by Bruce Macintosh
and James Graham

The Gemini Planet Imager

The Extreme Adaptive Optics Coronagraph was identified by the Gemini user communities during the Aspen Process as one of four next-generation instruments for Gemini. It was conceived as a high-performance adaptive optics (AO) system optimized for delivering images of very high contrast at small angular separations that would be suitable for detecting extra solar planets. Now more euphoniously and functionally named the Gemini Planet Imager (GPI), it is the first of the Aspen process instruments to enter the design and construction phase.

The primary science mission of GPI is to detect self-luminous extrasolar planets at near-infrared wavelengths. Detecting an old, cold Jupiter-like planet, which is a billion times fainter than the Sun at visible and near-infrared wavelengths, would be challenging even for a 30-meter telescope. However, a young (100 million-year-old) Jovian-mass planet retains the heat of its initial formation and is only a million times dimmer than its parent star in the near-infrared. More massive planets start hotter and cool more slowly and so remain significantly self-luminous for up to one billion years. Such faint companions are still undetectable by the Hubble Space Telescope or current-generation AO systems at separations less than a few arc seconds since they are hidden by light scattered by optical errors, diffraction, and imperfect AO correction of atmospheric turbulence. Gemini's Near-infrared Coronagraphic Imager (NICI, scheduled for first light in 2007) will be able to detect younger and brighter planets in wide orbits, but to probe solar-system-like scales requires the next generation of dedicated high-contrast adaptive optics systems like GPI (Figure 1, next page). Ultimately, in hour-long exposures GPI will be able to detect objects more than ten million times fainter than their parent stars, and be able to detect planets as old as approximately one billion years (depending on their mass) at separations between 5 and 50 astronomical units (AU).

Seeing the Firefly

The Gemini Planet Imager combines four techniques to achieve its goal of detecting the proverbial "firefly next to a searchlight." First, to correct the effects of atmospheric turbulence, it will include the world's most advanced AO system, with 1,600 active actuators on its deformable mirror (DM), controlled at greater than two kHz rates. Building such an AO system with conventional DM technology such as that used in ALTAIR would require a DM almost 40 centimeters (about 16 inches) across—far too large an optical system for the Gemini instrument volume constraints. Instead, GPI's primary DM will be a silicon micro-electro-mechanical system (MEMS) device, lithographically patterned and etched like a microchip (Figure 2, next page). The MEMS will be manufactured by Boston Micromachines. Versions with 1,024 actuators behind a continuous gold-coated facesheet are currently available and have been extensively tested in an extreme AO (ExAO) testbed at UC Santa

Cruz. The larger version for GPI is currently under development.

One limitation of current MEMS technology is the total available range of motion. At only 4 microns, it's not enough to fully correct atmospheric distortions on an average night, so GPI will use a second coarse, but high-stroke conventional DM synchronized with the MEMS. This is analogous to a home stereo "woofer/tweeter" arrangement. A fast visible-light spatially-filtered wavefront sensor and an advanced Fourier wavefront reconstructor help produce a point spread function (PSF) with most of the light removed in a distinctive "dark hole" region, as shown in Figure 1.

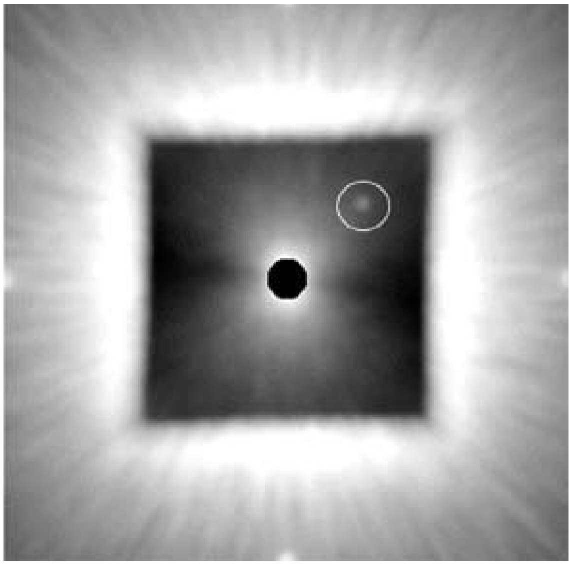

Figure 1. Simulated 20-second broadband near-infrared GPI image of a solar-type star at 10 parsecs (about 32 light-years), showing a 5-Jupiter-mass planet at 6 AU separation. Any bright star seen from the ground is surrounded by a halo of scattered light. Gemini Planet Imager's AO system and coronagraph partially clear out a "dark hole" region in the scattered light, allowing the planet to be seen.

The second major key to high-contrast imaging is the removal of small systematic and quasi-static errors that produce speckle patterns that can hide a planet. GPI's state-of-the-art internal optics will be polished to λ/200 surface quality or better. An infrared interferometer, tightly integrated with the coronagraph, will measure the time-averaged wavefront at nanometer accuracy, removing any small systematic bias in the measurements of the main visible-light wavefront sensor, including chromatic and non-common-path errors.

Even with perfect wavefronts, the familiar Airy diffraction pattern would completely swamp the light from a planet. Removing this diffraction pattern is the job of a coronagraph (named after Lyot's original device for studying the Sun's corona). GPI's coronagraph improves on Lyot's design by adding a grey scale apodizer to taper the transmission at the edges of the telescope, improving performance close to the star.

Finally, the sole science instrument will be a near-infrared integral field spectrograph (IFS), which will simultaneously produce a spectrum for every pixel in the instrument's three arcsecond field of view. With these three-dimensional data cubes astronomers can use wavelength information to distinguish planets from remaining artifact speckles. Broad molecular features (methane (CH_4) and ammonia (NH_3), for example) will likely dominate planetary atmospheres, so this spectrograph will be able to characterize planetary temperatures and surface gravities. The instrument will also include a dual-channel polarimetry mode for studying circumstellar dust disks.

Science with High-contrast Imaging

Why do we need direct detection to find more planets when more than 180 Doppler-detected planets are already known? Kepler's third law, $p^2 = a^3$, holds the reason. For a reliable detection using a method that detects orbital motion, a significant fraction of an orbit must elapse. The Doppler searches, which began accumulating significant quantities of data about a decade ago, now probe out to 4.6 AU from the parent star, although about half of the known planets lie within 0.9 AU. In another five years, they will have reached 6 AU. It is therefore impractical to explore the outer regions of solar systems, except by direct imaging.

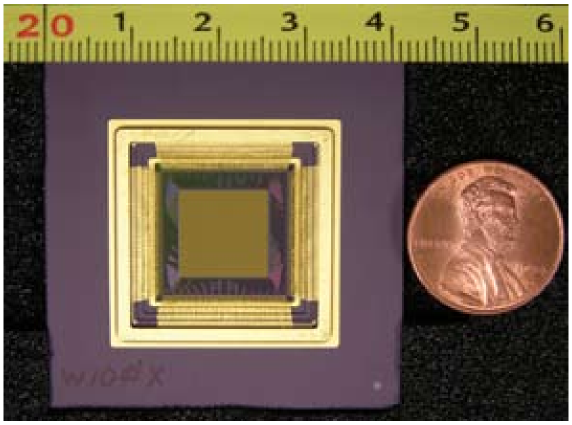

Figure 2. Gold-coated 1,024-actuator Boston Micromachines MEMS deformable mirror.

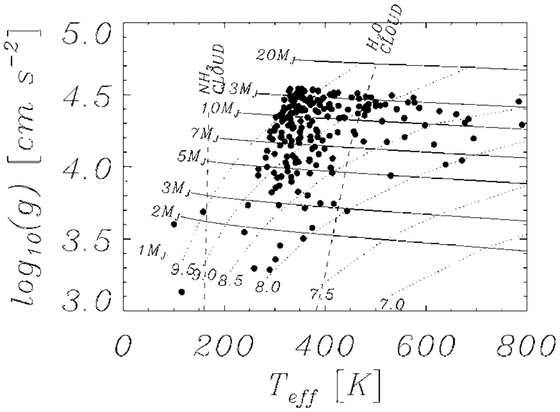

Figure 3. Atmospheric properties of planets discovered by GPI in a simulated observing campaign. Each dot is a planet, plotted on a grid of surface gravity vs. temperature. Solid near-horizontal lines indicate planet mass. Dotted near-vertical lines show constant age, labeled with $\log10_{(age)}$. Dashed lines show the formation of water vapor and ammonia clouds in the planets' atmospheres. The only known astronomical object that lies on this plot is Jupiter, with T_{eff} = 120 and $\log_{10}g$ = 3.4. Gemini Planet Imager will discover completely new classes of objects.

Extrapolation of current trends in planet abundance relative to semi-major axis suggests that the number of detectable planets will increase at least linearly with the outer limit of the survey, so we expect direct imaging to yield hundreds of planets. More significantly though, the abundance of planets beyond 5 AU holds clues to their formation processes and migration mechanisms. If Jovian planets can form by gravitational disk instabilities, as well as core accretion, then the outer regions of solar systems may have abundant Jovian- and super-Jovian-mass planets. If slower migration processes dominate, planets will cluster closer to their stars, and planet distributions may vary with stellar environment and age. Doppler techniques also work poorly on stars younger than a few hundred million years, since those stars have active, roiling photospheres that produce spurious Doppler shifts as sunspots rotate around the star. These adolescent stars will be GPI's prime hunting ground, allowing us to study the evolution of solar systems over time.

Perhaps the most alluring aspect of direct planet detection is that it opens up planetary atmospheres for spectroscopic study. Understanding these atmospheres will be a challenge, because direct detection will yield the discovery of the first objects with temperatures between that of Jupiter (125 K) and the coolest T dwarfs (700 K), (Figure 3). These are objects in which water (H_2O) and ammonia (NH_3) cloud condensation is expected to occur. Once we understand this new class of atmosphere and learn to infer composition and chemical abundances, we will have an entirely new method for exploring planet formation and evolution.

GPI will extend its science reach by adding imaging polarimetry to its capabilities, allowing unprecedented sensitivity to resolved debris disks, especially at sub-arcsecond scales that are hidden by the coronagraphs on HST.

GPI will be a facility instrument available to the whole Gemini user community, with a broad range of science missions. It will produce very high Strehl ratio images even at short wavelengths for bright objects, such as targets in our solar system. This will enable, for example, high-contrast mapping of satellite surfaces and atmospheres. GPI can vastly extend our set of visual binaries allowing any possible combination of main sequence stars up to an O/M binary to be imaged directly, leading to determination of orbits and masses. Brown dwarf and white dwarf companions will be easily detectable, and GPI can also map outflows from evolved stars. In general, the field of ultra-high-contrast imaging is unexplored to date. GPI will be able to produce complete information about the environment of any stellar target brighter than 9th magnitude (at I band) and will lead to many new and unanticipated discoveries.

The Gemini Planet Imager Project

Gemini Observatory has recently commissioned an international team of astronomers and engineers, led by the author to design and build GPI. Lawrence Livermore National Laboratory is the lead institution, responsible for project management and systems engineering. The project manager is David Palmer, who is also at LLNL. Other principal team members include René Doyon (Université de Montréal), Ben R. Oppenheimer (American Museum of Natural History, New York), Les Saddlemeyer, (Hertzberg Institute, Victoria), Don Gavel, (Lab for Adaptive Optics, UC Santa Cruz), James R.

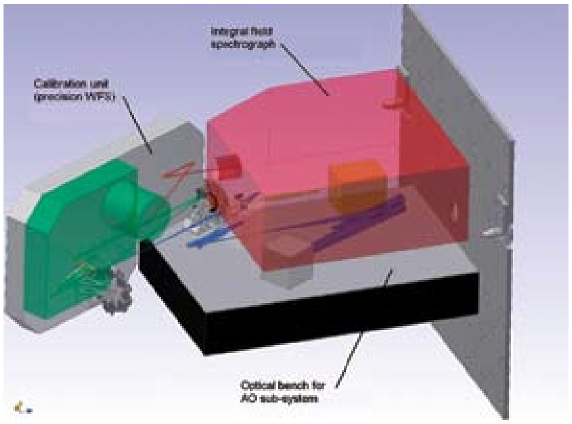

Figure 4. CAD design for GPI, with its covers removed, showing the plate for attaching to the Gemini Instrument Support Structure.

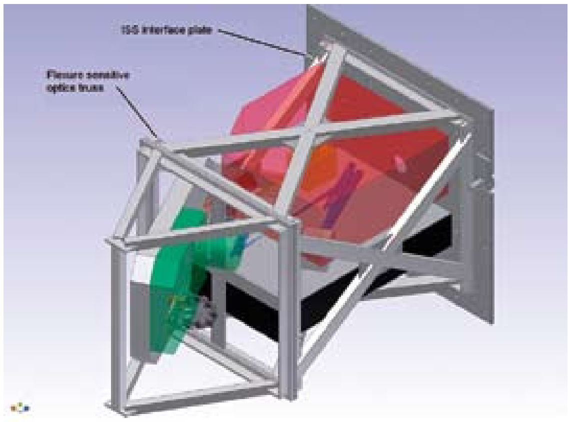

Figure 5. CAD rendering for GPI showing the major subsystems: the AO optical bench, coronagraph masks, precision infrared interferometer, and the science integral field spectrograph.

Graham, (University of California-Berkeley), James Larkin, (University of California-Los Angeles) and Kent Wallace, (Jet Propulsion Laboratory (JPL)). Mechanical design and overall software will be led by staff at the Herzberg Institute of Astrophysics, with their extensive experience in the Gemini environment. The optical layout and the real-time AO system will be designed at LLNL. The science integral field spectrograph will be designed and built at the University of California-Los Angeles, building on the OH-Suppressing Infra-Red Imaging Spectrograph (OSIRIS) instrument recently delivered to the W.M. Keck Observatory. JPL's interferometery group is responsible for the precision infrared wavefront sensor. The coronagraphic diffraction control system will be designed and tested at the American Museum of Natural History. The data reduction pipeline will be designed and implemented in Montréal, where they have developed many of the key concepts for extracting planet signals from data cubes. An international science team coordinated from Berkeley will provide strong science leadership. The GPI plan includes an extensive test and integration program, which will take place in the Moore Lab for Adaptive optics, at the University of California-Santa Cruz. Most of these institutions are part of the National Science Foundation's Center for Adaptive Optics, which has helped develop the field of "extreme" AO since its inception and laid the groundwork for this revolutionary capability. The GPI project had its official start in July, 2006. Preliminary design review is scheduled for June, 2007, test and integration proceeds through 2010, and first light is planned on Gemini South for late 2010.

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For more information see:

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Bruce Macintosh is a physicist at Lawrence Livermore National Laboratory, Associate Director for Extreme Adaptive Optics at the NSF Center for Adaptive Optics and Principal Investigator for the Gemini Planet Imager. He can be reached at: macintosh1@llnl.gov

James Graham is a professor of astronomy at UC Berkeley and Project Scientist for the Gemini Planet Imager. He can be reached at: jrg@berkeley.edu