A Gallery of Planet Hunters

-YUDHIJIT BHATTACHARJEE AND DANIEL CLERY

In 1992, astronomers announced that a whirling neutron star called a millisecond pulsar harbored the first known planets outside our solar system: extrasolar planets, or exoplanets. Two decades on, exoplanets are practically an astronomical commodity. Nearly 900 of them have been confirmed, and hundreds of fresh candidates are turning up every month. Some resemble the familiar orbs circling

our sun, but others are truly alien: hot Jupiters, mini-Neptunes, super-Earths.

To help readers navigate the bewildering variety of new worlds and their discoverers, *Science* presents this guide for the perplexed: an overview of planet-hunting techniques and representative efforts, followed by an informal glossary of popular exo-objects.

Radial Velocity

Radial velocity measurement is the mother of exoplanet search techniques. Michel Mayor and Didier Queloz of the Observa-

tory of Geneva in Switzerland used it in 1995 to make the first confirmed detection of an exoplanet around a sunlike star, and it's still going strong.

As a planet orbits a star, its gravity causes the star to move around their common center of gravity, usually inside the star. If we view such a system edge-on, the star would appear to be wobbling from side to side. Current telescopes can't detect such tiny movements, but they can spot a wobble back and forth along the line of sight because such changes in radial velocity raise and lower the frequency of the star's light.

To spot exoplanets this way, astronomers don't need a huge telescope or one in space—just an extremely sensitive spectrometer and lots of time. It can require between 500 and 1000 separate observations of a star to detect the signature of a planet circling around it. Today's best instruments can detect radial velocities down to about 1 meter/ second. Jupiter makes our sun move at 12 m/s, but small planets cause much smaller movements—Earth shifts the sun by less than 0.1 m/s.



Many groups around the world have hitched spectrometers to their telescopes and started looking for wobbling stars, but two groups have dominated the discovery of new exoplanets with several hundred detections each. The first is the Geneva Observatory team with an instrument called High Accuracy Radial velocity Planet Searcher (HARPS) fitted to the European Southern Observatory's (ESO's) 3.6-meter telescope at La Silla in Chile. The second team, led by Geoff Marcy of the University of California, Berkeley, uses the High Resolution Echelle Spectrometer (HIRES) on the Keck I telescope at Mauna Kea, Hawaii.

Since the Kepler space mission began detecting new candidate exoplanets by the thousands using the transit technique (see p. 567), radial velocity teams have changed focus from discovering new planets to confirming Kepler detections and measuring their mass. Kepler observations can measure a planet's size but not its mass, which is key to separating gas giants from rocky planets. Radial velocity fills that gap, and so the teams are trying to shift up a gear.



Because radial velocity measurement is so slow, both teams are aiming to develop new instruments and telescopes dedicated to planet searching. The HIRES team has built the Automated Planet Finder, a 2.4-meter telescope and spectrometer on Mount Hamilton near San Jose, California. Its spectrometer is about as sensitive as that of HIRES, and starting this month it will spend all night, every night looking for planets—taking 25 spectra per night.



Meanwhile, the HARPS team and collaborators have made another version of their spectrometer for the northern hemisphere. HARPS-N is fixed to Italy's 3.6-meter Galileo National Telescope in the Canary Islands, which can observe the same patch of sky that Kepler does. The researchers are also designing a next-generation spectrometer called ESPRESSO, which will operate from 2016 at ESO's Very Large Telescope at Cerro Paranal in Chile. VLT is an array of four 8.2-meter scopes; ESPRESSO will be portable enough to attach to whichever has available observing time. CREDITS (CLOCKWISE FROM TOP): (BANNER) ESO/T. PREIBISCH; © LAURIE HATCH/WWW.LAURIEHATCH.COM; TNG/A. HARUTYUNYAN; ESO/F. KAMPHUES

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Transits

The idea is simple enough: monitoring a star for the dips in its brightness caused by a planet passing in front of it. In practice, how-

ever, such transit-based detection is like trying to tell when a seagull flies across the beam from a lighthouse.

That's why it took astronomers years to convert the idea into a workable technique capable of finding not just gigantic planets, which block more than 1% of their star's light, but also planets the size of Earth. Their efforts have paid rich dividends, enabling the discovery of more than 231 exoplanets to date.



REDITS (CLOCKWISE FROM TOP RIGHT): NASA/KEPLER MISSION; SWISS SPACE

On a mountaintop in Arizona, eight remote-controlled robotic telescopes search the skies every night for transits around M dwarfs. The most common stars in our galaxy, M dwarfs are much smaller than the sun, so the dip in their brightness due to a transiting planet should be larger than the dimming of a sun-sized star. In 2009, MEarth discovered its first super-Earth, a planet orbiting a red dwarf 40 light-years from us.



The Transiting Exoplanet Survey Satellite (TESS)—recently chosen by NASA for possible launch in 2017—will aim to survey the brightest stars in the sun's neighborhood using an array of widefield cameras in search of exoplanets ranging from gas giants to extraterrestrial Earths in habitable zones. Some of those planets, researchers hope, will be candidates for follow-up studies of their atmospheres by the James Webb Space Telescope, scheduled for launch in 2018. Kepler Launched in 2009, NASA's Kepler spacecraft Ongoing has entered an extended phase, having completed its planned 3.5 years of observing. The mission has surveyed 150,000 stars and found more than 2740 planet candidates, 115 of which astronomers have confirmed to be planets by follow-up observations using ground-based telescopes. Several of the candidates are Earth-sized or smaller; in February, astronomers confirmed one of them to be a planet approximately the size of our moon. Data from Kepler are helping researchers get a better handle on how abundant different kinds of planets are.



If all goes as planned, by 2017 European astronomers will launch a spacecraft to look at transits of nearby bright stars already known to harbor planets. Characterizing Exoplanets Satellite (CHEOPS) chosen for development by the European Space Agency in 2012 is designed to reveal in detail the nature of those planets. Highprecision measurements by the satellite should help astronomers nail down planet sizes. Combined with radial velocity observations from the ground, which provide the mass of these planets, the observations will help figure out how dense they are.

Exoplanets

Microlensing

If you point a telescope at a star in the center of the galaxy and stare long enough, sooner or later a second star will pass in front of it. (Yes, it could take millions of years.) the foreground star can event enough gravity to bend the

Depending on its mass and position, the foreground star can exert enough gravity to bend the light from the background star, acting as a lens. Such "microlensing" makes the background star appear brighter than usual.

A planet orbiting the foreground star can make brightening or dimming contributions of its own. Such deviations from what would otherwise be a smooth microlensing event can be picked up by planet hunters to reveal the existence of the planet. With precise observations of this signal, astronomers can determine the mass of the planet and its distance from the parent star.

Using microlensing, astronomers can detect planets much less massive than Earth, which other methods would miss. The drawback is that it's a one-shot deal: Microlensing events, lasting days to weeks, are so rare that researchers are unlikely to get a second chance to study a particular foreground star. That's why ongoing microlensing-based searches involve networks of robotic tele-scopes that can watch big swaths of the sky to spot as many events as possible. The technique has yielded the discovery of 17 exoplanets to date.



In the mid-1990s, a group of Polish astronomers led the construction of a 1.3-meter telescope at the Las Campanas Observatory in Chile. The Optical Gravitational Lensing Experiment's main goal has been to search for dark matter using microlensing, but since the early 2000s, the telescope has also proved its utility as a planet-hunting tool. Its capabilities have greatly improved since first light. In 2009, the telescope was mounted with a new, 32-chip mosaic camera, a far cry from the single-chip instrument used in its early years.



A 1.8-meter telescope at Mount John University Observatory in New Zealand has been surveying the sky for microlensing events since 2006, driven by a collaboration among astronomers in Japan, New Zealand, and the United States. Microlensing Observations in Astrophysics (MOA) has the biggest field of view of any telescope involved in microlensing surveys: an area of 2.2 square degrees of sky. Observations using MOA have led to the discovery of rogue planets: planetary bodies that appear to be gravitationally unbound from any stars.

Astrometry

Like the radial velocity technique, astrometry seeks to detect the slight wobble in a star's position caused by the gravity of an orbiting planet. Astrometry does it by plotting the star's position in the sky with extreme accuracy, through many observations repeated over time. Astronomers have been claiming the detection of "unseen companions" to stars using astrometry since 1855, but none have stood up to scrutiny. To date, there have been no confirmed exoplanet detections using the technique.



Astronomers hope that things will change later this year when the European Space Agency launches Gaia, an orbiting observatory that will accurately map the positions and motions of a billion stars in our galaxy, 1% of its population. Gaia's goals include detecting tens of thousands of exoplanetary systems. Researchers hope that Gaia will tell them more about the distribution of exoplanets around the galaxy: Are there more near the center or in the spiral arms? Are planets more common in areas rich in heavy elements?

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Direct Imaging

The Holy Grail of exoplanet searching is direct imaging. If you can gather light from the planet itself, you can get a spectrum and find out the planet's temperature and what it's made of, compare its composition with those of its star and sister planets, and look for signs of life.

The problem is that a planet is very close to a star that is a million or more times brighter—a firefly in the glare of a searchlight. Spotting one is not impossible. A handful of planets have been observed by both ground-based telescopes and Hubble. These, however, have tended to be "low-hanging fruit": large planets with wide orbits around dim stars.

Direct imaging is all about contrast: picking out the faintest thing that can be discerned next to the star. Current systems can detect planets about a millionth as bright as their star. To do that, a telescope needs two things: a coronagraph and wavefront control. A coronagraph is simply an opaque patch that blocks the light of the star so that the dim planet can be seen. Starlight diffracted around its edge can still swamp the planet's light, so sophisticated optics are employed to ensure that this edge light is directed out of the way.

Wavefront control employs a range of techniques to improve the dynamic range of the image by correcting for optical faults in the telescope. In ground-based instruments, it is essential to include extreme adaptive optics: computercontrolled deformable mirrors that move in real time to correct for atmospheric distortion.

WFIRST Under Consideration



Atmospheric disturbance limits what ground-based telescopes can do, so to observe Earth-like planets will require instruments in space. Both NASA and the European Space Agency have designed dedicated planet-imaging spacecraft— Terrestrial Planet Finder and Darwin with mirrors several times the size of the Hubble Space Telescope's. But both projects have been shelved as too costly.

Hoping to get something more modest into orbit, exoplanet researchers have suggested adding a coronagraph to the proposed Wide-Field Infrared Survey Telescope (WFIRST), which was designed to look for exoplanets by gravitational microlensing (see p. 568) and to probe dark energy. WFIRST was supposed to have a 1.5-meter mirror, but that plan is being reconsidered since the U.S. National Reconnaissance Office gave NASA two 2.4-meter telescopes built for spy satellites (Science, 15 February, p. 748). NASA asked for proposals for using the two scopes; ideas include turning one into WFIRST and building a dedicated exoplanet imager. NASA will continue to study the proposals this year.



Several projects around the world are attempting to image exoplanets. Later this year, two purpose-built instruments will begin to bring direct imaging into the mainstream by improving contrast to about 1 in 10⁷. The Gemini Planet Imager is a secondgeneration coronagraph with adaptive optics that will be attached to the 8-meter Gemini South telescope at Cerro Pachón in Chile. SPHERE is a system being installed at the European Southern Observatory's Very Large Telescope (pictured) at Cerro Paranal in Chile that incorporates adaptive optics and three different coronagraphs. Both instruments will seek to image giant planets around nearby stars. They'll target young star systems because recently formed planets will still be hot and so will emit their own infrared light. Observed in the infrared, planets appear brighter and stars dimmer than at visible wavelengths.