

BROAD OVERVIEW

Scientific Context: The W. M. Keck Observatory (WMKO) is one of the cornerstones of U.S. ground-based optical/infrared astronomy. Over the past 15 years, its adaptive optics (AO) facilities have provided the U.S. community with unprecedented angular resolution over much of the sky, especially with the advent of laser guide star (LGS) AO in 2004. LGS AO on the two Keck telescopes has been extremely productive, e.g., having produced 71% of all the LGS-based refereed science papers worldwide since 2004, despite competing systems on other existing 8-10 meter telescopes. The success of Keck LGS AO has led to the development of the Next Generation AO (NGAO) facility proposed here. The design of NGAO is driven by a wide range of cutting-edge science cases developed by a broad user community. The key features of NGAO are excellent and stable correction (i.e. Strehl ratio) and outstanding sky coverage, including good performance at wavelengths as short as 0.7 μm . With these gains, AO will fully assume its place as an indispensable component of an astronomer's toolkit, making it possible for observing programs to be dictated purely by their science goals. As a result, NGAO has been identified as the top priority for new major instrumentation in WMKO's Strategic Plan.

At first light in 2019, NGAO will be the preeminent AO facility that advances a wide range of fields. We have defined four key science cases to guide its design and illustrate the gains from its powerful new capabilities. (1) NGAO detection of the dark matter substructure in galaxies using gravitational lensing will directly test the cold dark matter model, and monitoring of gravitational time delays between multiple images of lensed quasars will provide a powerful new probe of dark energy. (2) NGAO's sky coverage will allow for ambitious, comprehensive extragalactic surveys, greatly expanding the pioneering studies on the resolved properties of high-redshift star-forming galaxies by first-generation Keck LGS AO. Substantial leaps in resolved measurements of kinematics and metallicities will chart the evolution of galaxies over cosmic time in an unprecedented fashion. (3) NGAO's gain in Strehl ratio, resolution and contrast will lead to profound gains in our understanding of the Galactic Center. By detecting and mapping of the orbits of stars ten times fainter than currently possible, NGAO astrometry will test General Relativity in an unexplored regime and delineate the interaction of the supermassive black hole with its unusual environment. (4) NGAO will play a unique role in the direct imaging of exoplanets through studies of low-mass and young stars, whose faint optical fluxes render them inaccessible to extreme AO (ExAO) systems. Together, ExAO and NGAO will fully map the properties of gas-giant exoplanets across a wide range of stellar masses and ages, thereby revealing the diverse pathways of planet formation and evolution. NGAO's capabilities will also enable transformational studies in numerous areas outside these four key science cases.

Finally, every major AO improvement at WMKO has led to unanticipated discoveries. With its broad and unique range of capabilities, we can expect NGAO to do the same.

Community Context: NGAO represents a key synergistic element for the future competitiveness of U.S. astronomy. NGAO will provide a more spatially detailed view than JWST for both imaging and spectroscopy. NGAO will precede AO on the giant segmented-mirror telescopes (GSMTs) by at least five years, preparing the U.S. community for LGS AO science with GSMTs and then serving a complementary role with evolving instrumental capabilities once the GSMTs are in operation. Both the Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) projects are collaborators on this proposal because NGAO is an important proving ground for their planned techniques and technologies.

NGAO will be available to the U.S. community on the world's largest and most scientifically productive ground-based telescope. The U.S. Ground-based Optical/Infrared System Roadmap Committee (2012) found that 32% of U.S. survey respondents had used the Keck II Telescope in the past three years, a higher percentage than for any other U.S. facility. All Keck data, including from NGAO in the future, are made publicly available through the existing Keck Observatory Archive. Along with the current access, WMKO will provide 75 science nights to the community. NGAO access will be an excellent avenue to develop an experienced U.S. community prepared for high angular resolution science with GSMTs.

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Education: NGAO will build on a long tradition in the WMKO partner community of student training and advancement in instrumentation. Keck AO has been a vital hub for developing both astronomers and engineers. Several members of the NGAO science team were involved with Keck AO as graduate students and/or postdocs and are now faculty members (i.e. Michael Fitzgerald [UCLA], Michael Liu [Hawaii], Jessica Lu [Hawaii], Bruce Macintosh [Stanford] and Lisa Prato [Lowell]). Technical personnel involved in building Keck AO are now AO leads at other institutions (e.g. Erik Johansson [ATST/DKIST] and Antonin Bouchez [GMT]) and AO experts in industry (e.g. Scott Acton [Ball Aerospace, working on JWST] and Marcos van Dam [Flat Wavefronts]). Caltech and UC have excellent records of producing students with instrumentation-related skills; many did their thesis work with Keck AO and are now faculty members at U.S. or GSMT-partner institutions (e.g. Mark Ammons [LLNL], Michael McElwain [GSFC], Marshall Perrin [STScI], and Shelley Wright [Toronto]). An ethos of teaching and training has grown among these colleagues, with many of them actively engaged in developing instructional activities based on AO and instrumentation, especially via the Center for Adaptive Optics (CfAO). Following in this tradition, NGAO and its associated team members will provide excellent training for future astronomical and technical leaders.

The NGAO educational component includes (1) an Instrumentation Summer Intensive provided for graduate students, under the auspices of the UC Santa Cruz Institute for Scientist and Engineer Educators (ISEE); (2) technical and scientific involvement of graduate students in NGAO development; (3) mentoring of Hawaii college-level interns through the UC/University of Hawaii (UH) Akamai Internship Program; and (4) training of postdocs and engineers. Both the ISEE and Akamai Program have well-established processes to evaluate student training. Underrepresented groups will be recruited as part of the Summer Intensive and Akamai programs, using ISEE's extensive experience in this area and a core team committed to broadening participation in AO and instrumentation. Two of the NGAO co-PIs and five additional members of the science team are female faculty with excellent track records of recruiting women into the field. The strong participation of women in Keck AO science is illustrated by the fact that 42% of the 31 Keck-AO based theses published between 2009 and 2012 were awarded to women, at ten different institutions. Five of these women won prize postdoctoral fellowships, as did ten of the men.

We will involve students and postdocs in non-critical path NGAO technical developments and also in related science developments. For example, Professor Ghez will involve junior colleagues in science simulations for NGAO trade studies and performance assessments and also in developing data analysis tools to maximize the NGAO science return. Some junior colleagues will be directly funded by NGAO while others, as based on multiple past examples, will participate via other grant or fellowship funding.

The breadth of AO applications has rapidly increased beyond astronomy. AO is used in vision science, microscopy, lasers, communications, lithography, manufacturing and military applications. NGAO involvement would thus help prepare students and postdocs for a broad range of career opportunities.

Resources: MSIP support of NGAO would be highly leveraged. This includes (1) an existing preliminary level design for NGAO that has resulted from several years of investment in its science and technology; (2) already-funded NGAO components including a laser, beam transport system, and an upgraded imager and integral field spectrograph; (3) already-funded risk reduction activities including point spread function reconstruction and a near-infrared tip-tilt sensor; (4) substantial AO and instrument technical expertise at the collaborating institutions of ANU, Caltech, GMT, UCLA, UCSC, UH, TMT and WMKO; (5) very strong AO science expertise within the NGAO science team; (6) a strong WMKO track record in developing, managing, and implementing scientifically productive AO systems and instrumentation; (7) highly regarded education and training expertise with the UCSC Institute for Scientist and Engineer Educators and UH Akamai Program; and (8) substantial private funding from the Gordon and Betty Moore Foundation, the W. M. Keck Foundation and Friends of Keck.

NEW DEVELOPMENTS

In the month since MSIP proposal submission, the following related new developments have occurred:

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- Eleven refereed science papers based on Keck AO were published bringing the total to 515. Seven of these papers used LGS AO. A *Science* paper on the first potentially habitable Earth-sized planet (Quintana et al. 2014) made use of Keck NGS AO observations.
- A purported cloud of gas, termed G2, was predicted to collide in March 2014 with the supermassive black hole at the center of our Galaxy. This event was closely monitored by multiple observatories. Keck LGS AO target of opportunity observations, performed by NGAO co-PI Ghez et al., were used to track G2 during its periaapse passage. The scientifically interesting result - G2 survived its close encounter.
- The recent measurement of B-mode polarization from BICEP2 is higher than expected. If confirmed, the tension between *Planck*, BICEP2, and the local distance ladder determination of H_0 in a standard Lambda-Cold Dark Matter model, might be an indication of new physics such as additional neutrino families or non-trivial dark energy (e.g. Dvorkin et al. 2014). The rapid developments and tensions in the field highlight the importance of additional independent cosmological probes enabled by NGAO, like the low-redshift distance information provided by gravitational time delays (e.g. as proposed by NGAO science team member Treu et al. 2013).
- The 2014 Robert J. Trumpler award from the Astronomical Society of the Pacific for outstanding PhD thesis was awarded to NGAO co-PI Michael Liu's most recent graduate student, Brendan Bowler, for work on exoplanets directly imaged with the Keck AO systems.
- ISEE has expanded nationally to engage astronomy graduate students, postdocs, and observatory personnel in a professional development program. ISEE was awarded a new NSF grant (AST-1347767) from Astronomical Sciences' Education and Special Programs. This award stimulated the launch of ISEE Chapters at UCLA, UCSB, University of Houston, UC Boulder (includes ATST/DKIST partners), Pasadena (includes Caltech, TMT, JPL and Carnegie), New York City (includes the American Museum of Natural History, CUNY-Staten Island, and Columbia), and Michigan State. ISEE also has a quickly growing University of Toronto site. These new chapters expand capacity beyond the well-established California-Hawaii partnership initiated by the CfAO, evolving into the Akamai Workforce Initiative. ISEE's geographical reach will provide a strong infrastructure for ensuring broad participation in NGAO's student training activities.
- ISEE has launched a new mentor training program funded by the above NSF grant and the TMT, which will support our plans to engage graduate students in instrumentation. A new workshop that helps Hawaii observatory personnel develop productive student projects and then effectively mentor the associated students will be held in April 2014 on the Big Island. Participants include personnel from WMKO, Mauna Kea observatories, UH, and Maui companies that support astronomy. Future NGAO mentors will attend this workshop and join a growing community of scientist and engineer-educators that work together to engage students from diverse backgrounds.
- The preliminary design review for the new Keck II laser facility, which is designed to support NGAO, was successfully completed. Two longer lead subsystems were reviewed at the detailed design level and are now proceeding to fabrication, namely (1) the platform which will support the laser electronics and (2) the opto-mechanics that will take the output of the laser and feed it into the beam transport system. The laser is already in fabrication. First light is anticipated in 2015 for use with the existing LGS system and subsequently with NGAO.
- The new Keck II beam transport system, designed to support NGAO, had a successful second commissioning night, including achieving a comparable LGS spot size to the existing Keck I center launch system and demonstrating closed loop AO operation with good performance. The system will be in routine operation with the existing LGS system in 2014.
- The recent successful first light results from the Gemini Planet Imager and UCO Shane telescope AO systems have provided additional risk reduction for NGAO's planned usage of MEMS deformable mirrors for high-order AO correction.