Imaging extra-solar planets with adaptive optics and a MEMS mirror

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The Gemini Planet Imager will measure exoplanets that are a million times fainter than their host star.

From its invention some 400 years ago, the optical telescope has been our primary tool in learning progressively more about our solar system, our galaxy, and the formation of the universe. In the last 20 years, the optical telescope has revealed not only that planets exist around other stars, but also that these exoplanets are relatively common and come in an astonishing range of sizes and orbits. If we could directly image an exoplanet and study the spectrum of the light from it, we could know what that planet is made of, its surface temperature, the strength of its gravity and, potentially, if the planet harbors life.

Of the 500 exoplanets that have been detected by astronomers in the past two decades, almost all have been found by indirect means, such as the radial-velocity method. This is because directly imaging an exoplanet is extremely hard—planetary light-reflection and -emission is typically at least a million times fainter (and may be more than a billion times fainter) than the host star. This ratio of planetary-to-solar light intensity is referred to as the ‘contrast.’

High-contrast imaging requires the use of a coronagraph to suppress diffraction; otherwise the Airy-disc light phenomenon can overwhelm a planet’s reflected light. A further complication for ground-based observation is that the Earth’s turbulent atmosphere muddles starlight and can mask an exoplanet in its glare. Only very recently have astronomers been able to directly image exoplanets. Adaptive-optics (AO) technology, applied to large (8–10m diameter) telescopes, can reduce the deleterious effects of the atmosphere and make direct imaging of exoplanets possible.

A key component of an AO system is a multifaceted, deformable mirror (DM), the shape of which is adjustable, so that it can compensate for the atmospherically distorted light it collects. The spatial resolution of a DM is set by the actuators that control its facets: the more actuators, the more accurately the mirror surface can correct for atmospheric turbulence. DMs currently in use in astronomical AO have on the order of 100–300 actuators. Mapped onto the telescope primary mirror, the
GPI’s high-order DM is a micro-electrical-mechanical-system (MEMS) mirror. It has 4096 actuators on a 64 x 64 grid, with actuators separated by just 400μm from each other (see Figure 2). Boston Micromachines Corp. (BMC) developed this mirror through a multiyear research agreement with the National Science Foundation’s Center for Adaptive Optics and the Gemini Observatory. BMC’s low-actuator-count MEMS DMs already have wide use in vision-science AO systems. The key challenges faced by BMC while producing our new mirror were increasing actuator stroke and developing a device design that was more tolerant of the inherent limitations of the manufacturing process for DMs with thousands of actuators.

To exploit the potential of this new MEMS DM, we have developed several advanced AO technologies and algorithms to use in GPI. These include a self-optimizing and computationally efficient wavefront-reconstruction algorithm that determines the best actuator positions at the nanometer level, and a wavefront-sensor that prevents spatial aliasing in the sampled measurements of the wavefront. Many of these new techniques have already been validated with a 1024-actuator BMC mirror, demonstrating that a static phase plate with atmospheric-like phase errors can be corrected to a residual error of 4nm RMS.6

In 2010 we integrated a prototype 4096-actuator MEMS DM with the optics, hardware, and control computer of GPI’s AO system and demonstrated 1.5kHz wavefront control.7 In 2011, our final MEMS DM will be integrated into the GPI instrument, which will then be delivered to the Gemini South Observatory. GPI will be the world’s most powerful astronomical AO system and will conduct a survey of nearby stars, potentially imaging up to 100 new extrasolar planets.

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Lisa Poyneer specializes in signal processing for adaptive optics and is the lead AO control engineer on the Gemini Planet Imager

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project. She has developed several new techniques that enable high-performance AO, including the spatially filtered wavefront sensor, the Fourier-transform wavefront reconstruction, and the optimized-gain and predictive-Fourier wavefront control algorithms.

References