suppress starlight by a factor of 10^7 in the quest for planet images. The main drawback lies in its operational complexity: Two widely separated space vehicles must perform properly in precise alignment.

No direct-detection technique has yet demonstrated end-to-end performance sufficient to detect Earth-like exoplanets, but progress is being made. Investment in several promising techniques should ensure that at least one practical approach will emerge in the next 5–10 years.

Detection of planets at mid-IR wavelengths is an appealing prospect. At 10 microns, Earth's thermal emission is "only" a million times fainter than the Sun's. But at such long wavelengths, coronagraphs would have to be huge and unwieldy. So interferometry is the favored approach in the mid-IR. An IR interferometer consists essentially of two telescopes joined on a common structure or mounted on separate spacecraft that maintain a controlled distance by precise formation flying. The offending starlight is suppressed by the introduction of a phase shift of the light entering one of the two telescopes to get destructive interference for light that arrives along their common axis. Off-axis light from a planet, traveling a longer optical path, would have a different phase shift and thus escape the interferometric suppression of the starlight.

The essence of the idea was introduced in 1978 by Ronald Bracewell at Stanford University.[15] But the sensitivity needed for finding small planets will also require the subtraction of instrumental and astronomic backgrounds by sophisticated beam-chopping methods that employ additional telescopes. That might require the development of an array of telescopes flying in formation. Various proposals for ambitious interferometric planet-finding missions have been put forward, most recently the *Darwin* mission proposed to the ESA.[16] That approach would probably be chosen first only if surveys of potential target stars revealed dust emission levels too high for coronagraphic missions to overcome.[17] It could however be that the dust levels are so high—an order of magnitude above our solar system's—that neither technique would work.

Comparing techniques

The capabilities of different planet-detection techniques vary enormously, both in the types of stars they favor and in the ranges of planet masses and orbits over which they are sensitive. Sensitivity is often plotted as contour lines in the space of planetary masses M and orbital radius R. But such presentations ignore many issues. For example, a Doppler survey could concentrate on Sun-like stars to look for giant planets in systems like our own or, alternatively, on low-mass stars where even an Earth-mass planet in the faint star's close-in habitable zone would yield a detectable Doppler signal. A transit search could monitor as many as 10^5 stars, but with a low probability of seeing any given planet in transit.

To directly compare such different missions, the Exoplanet Task Force has developed a standardized "depth of search" display. First, as in figure 1, R is replaced by the scaled equivalent radius

$$R_E \equiv R/\sqrt{L},$$

where L is the parent star's luminosity. Because the star's radiant intensity falls off with distance like $1/R^2$, planets with the same R_E will have similar temperatures irrespective of stellar type—other things being equal. In units of AU and solar luminosity $L_\odot$, as used in figure 5, the habitable zone (within which a planet could have stable liquid water at its surface) is centered at $R_E = 1$ and presumed to range from 0.75 to 1.8 for almost all stars.

Then, for each star in a survey, one calculates the probability that if the star indeed had a planet of given M and R, that planet would be detected. The calculation requires a few reasonable assumptions about planetary properties such as albedo and size. We define a depth-of-search function $S(M,R_E)$ as the sum of all those probabilities over all the stars in the survey.

Figure 5 compares $S(M,R_E)$ distributions for planet surveys of various kinds and sizes. At each point (M,R_E) in those search-depth plots, S is the number of stars around which that survey would detect such a planet if *every* star actually harbored one. The function provides a measure of the statistical robustness of each survey technique.

The gold standard is large-scale Doppler surveys, for which S exceeds 1000 over a broad range of planet masses and orbits (see figure 5a). Surveys with such reach can expect to find hundreds of planets and thus allow statistical studies of the properties of the planet population. By contrast, a survey with $S = 10$, even over a very broad range of masses and orbits, could expect few if any detections. But if one of those planets turns out to be an Earth twin that can be characterized spectroscopically, the scientific value would be enormous.

Figures 5a and 5b compare two different prospective Doppler surveys. The first is a 15-year survey of 1000 bright, mostly Sun-like stars. That large-scale survey should provide robust statistics on giant planets well into the orbital regime where Jupiter lives. The second search-depth plot describes a 5-year IR Doppler survey of only 120 low-mass stars, using many telescope observations of each star to reduce noise. Because the habitable zone of those cool, lightweight stars is close in and the Doppler oscillation amplitude grows with decreasing stellar mass, even a $1M_\oplus$ planet in the zone could produce a detectable signal.

Figure 5c shows the predicted sensitivity of the *Kepler* transit-search mission over six years. Although *Kepler* will survey 10^5 stars, the probability of a planet's orbit crossing the satellite's line of sight drops sharply with orbital radius. Still, *Kepler* has enough sensitivity in the habitable zone to provide a statistical measure of the frequency of Earth-like planets.

The last plot, figure 5d, shows the sensitivity of a prospective direct-imaging coronagraphic mission. The plot assumes a 2.5-m telescope operating at a wavelength of 800 nm with an advanced coronagraph capable of imaging a planet separated from its glaring star by as little as 0.8 μas. The telescope's modest aperture would limit the survey to a few hundred stars relatively nearby, and Earth-like planets could only be detected around the very closest of them. But the mission as envisioned will have the virtue of being able, by itself, to spectroscopically characterize any planet it finds.

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