Extending the Search for

A new imager will allow astrophysicists to study the atmospheres of distant planets.

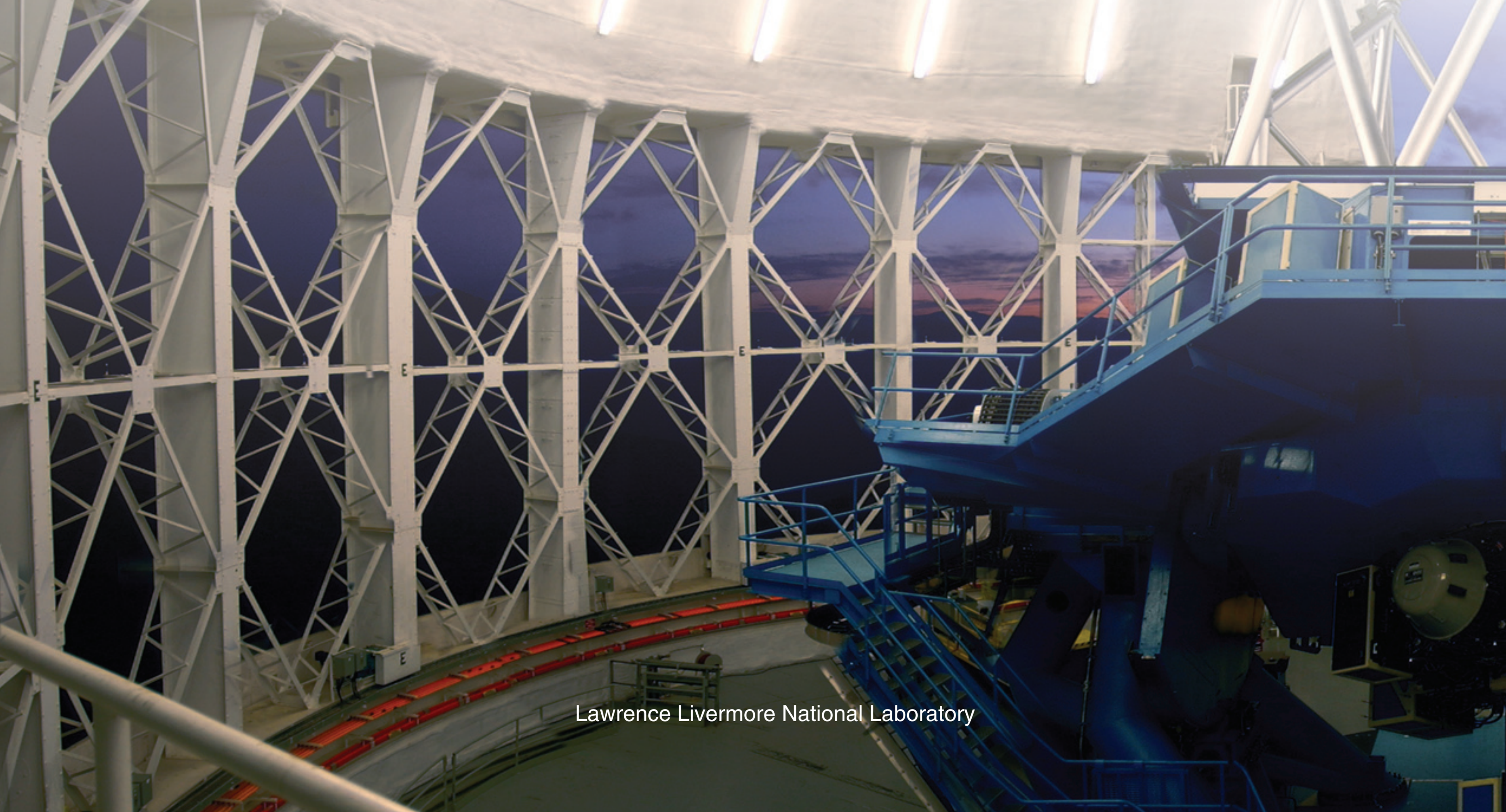
THE discovery of other solar systems beyond ours has been the stuff of science fiction for decades. Great excitement greeted the positive identification of the first planet outside our solar system in 1995. Since then, scientists have identified approximately 250 extrasolar planets (exoplanets), but they have had no way to study the majority of these planets or their atmospheres.

That will change when the Gemini Planet Imager (GPI) comes online at the Gemini South telescope in Chile in 2010. The imager's primary goal will be to detect more planets outside our solar system, providing important new data about how planets form and solar systems evolve. The most intriguing component on the imager is a spectrograph, which will measure the infrared light emitted by a planet's atmosphere. With it, GPI (pronounced gee-pie) will identify the atmosphere's chemical composition. Scientists can use the atmospheric data to make inferences about a planet's temperature, pressure, and gravity.

Lawrence Livermore scientists are part of an international collaboration developing GPI. Livermore astrophysicist Bruce Macintosh leads the design team, and engineer Dave Palmer is project manager. Macintosh notes, "For the first time, we will be able to study the atmospheres of planets in other solar systems."

The Detection Challenge

GPI's extreme adaptive optics correct for the distortions caused by our atmosphere, allowing researchers to directly observe planets that are not now visible from Earth or from the orbiting Hubble Space Telescope. Most exoplanets discovered thus far were identified not by direct observation but rather by noticing a wobble in a star's motion. The wobble



Extrasolar Planets

indicates a large object is nearby, and its gravity is affecting the star's motion.

This indirect detection process, called the radial velocity method, can probe objects up to 5 astronomical units (AU) from their parent stars, or 5 times the distance from Earth to the Sun. To determine whether an object is a planet, scientists must observe it completing an orbit around its parent star. But the farther a planet is from its star, the longer its orbit, and high-accuracy radial velocity measurements have been available for only 11 years. Scientists would need to record data for another year to find a perfect twin to the giant Jupiter, which takes 12 years to circle the Sun. Identifying a planet like Saturn, with an orbit of more than 30 years, would take decades.

Another method of detecting a planet uses direct observation of a star's light. When a planet orbits a star, the star's light appears to dim at regular intervals as the planet moves between its parent star and Earth. However, because of the time involved, observing such transits is effective only when planets are closer to their stars than Mercury is to the Sun.

Yet another detection technique is to observe the microlensing effect, in which a star aligned between Earth and a second star causes light from the second, more distant star to brighten visibly. A planet orbiting the closer star will modify the lensing effect, adding a spike of brightness to the otherwise smooth magnification curve. (See *S&TR*, July/August 2006, pp. 11–16.)

These detection methods typically reveal young, hot, giant planets that are close to their stars. Some of the planets detected to date are more massive than Jupiter, and their orbits may last only a few days, much shorter than the orbit of any planet in our solar system. An Earth-like planet is too small to observe with current technology.

Planet discoveries by direct observation are limited because light from a hot, giant exoplanet and that from the star it orbits blur in the sky. Distinguishing the planet's light from the much brighter star is virtually impossible with today's instruments. In addition, as stars and planets age, their heat dissipates, dimming the light they emit. For example, Jupiter is a billion times fainter than the Sun and would be challenging to detect in another solar system even with a 30-meter telescope.

A young planet (about 100 million years old) with the mass of Jupiter would retain more heat from its initial formation and thus would appear much brighter than Jupiter. But this planet would still be a million times dimmer than its parent star.

"Trying to observe exoplanets is like trying to find a firefly next to a searchlight," says Macintosh. "GPI provides an efficient way to get rid of the searchlight, to the

The Gemini South telescope sits on Cerro Pachon in Chile. (Courtesy of Gemini Observatory and the Association of Universities for Research in Astronomy.)

extent possible, and capture high-contrast images of planets.” (See the box on p. 8.) With GPI, astronomers can detect objects more than 10 million times fainter than the parent stars and find planets in more distant orbits.

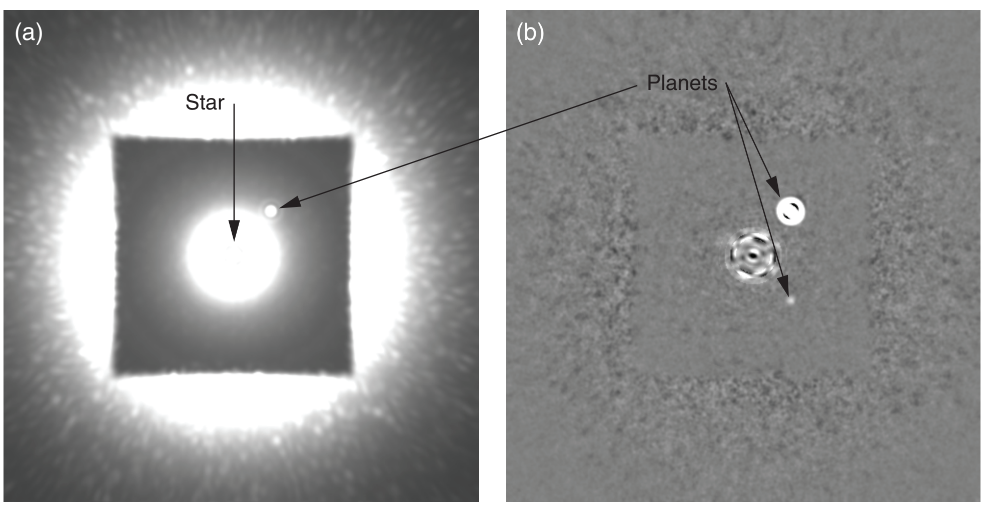
Why Find More Planets?

Data collected from ground- and space-based telescopes indicate that direct imaging will yield hundreds of planets, many of them beyond 5 AU. The real value of identifying these distant planets is finding clues about how solar systems evolve and how planets migrate into their orbits. Until recently, scientists used observations of our solar system to make assumptions about the evolution of other systems. However, data on systems beyond ours are showing important differences. While our planets revolve in relatively circular orbits around the Sun, many exoplanets have highly elliptical orbits. In addition, dozens of other solar systems have very large Jupiter-like planets close to their suns.

Radial velocity techniques work poorly on stars younger than a few hundred million years old. The intensely bright portion of a star’s light is hot and roiling, producing spurious measurements as sunspots rotate around the star. “These adolescent stars will be GPI’s prime hunting ground,” says Macintosh, “allowing us to study the evolution of solar systems over time.”

Planets under Construction

Solar systems are thought to start as disks of gas and dust rotating around a young star. Dust accounts for about 1 percent of the disk’s initial mass, while the remainder is primarily hydrogen and helium. Dust grains bump into one another and stick together, gradually accreting into larger particles. As particle growth continues, larger objects called planetesimals form and eventually grow into protoplanetary cores. Researchers had theorized that the small, rocky, terrestrial planets close to the Sun formed from such cores after several million years.



(a) In a simulated image of a 100-million-year-old star, the Gemini Planet Imager removes most of the scattered starlight over a square “dark-hole” region to reveal a planet. (b) Postprocessing the image using multiple wavelengths eliminates the remaining scattered starlight, revealing a second Jupiter-size planet.

According to this theory, called core accretion, the gas giants Saturn and Jupiter formed farther from the Sun where the planet-building material contained ices. Their cores of rock and ice collected large amounts of the disk’s gases, forming their thick atmospheres. Uranus and Neptune captured less of the gaseous material and are thus largely composed of ice.

The discovery of exoplanets much more massive than Jupiter and very close to their stars punched holes in the core accretion model. Those gigantic gas planets would take up to 100 million years to develop by core accretion, and protoplanetary gas disks are known to dissipate within 10 million years. In addition, not enough mass is close to the star for core accretion to generate such large planets.

An alternative proposal is that gas giants form not only by core accretion but also by gravitational disk instabilities. As the young disk of gas and dust orbits its star, clumps of gas can form quickly in unstable areas of the disk to become massive, gassy protoplanets. The astrophysics community is uncertain, however, whether these instabilities can arise in the inner regions of protoplanetary disks, where many giant exoplanets are found today.

Gravitational interaction between nascent planets and the gaseous disk may change a planet’s orbit. Protoplanet interactions are effectively chaotic, shoving material into new orbits, either toward a star or away from it. With this migration process, a rapidly orbiting planet could form far from its star and move inward. In our solar system, Jupiter may have migrated inward to its present location, while Neptune may have moved outward.

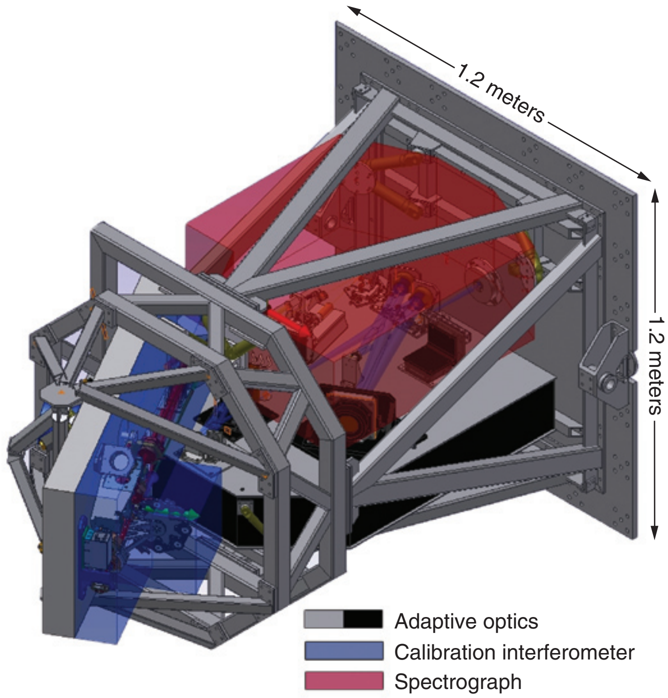
“The number of exoplanets beyond 5 AU holds clues to their formation processes and migration mechanisms,” says Macintosh. If Jupiter-like planets form by gravitational disk instabilities as well as core accretion, then the outer regions of solar systems may have many planets with Jovian and super-Jovian masses and, thus, will be similar to our solar system. If migration processes dominate, large planets will cluster closer to their stars, as many of the identified exoplanets do. "It is entirely possible that our solar system is an anomaly," says Macintosh.

Dust to Dust

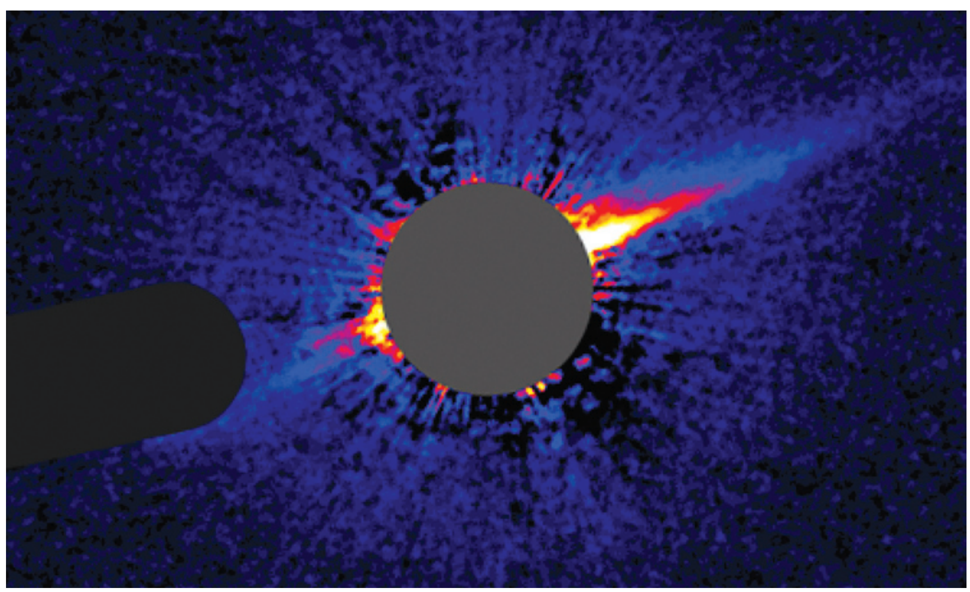
Gas disks dissipate as the primordial dust grains blow away or spiral into the star. Any remaining solids, such as cometary and asteroidal planetesimals, continue to orbit the star, and their collisions replenish a disk of dusty debris similar to the Kuiper Belt at the outer edge of our solar system. The Kuiper Belt, which extends from the orbit of Neptune outward, is composed of icy dust, comets, and other objects, including the dwarf planet Pluto.

Dusty debris disks, cousins to our Kuiper Belt, surround at least 100 stars. However, researchers have studied only about 20 in detail because observing dust so close to a bright star is difficult. Most of these disks must be viewed along their edges, an orientation that eases detection. Michael Fitzgerald, a postdoctoral researcher at Livermore, has studied debris disks for several years and looks forward to the vistas that GPI will open.

"With GPI, we will be able to identify not only the edge-on disks but also those viewed toward their faces," says Fitzgerald. "Our instruments are too weak now to separate light from a star and that from a debris disk observed face on." Until GPI is available, Fitzgerald and his colleagues use the best optics they can find—the telescopes at the W. M. Keck Observatory in Hawaii and data from the Hubble Space Telescope.



The components of the Gemini Planet Imager will be mounted on the Gemini South telescope's instrument support structure. Livermore is developing the adaptive optics system, the Jet Propulsion Laboratory is building the calibration interferometer, and the University of California at Los Angeles is building the spectrograph. The imager will be in an enclosure with electronics mounted on the sides. (Rendering by Darren Erickson, Herzberg Institute of Astrophysics.)



The extremely lopsided disk of debris around star HD 15115 has a needlelike shape (blue) in this image from the Hubble Space Telescope. A star about 10 light years away may be responsible for the formation. The Gemini Planet Imager will greatly improve information about dusty debris disks around stars, leading to insight into how planets and solar systems form. (Courtesy of the National Aeronautics and Space Administration, European Space Agency, and Paul Kalas of the University of California at Berkeley.)

Inside the Gemini Planet Imager

In a package measuring about 1 by 1 by 2 meters, the Gemini Planet Imager (GPI, pronounced gee-pie) will incorporate the world's most advanced astronomical optics systems to find and study distant planets. GPI will be installed at the Gemini South telescope at the Gemini Observatory in the high-altitude desert of Chile. GPI's adaptive optics system will correct for atmospheric turbulence. A coronagraph will reduce diffraction patterns, and an interferometer will measure instrument aberrations that cause speckles in images. Perhaps the most intriguing device in GPI is a spectrograph to distinguish planets from any remaining speckles and examine planetary atmospheres.

Since time immemorial, stargazers have had to contend with the distortions caused by Earth's atmosphere. Starlight passes through temperature layers and winds in the atmosphere that cause the star to appear to "twinkle." The planets in our solar system do not twinkle because they are much closer to Earth than the stars, comparatively reducing the effects of atmospheric distortion.

Adaptive optics "straightens" the wavefronts of light, improving the image resolution and contrast. A wavefront sensor samples the light collected by the telescope's primary mirror and sends the data to a computer that controls a deformable mirror, a mirror whose surface shape can be changed. Tiny actuators move the mirror faces hundreds of times per second to compensate for atmospheric conditions. Deformable mirrors have improved astronomical imaging at land-based telescopes by a factor of 10. Adaptive optics systems work best with longer wavelength light—the infrared and near-infrared regions of the radiation spectrum rather than the visible.

GPI will take adaptive optics a large step toward even greater contrast and resolution. Its deformable mirror will have 1,600 active actuators. A conventional deformable mirror would have to be almost 40 centimeters across to hold that many actuators, far too large for use on the Gemini South telescope. Instead, GPI's primary deformable mirror will be a silicon microelectromechanical system (MEMS) device, lithographically patterned and etched like a microchip. Versions with 1,024 actuators have been extensively tested using the extreme adaptive optics system at the University of California (UC) at Santa Cruz and are now available. The larger version for GPI is under development.

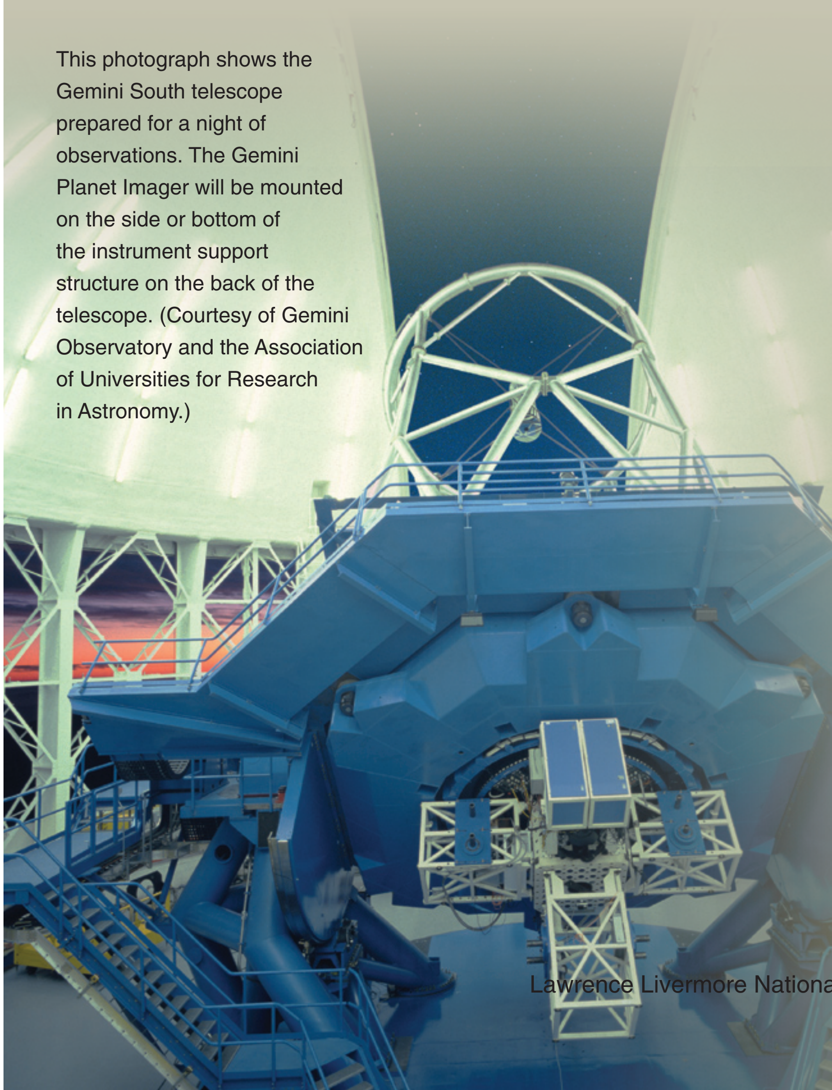
One limitation of current MEMS technology is that its range of motion is just 4 micrometers, not enough to fully correct atmospheric distortions on an average night. GPI will include a second conventional deformable mirror synchronized with the MEMS mirror. This combination is analogous to the woofer–tweeter arrangement on a home sound system, but instead of providing the full range of sound, GPI gathers the full range of light.

A coronagraph, originally developed for blocking light from the Sun to study the corona, will be an important component. GPI's coronagraph will incorporate an apodization device that changes the input intensity profile and thus reduces diffraction edge effects. In addition, an infrared interferometer will constantly measure the visible-light wavefront with nanometer accuracy and remove small errors that produce speckle patterns.

All of these tools correct incoming light to make visible new stars, extrasolar planets, protoplanets, stellar dust, and other celestial objects. A near-infrared integral field spectrograph will use the enhanced data on incoming light to simultaneously produce a spectrum for every pixel in GPI's field of view, creating three-dimensional cubes of data. Researchers expect spectrographic results to show that methane and ammonia dominate planetary atmospheres. The spectrograph will also characterize planetary temperatures and surface gravities, and its dual-channel polarimetry mode will facilitate the study of circumstellar debris disks.

The GPI design collaboration includes scientists from Lawrence Livermore, University of Montreal, American Museum of Natural History, Herzberg Institute of Astrophysics, UC Santa Cruz Center for Adaptive Optics, UC Berkeley and Los Angeles, and Jet Propulsion Laboratory. Livermore is designing the optical layout and the real-time adaptive optics system. The project began in June 2006 and is scheduled for completion in late 2010.

GPI has a broad range of science missions. Scientists will use its high-contrast imaging capability to map bright objects such as moons and planetary atmospheres in our solar system, binary stars that cannot now be identified, and brown dwarf and white dwarf companions. "Because ultrahigh-contrast imaging has never been available for such explorations, we expect many discoveries," says Livermore astrophysicist Bruce Macintosh. "But the most exciting applications for GPI will be to find more extrasolar planets and learn about their atmospheres."



This photograph shows the Gemini South telescope prepared for a night of observations. The Gemini Planet Imager will be mounted on the side or bottom of the instrument support structure on the back of the telescope. (Courtesy of Gemini Observatory and the Association of Universities for Research in Astronomy.)

Debris disks are old and therefore cold, so detecting their thermal emission is a challenge. They can, however, be identified by imaging the light scattered by the dust. Lumps and wiggles in the processed images indicate dust linked to a planet's gravitational pull in what are called resonances. As a planet migrates toward or away from its star, material can become caught in these resonances. For example, Pluto and other objects in the Kuiper Belt appear to be caught in Neptune's resonances. Such dust perturbations arising from planets offer important clues about the evolution of planetary systems.

Fitzgerald was part of a team that identified a highly unusual debris disk around a star known as HD 15115. Images taken with the Hubble and Keck telescopes show a needlelike shape, which may result from the gravity of another star about 10 light years away. The needle's blue color indicates the presence of small, freshly produced grains.

"Observing debris disks nearly face on will make resonances more easily visible," says Fitzgerald. "Spectral data from GPI will tell us about the dust's composition, and GPI's high-contrast images will allow us to disentangle grain sizes, properties, and distributions in the disk. As we learn more about the distribution of dust grain sizes, we can study the dynamics of the disk."

The polarimetry feature in GPI will produce entirely new measurements of debris disks. "What we want to achieve is a census of planetary system structures," says Fitzgerald. "By examining the connection between the distributions of planets and primitive bodies that produce the debris disks, we can gain insight into the relative importance of migration processes that affect how planetary systems form and evolve."

Best Yet Direct Image

Another researcher eager for GPI to come online is astrophysicist Christian Marois. Marois recently completed a postdoctoral fellowship at Livermore and is now at the Herzberg Institute of Astrophysics in Canada. As a graduate student at the University of Montreal, he developed a tool called angular differential imaging (ADI) for directly observing distant planets. ADI is currently the most efficient way to look for planets and can also be used to image debris disks.

ADI was a critical component of the Gemini Deep Planet Survey, which used the Gemini North telescope on Mauna Kea in Hawaii. Simulations indicated that ADI at Gemini could detect planets two times the mass of Jupiter located 40 to 200 AU from their stars. In fact, for the 85 young stars studied in the survey, ADI detected 300 candidate planets. "Unfortunately," says Marois, "later investigation revealed that all the candidates are background stars instead of planets."

ADI collects a long sequence of exposures for one star with an imaging camera whose field of view rotates with the telescope tracking the target star. In this configuration, the optics of the telescope and the imaging camera stay aligned. Speckles arising from optical and atmospheric aberrations look like planets in the images, but their positions do not rotate with the changing field of view. To improve

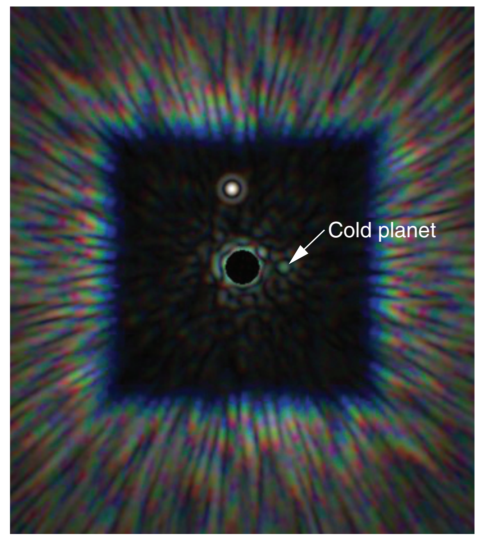
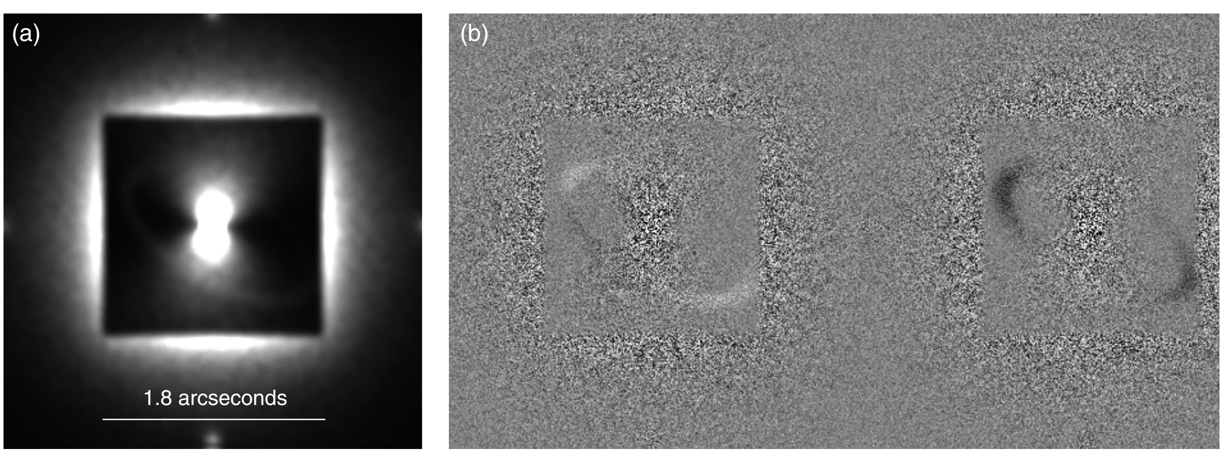


Image-processing techniques developed for the Gemini Planet Imager will suppress bright starlight and atmospheric aberrations to make faint planets visible. As this image from a simulation shows, researchers will be able to detect a hot, massive planet or background object (white) and a faint, cold planet (green).

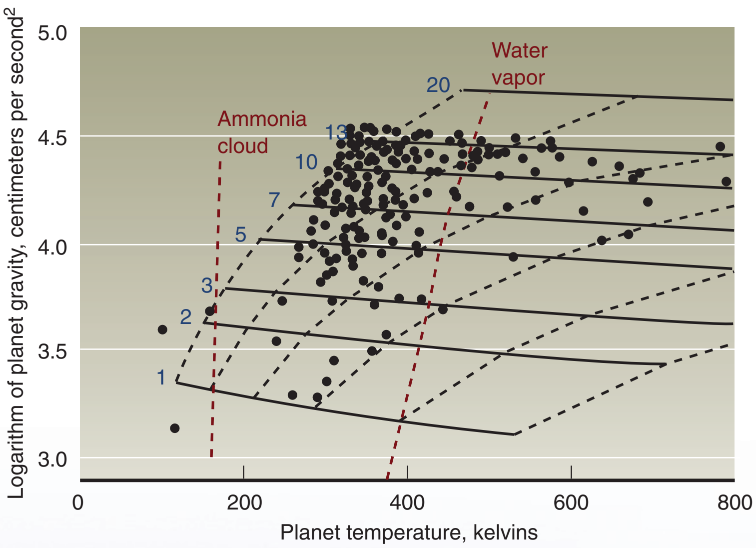


A device on the Gemini Planet Imager will measure the polarization of light to help astrophysicists examine dusty debris disks around stars. This simulation of a debris ring demonstrates the level of sensitivity that can be achieved (a) in conventional imaging and (b) by analyzing the polarization of light.

the images, Marois developed a subtraction process to suppress the speckle "noise." The collection of residual images is then rotated to align the field, further reducing the noise. With current instrumentation, this ADI method effectively identifies planets with 40- to 200-AU orbits, but it is limited for planets with orbits inside 40 AU.

"Our next step," says Marois, "is to improve the field-of-view rotation with a multiple-wavelength speckle suppression technique." With this technique, a coronagraphic mask placed in front of the star eliminates the star's brightest light, allowing researchers to image a background object or faint planet.

At Livermore, Marois calculated the level of image contrast based on the contribution of GPI's many optics. Then using the age and mass of Jupiter as a control point, he ran a Monte Carlo computer simulation to predict the sizes and ages of planets that GPI will detect. Jupiter is massive enough but too old and cool—165 kelvins—for GPI to detect if it were in another solar system. Earth at 287 kelvins is hot enough but too small for detection.



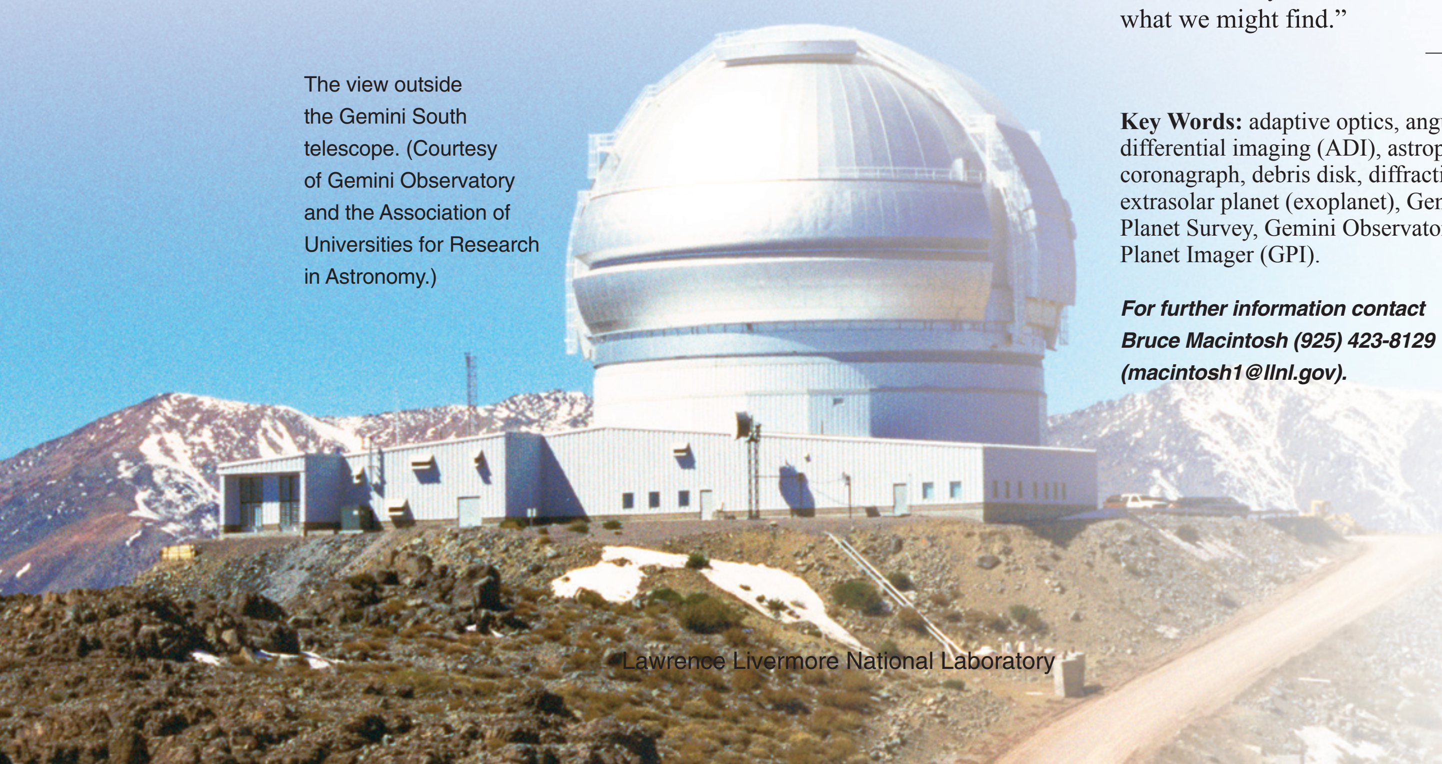
This graph from a simulated sky survey estimates the number of extrasolar planets (dots) that could be found using the Gemini Planet Imager. Planets will range from 1 million to 1 billion years old and have temperatures between 200 and 400 kelvins. Blue numbers indicate the mass of a planet compared to that of Jupiter. Red dashed lines show the conditions in which water vapor and ammonia clouds form. Jupiter, with a temperature of 165 kelvins, is the only planet to be observed to date within the temperature range shown on the graph. (Graph courtesy of James Graham, University of California at Berkeley, based on planet models by Adam Burrows, University of Arizona.)

Finding Life

And what about finding a planet that might harbor life? Earth orbits the Sun in what astronomers call the "Goldilocks" zone: not too hot, not too cold, but just right for living things to grow and thrive. A small exoplanet like Earth that is warm, rocky, and close to its star cannot be detected even with GPI.

In 10 to 20 years, the National Aeronautics and Space Administration plans to launch the Terrestrial Planet Finder, a wandering spacecraft designed to detect Earth-like planets. "Until then, we have GPI," says Macintosh. "Who knows what we might find."

—Katie Walter



The view outside the Gemini South telescope. (Courtesy of Gemini Observatory and the Association of Universities for Research in Astronomy.)

Key Words: adaptive optics, angular differential imaging (ADI), astrophysics, coronagraph, debris disk, diffraction imaging, extrasolar planet (exoplanet), Gemini Deep Planet Survey, Gemini Observatory, Gemini Planet Imager (GPI).

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