Planets and Stars under the Magnifying Glass

Using the microlensing technique, astronomers discover an Earth-like planet outside our solar system.

LOOKING out to the vastness of the night sky, stargazers often ponder questions about the universe, many wondering if planets like ours can be found somewhere out there. But teasing out the details in astronomical data that point to a possible Earth-like planet is exceedingly difficult.

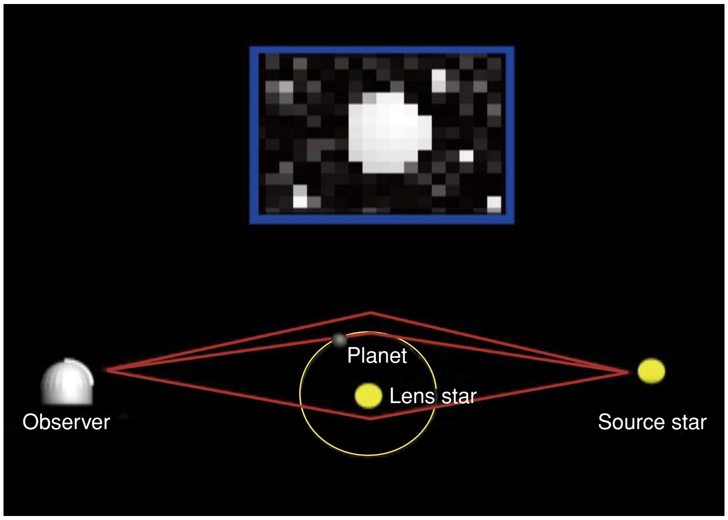
To find an extrasolar planet—a planet that circles a star other than the Sun—astrophysicists have in the past searched for Doppler shifts, changes in the wavelength emitted by an object because of its motion. When an astronomical object moves toward an observer on Earth, the light it emits becomes higher in frequency and shifts to the blue end of the spectrum. When the object moves away from the observer, its light becomes lower in frequency and shifts to the red end. By measuring these changes in wavelength, astrophysicists can precisely calculate how quickly objects are moving toward or away from Earth. When

This artist's rendition shows the Earth-like extrasolar planet discovered in 2005. (Reprinted courtesy of the European Southern Observatory.)

a giant planet orbits a star, the planet's gravitational pull on the star produces a small (meters-per-second) back-and-forth Doppler shift in the star's light.

Using the Doppler-shift technique, astrophysicists have identified 179 planets within the Milky Way Galaxy. However, most of these are giant gas planets, similar in size to Jupiter and Saturn, and they orbit parent stars that are much closer to them than the Sun is to Earth. Planets similar in size to Earth have also been found, but they, too, are so close to their suns that they would be much hotter than Earth and too hot for life to exist.

In 2005, an international collaboration of astronomers working with telescope networks throughout the Southern Hemisphere uncovered clues to a small, rocky or icy planet similar to Earth. The new planet, designated OGLE-2005-BLG-290-Lb, is the farthest planet from our solar system detected to date. The discovery was made by the Probing Lensing Anomalies Network (PLANET) using microlensing—a technique developed nearly two decades ago by Livermore astrophysicists as part of the Massively Compact Halo Object (MACHO) Project, which searched for evidence of dark matter.



Gravitational microlensing (top box) occurs when light from a source star is bent and focused by gravity as a second object (the lens star) passes between the source star and an observer on Earth. A planet rotating around the lens star will produce an additional deviation in the microlensing.

About the New Planet

According to Livermore astrophysicist Kem Cook, OGLE-2005-BLG-290-Lb is a low-mass planet. "It's about 5.5 times the mass of Earth," says Cook, who is a member of the PLANET collaboration. "The planet orbits a dim star about 390 million kilometers away from it, and one orbit takes about 10 years." OGLE-2005-BLG-290-Lb is thus more than twice as far from its parent star as Earth is from the Sun. If the planet were in our solar system, it would be located between Mars and Jupiter. "It is the smallest extrasolar planet we've found orbiting a normal star," Cook says, "and the most like Earth of any discovered so far."

OGLE-2005-BLG-290-Lb orbits a faint red dwarf that lies about 22,000 light years from Earth, close to the center of the Milky Way Galaxy, in the constellation Sagittarius. Red dwarf stars are relatively cool, stellarly speaking. Temperatures on the planet would thus be similar to those on Neptune or Pluto—about –220°C, too cold for liquid water or even liquid oxygen, which freezes at –219°C. "The planet must be made of rock or ice," says Cook. "Its mass is too small to have been formed of only gas, so we can discount that it's a gaseous planet."

This discovery joins a relatively short lineup of planets identified so far. "When we consider the number of stars out there," Cook says, "the fact that we stumbled on one small planet means that thousands more are waiting to be found."

Detection through Microlensing

The concept of microlensing took root in the fertile mind of none other than Albert Einstein. In 1936, Einstein published a paper in *Science* on a theory involving what might occur to the observed light from a star (star A) if another star (star B) were directly in the line of sight between an observer on Earth and star A. Einstein showed that when the two stars are exactly aligned with the observer, a ringlike image forms. If star B moves a small distance from the line of sight, the observer will see two images of star A.

Because of the geometry of microlensing, the observer would not be able to resolve either the ringlike image or the double images. Instead, star A would appear to brighten because the total luminosity of the two images or ring would be greater than the luminosity of star A by itself. This brightening is caused by the microlensing effect in which star B's gravity acts as a gravitational lens, bending the light from star A around star B and focusing it toward the observer.

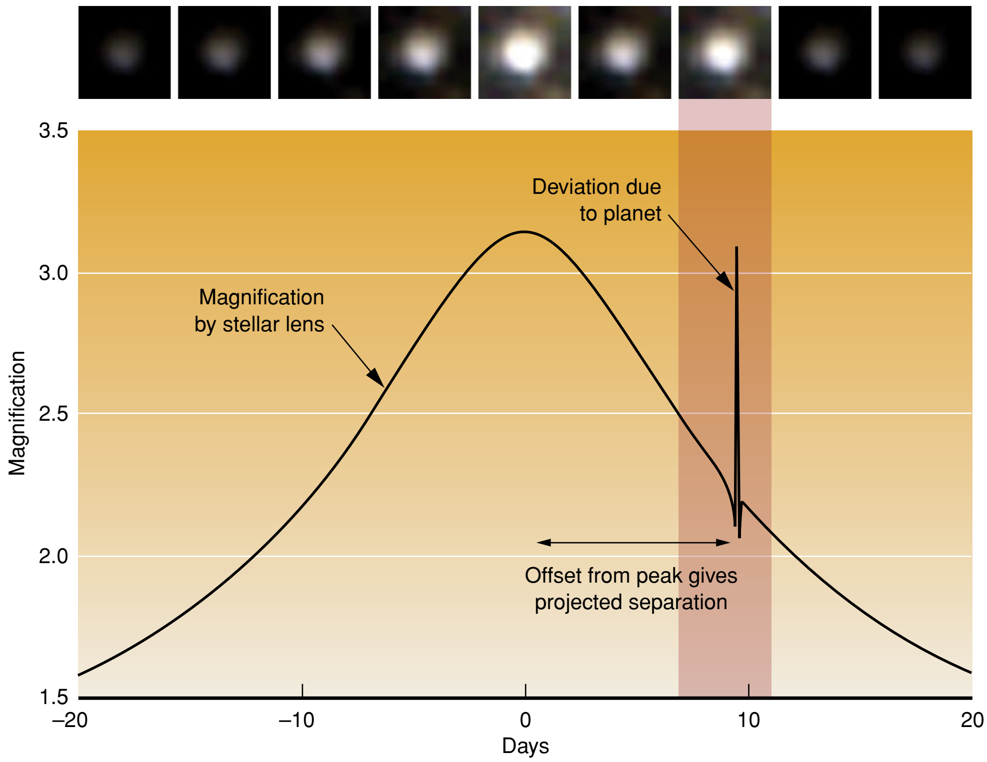
Scientists can distinguish microlensing from other phenomena that lead to brightening, such as a flare or a variable star. A microlensing light curve is well defined, and the lensing effect is wavelength independent. Another distinction is that the microlensing event for a star does not repeat. If a second brightening appears before or after the peak in amplification, the so-called bump is probably caused by a variable star. A planet orbiting the closer (lensing) star will also modify the lensing effect, adding a spike of brightness to the otherwise smooth magnification curve.

MACHO Started It All

Although Einstein proposed the possibility of microlensing, astronomers did not have the technology to observe the effect for more than 50 years. According to Cook, such observations became feasible in the late 1980s when new imaging techniques were developed for the Strategic Defense Initiative (SDI). President Ronald Reagan established SDI in 1983 to develop ground- and space-based systems to protect the U.S. from attack by strategic nuclear ballistic missiles. Scientists working on SDI were asked to find methods to observe a large area of sky in search of incoming objects. "These systems required wide-field-of-view cameras that could record a slice of the sky over time and imaging software to interpret the data," says Cook. "Once these technologies were available, astronomers began to apply them to their own field."

In 1987, Livermore astrophysicist Charles Alcock, who is now the director of the Harvard-Smithsonian Center for Astrophysics, wanted to apply this imaging technology to search for comets at the outer edge of the solar system. He had read a 1986 scientific paper written by Bohdan Paczynski, an astrophysicist then at Princeton University, proposing the use of gravitational microlensing to identify MACHOs. Alcock realized a new technology, the large-format charge-coupled device (CCD), was sensitive enough to detect the tiny increase in brightness that occurs when a massive object passes in front of and microlenses a star.

Alcock, Cook, and Livermore physicists Tim Axelrod and Hye-Sook Park formed a team to study this application. The scientists did not work with actual SDI equipment. Rather, they considered possible designs for a system that used SDI technology to produce many thousands of digital images from the night sky, reduce the data, and interpret the results. In 1989, Livermore's Laboratory Directed Research and Development Program funded the MACHO Project, and design work began in earnest. The MACHO team created an optical imaging system with an exceptionally wide field of view and a large detector. The area imaged by the system was about 10 times larger than the area covered by telescopes in operation at that time.



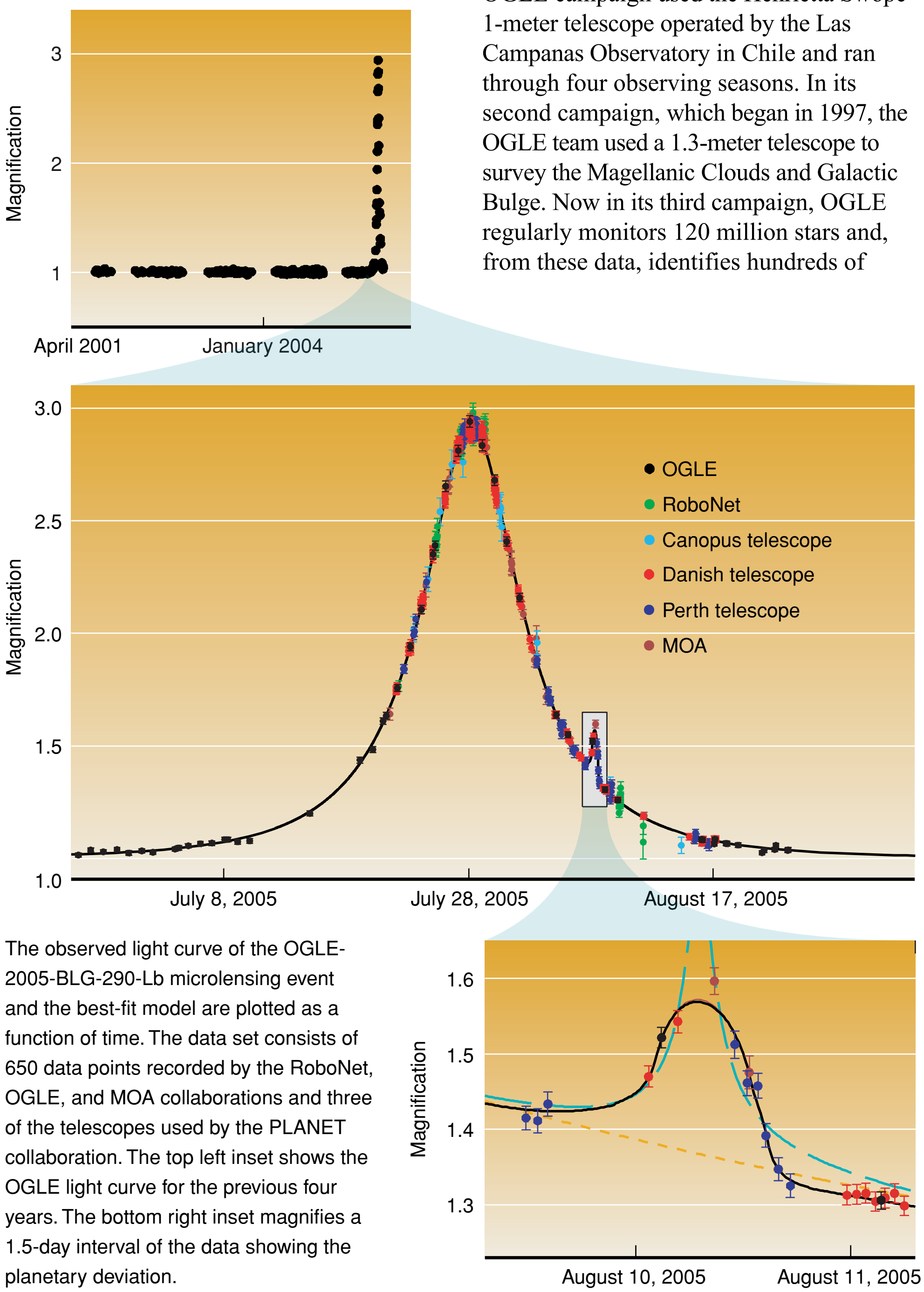
Data from a microlensing event indicate a smooth, symmetric magnification curve as a lens star moves between a source star and an observatory on Earth. The short spike in magnification is caused by a planet orbiting the lens star.

As work progressed, astronomers outside the Laboratory began to take interest in the possibilities offered by the new system. Several organizations, including the University of California's Center for Particle Astrophysics, began a search to find a location suitable for building a telescope and devoting research efforts to the MACHO Project. The potential site had to offer a clear view of the Large Magellanic Cloud (LMC), a neighboring galaxy that is visible from the Southern Hemisphere. The Australian National University agreed to dedicate its 1.27-meter reflecting telescope at the Mount Stromlo and Siding Spring Observatories to the MACHO Project for four years. The first optical imaging system to fully exploit the new generation of large-format CCD images was installed on this telescope.

The MACHO Project has evolved into a second-generation sky survey called SuperMACHO, which uses the National Science Foundation's Victor M. Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory in Chile. The SuperMACHO team, which includes Cook and Livermore scientists Sergei Nikolaev and Mark Huber, is searching for signs of microlensing by MACHOs between stars in the LMC and Earth. The team's goal is to determine what causes a large number of reported microlensing events toward the LMC.

The MACHO Project also served as a prototype for other collaborative sky surveys, including the Optical Gravitational Lensing

Experiment (OGLE) and Microlensing Observations in Astrophysics (MOA). The OGLE survey, a Polish collaboration that began in 1992, focused on microlensing toward the bulge of the galaxy. The first OGLE campaign used the Henrietta Swope 1-meter telescope operated by the Las Campanas Observatory in Chile and ran through four observing seasons. In its second campaign, which began in 1997, the OGLE team used a 1.3-meter telescope to survey the Magellanic Clouds and Galactic Bulge. Now in its third campaign, OGLE regularly monitors 120 million stars and, from these data, identifies hundreds of microlensing events per observing season. In the 2005 season, the team observed about 600 microlensing candidates.



The observed light curve of the OGLE-2005-BLG-290-Lb microlensing event and the best-fit model are plotted as a function of time. The data set consists of 650 data points recorded by the RoboNet, OGLE, and MOA collaborations and three of the telescopes used by the PLANET collaboration. The top left inset shows the OGLE light curve for the previous four years. The bottom right inset magnifies a 1.5-day interval of the data showing the planetary deviation.

Telescopes on the Prowl

The OGLE team's success in identifying candidate events rests in part on its automatic early-warning system, which analyzes image data in real time. The warning system's software measures the light intensity of all the stars in each image. If a star's intensity differs in three consecutive images, the system flags that star for further analysis. Astronomers then visually inspect the recorded light curves of flagged stars. They also check each star's position on recent CCD frames to ensure that changes in brightness are not caused by bad pixels or bright neighboring stars.

If a star passes the checks, the survey team announces it as a microlensing candidate to the observation networks. Alerts are posted on survey project Web sites, and e-mail announcements are sent to interested parties. Networks of telescopes are then programmed to provide round-the-clock coverage, and like runners handing off a baton in a relay race, telescope stations pass monitoring activities from one telescope to the next as an event moves through its cycle.

Microlensing events typically last for 15 to 90 days. Survey teams such as OGLE produce light curves that are sampled about once per day. The brightening caused by an intervening star usually lasts about a month—long enough to be visible in data recorded on this time scale. More precise resolution is required to capture the faint, elusive signal that heralds a planet. The planetary brightening may last a few days for a giant planet or only a few hours for one the size of Earth. Detecting a planet thus requires quick, highly precise data collection 24 hours a day. Sampling on these shorter time scales must be done separately. Scientists on the PLANET team and their partners at the United Kingdom's Robotic Telescope Network (RoboNet) train

PLANET Formation

Astronomy centers began to establish microlensing collaborations in the early 1990s to build on the success of surveys conducted by the Massively Compact Halo Object (MACHO) Project. Collaborations such as the Optical Gravitational Lensing Experiment (OGLE) provide networks of telescopes to track microlensing events on long time scales. These microlensing survey teams record data at intervals of 1 to 5 days. Sampling at shorter time scales, for example, once a day or every hour, is done separately by collaborations such as the Probing Lensing Anomalies Network (PLANET).

Established in 1995, PLANET is an international collaboration that provides astronomers with access to Dutch, South African, and Australian telescopes. PLANET's primary goal is to study the anomalies found in the light curves of microlensing events. Not all of these indicate the presence of a planet—many astronomical events can cause deviations in microlensing data. For example, the source star may be so large that the lens star magnifies only part of it at one time, or light from other stars may blend with amplified light along an event's line of sight. Another common anomaly occurs when two lenses are so close to each other that their magnification patterns overlap, an effect called binary lensing.

Detailed data recorded over short sampling times provide the clues needed to differentiate these anomalies. Therefore, when a microlensing candidate is announced, one or another of PLANET's telescopes is focused on the target area 24 hours a day. The PLANET network of 1-meter-class telescopes consists of the European Southern Observatory's 1.54-meter Danish telescope at La Silla in Chile, the Mount Canopus Observatory's 1.0-meter telescope in Australia, the Perth Observatory's 0.6-meter telescope in western Australia, the Boyden Observatory's 1.5-meter telescope in South Africa, and the South African Astronomical Observatory's 1.0-meter telescope. In 2005, PLANET joined forces with the Robotic Telescope Network (RoboNet), which is operated by the United Kingdom. RoboNet has 2-meter fully robotic telescopes, one in Spain and the other in Hawaii.

The MACHO Project completed its survey in 2000. OGLE continues to find 500 to 600 microlensing events annually and sends alerts to other telescope networks, such as PLANET. "The Polish system is positively spewing out microlensing events," says Livermore astrophysicist Kem Cook, who is a member of the PLANET collaboration. "MACHO, even at its peak, recorded about 100 events a year." The large number of microlensing alerts keeps PLANET telescopes busy from May through September, when the Galactic Bulge is visible in the Southern Hemisphere.

The PLANET/RoboNet collaboration uses telescopes throughout the Southern Hemisphere, including the 1.5-meter telescope at the Boyden Observatory in South Africa. (Reprinted courtesy of the Boyden Observatory.)

their telescopes on identified sections of the sky and record data on the finer time scale.

Confirming the discovery of OGLE-2005-BLG-290-Lb involved four survey teams: PLANET/RoboNet, OGLE, MOA, and an informal consortium called MicroFUN (the Microlensing Follow-up Network). Scientists working on the OGLE collaboration first detected the home star of the planet on July 11, 2005. Once the microlensing event was announced, the PLANET/RoboNet collaboration, which included Livermore scientists, used a network of telescopes in the Southern Hemisphere to survey the targeted section of the Galactic Bulge in the Milky Way. (See the box on p. 15.) A tiny change in the microlensing light curve, signaling a possible planet, was observed on August 10, 2005, from PLANET's Chilean telescope in La Silla and was noted in light curves recorded by the Perth Observatory in Australia. The additional brightening was about 15 percent of the total light recorded and lasted for only 12 hours. The MOA survey team later identified the microlensing event on its images and confirmed the deviation. The planet's discovery was announced in a letter published in the January 26, 2006, issue of *Nature*. Altogether, the six-month effort involved 73 collaborators affiliated with 32 institutions in 12 countries.

More Planets in the Offing?

The small, frozen planet has planetary scientists taking note. A popular model of planetary formation suggests that red dwarf stars should be likely suns for Earth- to Neptune-mass planets with orbits up to 10 times greater than Earth's orbit of the Sun. The discovery of OGLE-2005-BLG-290-Lb supports this theory. "It's not an exaggeration to say that the discovery opens a new chapter in the search for planets that could support life," says Cook.

The collaboration continues, with the observing networks on call to monitor microlensing alerts for evidence of other planets. In the future, astrophysicists hope a microlensing detection system can be launched in space. "That would be the ideal situation," Cook says. "With a system in space, we could avoid the problems of weather and atmospheric distortion. So perhaps one day, we'll be able to move the search for planets away from Earth."

—Ann Parker

Key Words: extrasolar planets, gravitational microlensing, Massively Compact Halo Object (MACHO) Project, Microlensing Observations in Astrophysics (MOA), OGLE-2005-BLG-290-Lb, Optical Gravitational Lensing Experiment (OGLE), Probing Lensing Anomalies Network (PLANET), Robotic Telescope Network (RoboNet).

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