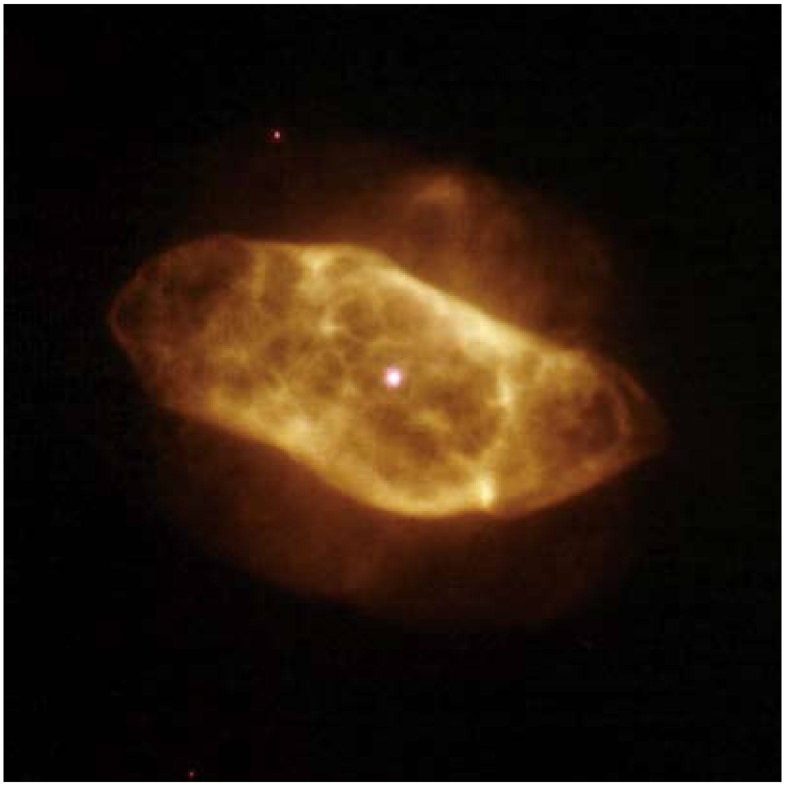
GeminiFocus

Newsletter of the Gemini Observatory

December2006

NGC 7009 (The Saturn Nebula) With Adaptive Optics (AO)



This Gemini North image shows the well-known planetary nebula NGC 7009 (the Saturn Nebula) in the near infrared with adaptive optics. The image has a full-width-half-maximum of 0.1 arcsecond (K band) and was produced by combining ALTAIR/NIRI images in K, Br-gamma, and H_2 (1-0) bands. The data were obtained in October, 2006 and are now available on the Gemini Science Archive.

Cover Image:

Adaptive optics image of Jupiter obtained with Gemini North using the ALTAIR/NIRI system. Find more details in the director's message on page 4.

GeminiFocus
Newsletter of the Gemini Observatory

In This Issue:

This special issue is devoted to the Gemini adaptive optics program, and was led by Jean-René Roy, Deputy Director and Head of Science at Gemini Observatory.

Gemini North Laser Propagation - Gemini Observatory Image

Managing Editor, Peter Michaud

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Designer, Kirk Pu'uohau-Pummill

by Doug Simons

Adaptive Optics: a Special Issue – a Core Gemini Program

Figure 1. Gemini adaptive optics image of Jupiter using the same data used for the image on the cover. This version was processed using different color assignments for each filter and enhanced by Christopher Go, the Philippine amateur astronomer who first spotted and identified the new red spot on Jupiter.

Take a close look at the cover of this issue of *GeminiFocus*. Note the wisps of detail between the Great Red Spot on Jupiter and its "little brother" to the south, as they exchange pleasantries in the form of gas and clouds while slowly passing each other. Note the structure in the white equatorial belts, that little white spot just above the equatorial belt, and the dark eddies of gas undulating across Jupiter's disk. Have you ever seen an image of Jupiter like this, made from the ground? Can you figure out how this was done at Gemini?

Think about it. The resolution is so high that it had to involve adaptive optics (AO), but Jupiter is much too extended to use as a natural beacon for an AO system, so how was this done? Well, it turns out that the Jovian moon Io was used as a wavefront reference. It's not included in this image but is actually off the frame, to the right. Now consider that Jupiter is moving at a non-sidereal rate and the AO reference was moving at another non-sidereal trajectory on the sky. Furthermore, the servo loops had to lock quickly during the brief time that Io was illuminated (before entering Jupiter's shadow) and was close enough to act as a wavefront reference for ALTAIR (the Gemini North facility AO system) so that correction across Jupiter's entire disk was possible.

Finally, this is a multi-wavelength image of a disk of gas that is rotating fairly rapidly, meaning a fast sequence of images was needed to avoid blurring when they were combined. This was a non-trivial image to record when you consider the sophistication of the systems needed to do this. The fact that this was the first time we attempted such an observation at Gemini made it all the more satisfying for our AO team.

The cover for this edition of *GeminiFocus* was deliberately chosen to illustrate in no-nonsense terms that we "do" AO at Gemini Observatory.

Figure 2. Propagation of the Gemini North solid-state sodium laser during its commissioning in October, 2006. The lights of Hilo can be seen to the left and the final glow of astronomical twilight to the right. Thanks to the Canada-France-Hawai'i Telescope staff for their hospitality and access to the catwalk necessary to obtain this image.

The Gemini telescopes were designed from the outset to take advantage of the natural seeing conditions available at two of the best sites in the world. Together with the advanced AO systems now in use and under development at Gemini, the sites and technology implemented by the observatory provide our community with truly exciting research opportunities.

On the pages that follow, you will find a remarkable collection of articles which describe the science, technology, and programmatics of Gemini's AO efforts and provide a global context for Gemini's AO program. A wide range of authors provided these articles, which describe the evolution of AO systems used at Gemini from the early days of Hokupa'a-36 at Gemini North to the multi-conjugate adaptive optics (MCAO) system now in development for Gemini South and beyond. Instruments designed to be used with AO systems are discussed, including the Near Infrared Integral Field Spectrograph (NIFS), Gemini South Adaptive Optics Imager (GSAOI), and FLAMINGOS-2—a near-infrared imager and multi-object spectrograph for Gemini South. We then explore the next-generation of coronagraphs under development within Gemini's instrument program, including the Near-Infrared Coronagraphic Imager (NICI) and the Gemini Planet Imager (GPI). Research completed with Gemini's AO systems is then covered, ranging from planet searches to studies of the center of the Milky Way to observations of distant quasars. Finally, a fascinating comparison of astronomical AO investments worldwide is presented. This shows how Gemini's AO investments compare to those made at other major observatories around the world, as well as those of various university-based AO groups.

As impressive as the cover image of Jupiter is, the future of AO at Gemini is far more exciting. The commissioning of the laser AO mode of ALTAIR is nearly complete, which will open large swaths of the sky for AO exploration by our community. Next, NICI will be deployed early next year in Chile, with its own natural guide star AO system to support coronagraphic imaging of nearby stars in search of low-mass companions and disks. Soon thereafter in 2007, we will begin commissioning our MCAO system—the only one of its kind in the world and capable of providing images and spectra across arcminute sized fields over most of the sky. Between GSAOI and FLAMINGOS-2, Gemini astronomers will be able to tap near-infrared imaging and multi-slit spectroscopy using an MCAO feed—a combination never before offered in astronomy.

Our AO investments won't stop there. We have just contracted with one of the world's premier teams in AO, led by Lawrence Livermore National Laboratory, to build GPI. This instrument alone represents a near doubling of AO investment at Gemini Observatory. Intended to provide direct imaging and spectroscopy of extrasolar planets, GPI stands to revolutionize this field of astronomy. Pending the results of a one-year campaign of ground-layer seeing measurements on the upper ridge on Mauna Kea, Gemini is also considering developing a ground layer AO (GLAO) system. This is intended to provide point-spread functions (PSFs) consistent with good seeing conditions most of the time for any instrument bolted on the back of the telescope. If pursued, GLAO will be available sometime early in the next decade to astronomers at Gemini North.

Make no mistake, these are lofty goals. They require not just ambition, money, and lots of hard work, but also the invention of new technologies, like a 50-watt sodium laser system and micro-electro-mechanical systems (MEMS)-based deformable mirrors. We recognize that when and where Gemini's development program can benefit all of astronomy, it should, and that the aforementioned investments should do precisely that. Such technology investments are not only meant to keep Gemini competitive, but also a leader in several sectors of AO. Our community rightfully demands and deserves nothing less than Gemini's world-class AO systems described in this issue of *GeminiFocus* to pursue their research. There are plenty of risks associated with such an ambitious program, but Gemini's AO program is being built upon the foundation of success and expertise that made our cover image of Jupiter possible. In time, I am sure I will look back and think how trivial it was to record that image, compared to what is envisioned for the next decade at Gemini. For now though, it serves as a reminder of how far we've come with our AO program in such a short time at Gemini, and as a precursor of much more spectacular science to come.

Douglas Simons is Director of Gemini Observatory and can be reached at: dsimons@gemini.edu

by Damien Gratadour

From Classical AO to MCAO

The Story of Telescopes and Their Limitations (in a Nutshell...)

Since the astronomer Galileo Galilei first used a refractor to scrutinize the night skies in 1609, astronomers have not ceased in the invention of new ways to discern more details on the celestial sphere. The first approach has often been to increase the size of their observational machines. This worked until certain effects limited the gains realized by increasing light-gathering power and forced astronomers to invent new designs for their telescopes.

For nearly a century after Galileo's first attempt, the size of refractors grew considerably. This allowed astronomers to increase the magnification, which led to two highly limiting effects: chromatic aberration and the size of the telescope itself. Chromatic aberration is due to the separation of light into colors when passing through a lens. It causes a ring of colors to appear around bright objects. Compounding this, between the physical mass of their tube and the lens itself, both can deform under their own weight. Not to mention that heavier instruments are more difficult to manipulate.

About eighty years after Galileo's first refractor, Sir Isaac Newton found a solution for these two issues: use mirrors instead of lenses. This new design permitted the same magnification with a telescope ten times more compact and, most importantly, without chromatic aberration. The reflector era had begun.

Still following the first principle of "how to enhance the resolution," astronomers again started to increase the size of their telescopes; and, by the mid-1800s, the largest reflectors had become powerful enough that atmospheric distortion became a major obstacle. In addition, the locations of most telescopes were far from optimal, particularly from an image-quality point of view. It was only at the dawn of the 20th century that consideration of the observing location for image quality became a strong driver for a telescope's site selection.

Atmospheric turbulence is caused by the presence of air pockets at different temperatures (and thus densities) in the atmosphere. The refractive index (how much bending the light undergoes) of air depends on its temperature. The light rays, passing through the different air pockets on their way to the ground, bend in random ways. As a result, the stars appear to twinkle if you look up at the night sky with your naked eye. Through a telescope, the image appears blurry and pulsating. Astronomers had to wait until the mid-20th century until a solution was proposed by Horace W. Babcock in 1953 to solve this issue. His idea consisted of using a mirror that would deform in real time to counteract the always-changing aberrations caused when light crosses through the turbulent atmosphere. The first trials on telescopes started only in the 1970s (for

Figure 1.
Color composite of the planetary nebula M2-9 using ALTAIR AO images (upper panel) in the following bands: K' (green), K+H_2(1-0) (violet) and FeII (orange). Field of view is 30 x 30 arcseconds with NIRI at f/14. Bottom: HST WFPC2 optical image (1997).

military applications). The first astronomy-based, common-user systems were implemented at the European Southern Observatory (ESO) and Canada-France-Hawai'i Telescope (CFHT) in the early 1990s. The era of Adaptive Optics (AO) was born.

The systems now used on the largest ground-based telescopes like Gemini North, Keck II and Very Large Telescope (VLT), deliver images in the infrared (see Figure 1) comparable to visible images delivered by the Hubble Space Telescope (HST)—a telescope not limited by atmospheric turbulence. Both approaches, far from being mutually exclusive, are nicely complementary. Because of the difference in aperture, AO can produce sharper images than the HST in the infrared, and in some cases, it also goes deeper, but only on a limited part of the sky (although LGS and multi-conjugate AO techniques are striving to close this gap).

From Classical AO to MCAO

In a classical adaptive optics system, or natural guide star (NGS) AO, the atmospheric turbulence is probed by what is called a wavefront sensor (WFS), which collects the light from a guide star (or "guide source," since it could be any object with a star-like appearance, i.e., a quasar). The most common WFS concept used for AO systems is the Shack-Hartmann type, a device that separates the light entering the telescope's pupil in many sub-regions, called sub-pupils, using a lenslet array. The light in all these sub-regions is then collected on a CCD. By analyzing the deviation of the light in each of these sub-pupils in real time, one is able to compute, using a real-time controller (RTC), the corresponding wavefront distortions and thus the command that should be applied to the deformable mirror in order to correct the deformations in the wavefront. However, there are two limitations to this. First, atmospheric turbulence evolves in a volume (the whole thickness of a column in the atmosphere). Second, the induced distortions change on a spatial scale that is on the order of tens of centimeters and on a time scale on the order of tens of milliseconds. Thus, the turbulence has what is called a limited spatial coherent scale and a limited temporal coherent scale.

Since the system is supposed to work fast enough to be efficient (typically at frequencies greater than 100 Hz, so that each measurement is made during a time corresponding to the temporal coherent scale), the wavefront sensing requires a bright guide source. Thus most of the NGS AO systems available nowadays on 8- to 10-meter telescopes are limited to stars brighter than magnitude 13 - 15 (visible). On the other hand, as the wavefront sensor probes the turbulence using the light coming from a point-like reference source, the measurements of the distortions induced by the atmosphere are accurate enough only within a small region of sky, called an isoplanatic patch. Its size is set by the spatial coherent scale and the vertical distribution of the turbulence.

The best astronomical sites have an isoplanatic patch of about 20 arcseconds from the guide source at 2.2 microns. This means that a good correction level can be achieved using AO systems in a 40 x 40 arcsecond field around the guide source. The two characteristics combined means that only a small fraction (about 2%) of the sky can be observed using NGS AO systems. This is a huge limitation on the strategic scientific use of AO.

In order to reduce the impact of the limited availability of the NGS, laser guide star (LGS) AO systems have been developed for astronomical use during the last few years. In this approach, an artificial star is created at a high altitude in the atmosphere, using a laser beam (~10 watts) that excites an atmospheric layer containing sodium atoms located at an altitude of approximately 90 kilometers (about 55 miles). However, because the laser beam is deflected by an unknown and random amount on its way up, the image motion cannot be measured with this technique. Thus, a natural guide star (whose light is only propagating downward) is still required to measure image motion and achieve an acceptable correction level. However, the required star can be quite faint (brighter than ~18th magnitude), which increases the possible sky coverage to as much as 30% of the sky (at 2.2 microns).

Nevertheless, these systems still suffer strong limitations. One constraint is that they are highly sophisticated and use new technologies that are not yet completely mature. The use of the laser also introduces additional difficulties for recovering the shape of the wavefront since it is an extended and variable reference source and suffers from what is called "cone effect." The cone effect is a result of the fact that the laser guide star is formed in the atmosphere and not located at infinity like a natural guide source.

Another, and more important limitation, is that the corrected field of view available through the use of AO NGS/LGS systems is still limited to about 40 *x* 40 square arcseconds (at 2.2 microns). This is very small compared to the apparent angular size of objects like close star clusters or even nearby galaxies.

Such issues have not deterred astronomers in their quest for the most accurate view of the universe. Indeed, they have acted as strong stimulants to build larger and more elaborate instruments and software. For instance, the complex logistics for avoiding interference with Earth-orbiting artificial satellites and local aircraft traffic are being handled now in a satisfactory way, resulting in only a few shut-downs due to "sky-traffic."

To increase the size of the corrected field of view as well as the sky coverage of AO systems, astronomers developed a novel approach. Such a concept emerged about ten years ago, and will soon be implemented and commissioned on the Gemini South Telescope. It is called Multi-Conjugate Adaptive Optics, or MCAO.

The MCAO Concept and its Applications

The idea behind MCAO is based on better modeling and monitoring of the atmosphere. As described previously, atmospheric turbulence develops and evolves in a volume. On the other hand, classical NGS or LGS AO systems operate as if the atmospheric turbulence is evolving in a plane (which is a good approximation inside the isoplanatic patch). To go beyond this approximation and obtain an acceptable correction level over a field of view greater than the isoplanatic patch, one needs to consider the whole turbulent volume.

In theory, the turbulent atmosphere is a continuous volume, meaning that it is composed of a very large number of thin turbulent layers. In practice, measurements of the turbulence over the best astronomical sites have shown that it is concentrated in a finite number of dominant layers, located at different altitudes and with different thicknesses. This means that the turbulent volume over these sites can be very well modeled by a certain number of turbulent layers (typically two to five). Thus, a system that will use a corresponding number of deformable mirrors, conjugated at the corresponding altitudes (meaning located along the instrument's optical path at some preferred positions with respect to the telescope focal point) would be able to correct for those turbulent volumes (hence the term multi-conjugate). In order to control these multiple mirrors in a stable way, one needs a larger number of wavefront sensors to probe a volume of turbulence. This approach is called tomography and is similar to what is done in medical or geological 3-D imaging.

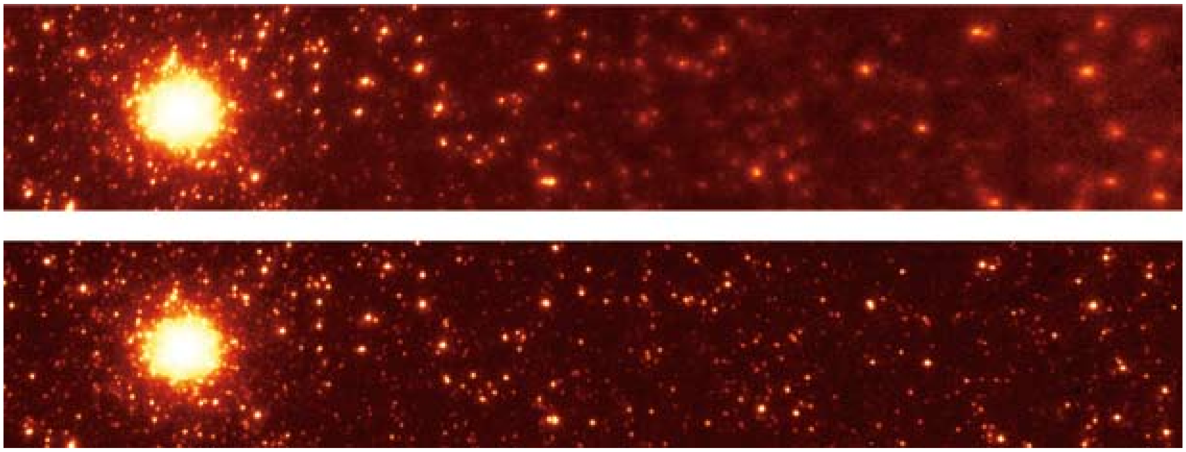


Figure 2.
H band mosaic images of the core of M33 with field lens out (top) and field lens in (bottom). These images were obtained on August 18, 2005 under favorable turbulence conditions within a period of 30 minutes. Field of view is 50 x 6.5 arcseconds at f/32 using the core of M33 as a guide source (approximate R magnitude of 14.5).

Knowing the location of the dominant, if any, turbulence layer in the atmosphere is important. As demonstrated by recent results at Gemini, conjugating correctly to the dominant turbulence layer (using what is known as a "field lens") can lead to a dramatic increase in the size of the isoplanatic patch (see Figure 2).

Like a classical AO system, the guide stars for an MCAO system can be solely natural guide stars, or a mix of laser and natural guide stars. Of course, the latter case provides significantly better sky coverage than the pure natural guide star case (for instance, the Gemini MCAO system will allow coverage of nearly 70% of the sky (in the J band, at a galactic latitude of 30 degrees while a classical AO system like ALTAIR can only cover 12%). On the other hand, any LGS-based MCAO system will require at least three natural guide stars because of an effect called tip-tilt anisoplanatism which is essentially a generalization of the need for a tip-tilt guide star in an LGS AO system.

As in the case of classical LGS AO, the tip-tilt fluctuations in the direction of each laser guide star cannot be measured. This leads to an inability to determine the global tip-tilt of the wavefront and requires one additional natural guide star to measure it. In addition, there are three other low-order modes that correspond to differential astigmatic distortions as well as the focus between the mirrors. This leads to an overall differential tip-tilt and requires the use of two additional natural guide stars. Thus, an archetypal MCAO system is composed of at least two deformable mirrors, three or more natural guide star wavefront sensors, or three or more laser guide star wavefront sensors coupled to three natural guide star wavefront sensors. While it might seem that the addition of three natural tip-tilt guide stars would limit the use of MCAO, the reverse is true since the field of view is significantly larger and the tip-tilt guide stars can be quite faint resulting in much better coverage on the sky.

The Gemini MCAO system is an instrument under construction for Cerro Pachón and is composed of three deformable mirrors, five laser guide star wavefront sensors and three natural guide star wavefront sensors (for a more detailed description of the MCAO system, please refer to the corresponding article on page 48 of this issue). It will deliver diffraction-limited images in the near-infrared over a one-arcminute field of view with high and uniform correction over the entire field. The MCAO system will not produce scientific data by itself since it is an interface between the telescope and the scientific instruments that stabilizes the beam and largely restores the diffraction limit of the telescope. Two instruments to be fed by MCAO, able to collect scientific data over such a field of view and with the appropriate sampling, are already planned to be installed on Gemini South. The Gemini South Adaptive Optics Imager (GSAOI) is a 4 x 4K near-infrared camera that will operate in the 1 to 2.5 micron range, with a field of view of 80 x 80 arcseconds. It is being built by the Research School in Astronomy and Astrophysics (RSAA) at the Australian National University (ANU). In addition, FLAMINGOS-2, a near-infrared multi-object spectrograph, built by the University of Florida, will provide spectroscopic capabilities with a resolution up to R = 3000 over a two arcminute field of view.

The MCAO science goals are divided into three themes, benefitting from its specific capabilities:

- to determine the global mass distribution of stars (in order to probe the bottom of the hydrogen-burning sequence and the sub-stellar distribution as a function of the environment);

- to understand the evolution of galaxies through stellar population studies (in order to calibrate the type Ia supernova (Sn la) zero point, to explore the stellar population in starburst galaxies or even study intergalactic stars); and

- to explore the evolution of distant field and clusters of galaxies (in order to constrain the internal characteristics of galaxies: metallicity/kinematics/extinction/star formation rate, as well as to study lensed galaxies and galaxy clusters).

The MCAO project and dedicated instrument suite are designed to remain competitive after the launch of the JWST, sometime near 2013.

Toward the Extremely Large Telescopes

Most of the current NGS/LGS AO systems are designed for coupling with near-infrared instruments because, at visible wavelengths, sky coverage is very poor, especially with NGS AO systems. For LGS AO systems, the cone effect (due to the fact that the artificial star is produced at a finite distance from the telescope) is a highly limiting factor because the diffraction limit is much smaller at visible wavelengths. Thus, in the near future, LGS-based MCAO systems, (which will be able to increase the sky coverage as well as solve the cone effect issue thanks to the use of multiple laser guide stars) will allow the possibility of obtaining high-angular resolution visible wavelength data from the ground.

Concerning future Extremely Large Telescopes (ELTs), AO systems are mandatory if these telescopes are to function at a scientifically viable level. The limiting effect of turbulence, wind buffeting, gravity or even temperature gradients grow with telescope diameter. As in the case of currently available large telescopes, reasonable sky coverage can only be achieved with LGS AO systems. Moreover, as in the case of visible observations with large telescopes, the diffraction limit of near-infrared observations with an ELT is much smaller and the cone effect becomes highly limiting. Thus MCAO is a must for future ELTs. The Gemini MCAO system will ensure a smooth transition towards the design of the first-generation instruments dedicated to these telescopes.

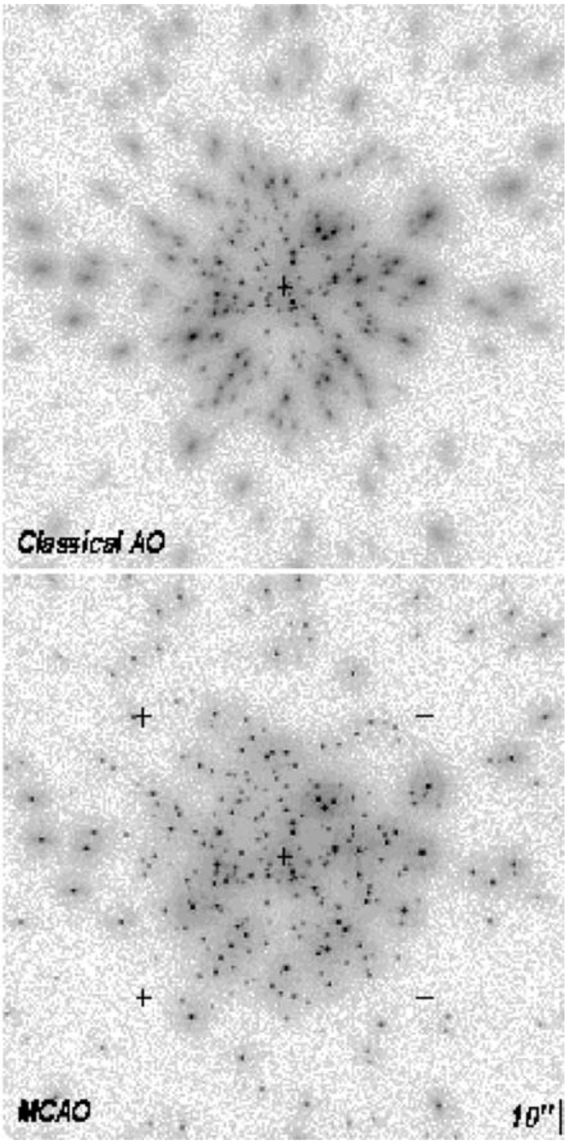
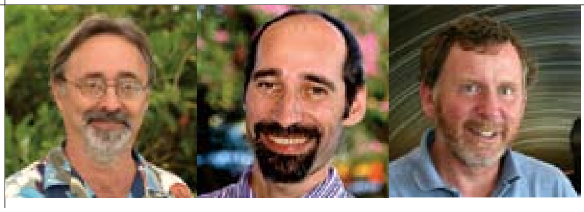


Figure 3. Illustration from simulations of the gain realized by the use of MCAO on a wide field of view. At top is the classical AO case, at bottom the MCAO case. Each field is 165 arcseconds wide. The position of the guide stars (one in the case of classical AO, five in the case of MCAO) are indicated by the crosses.

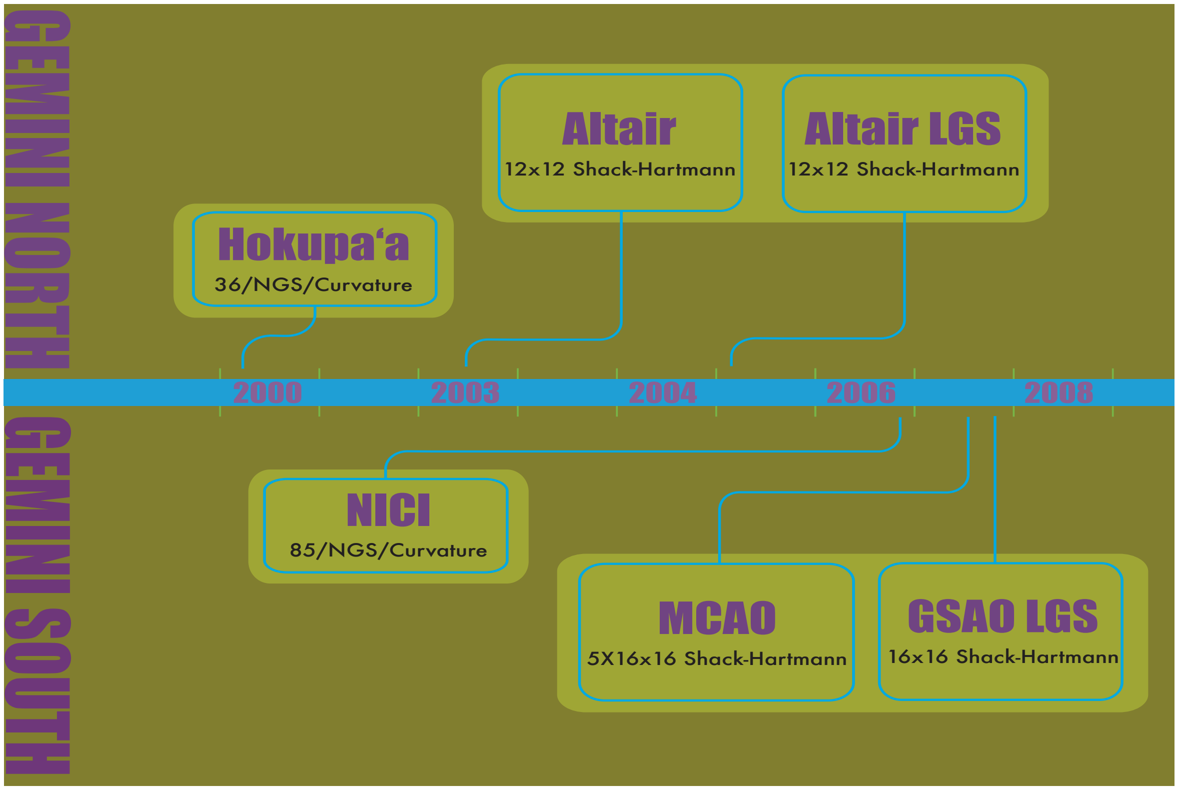
Damien Gratadour is a Gemini adaptive optics science fellow at Gemini South and can be reached at:
dgratado@gemini.edu



by Jean-René Roy,
François Rigaut
and Mike Sheehan

The Gemini Adaptive Optics Program

Overview, Strategy and History



Following the 1993 optical fix on the Hubble Space Telescope (HST), the power of high spatial resolution has been demonstrated again and again. Ground-based telescopes cannot compete with HST in the optical and ultraviolet windows for fine imaging but can compare and even surpass HST in the near-infrared by using adaptive optics. Hence, AO is central to Gemini's scientific mission with both Gemini telescopes equipped (or soon to be equipped) with superb AO systems. From 1996 to the present, the Gemini Board and partner agencies have repeatedly directed the observatory to develop and maintain an ambitious, extensive and strategic AO program. (Note: you can read more about these programs in the Gemini Science Requirements documents at http://www.gemini.edu/science/scireq3.html)

The Gemini telescopes are unique among the family of large 8- to 10-meter-class telescopes because they are optimized for maximum performance in the infrared. They were designed and built to deliver the finest image quality and highest Strehl ratios allowed by the site conditions, to deliver diffraction-limited images and to have the greatest sensitivities in the thermal infrared achievable on the ground.

Beginning in 1997, when we first embarked on building the ALTAIR facility AO system, we established a stepped approach with a succession of well-phased AO systems and instruments capable of producing science at the forefront of astronomical research. The Gemini AO program is a carefully planned succession of facilities that enable AO on both telescopes, and instruments that can exploit the excellent image quality. The AO instruments have included the Hokupa'a-36 system as well as ALTAIR currently on Gemini North, and the multi-conjugate adaptive optics (MCAO) system (recently named CANOPUS) now being integrated at Gemini South. The instruments that utilize AO are the Near Infrared Imager (NIRI) and the Near Infrared Integral Field Spectrograph (NIFS) at Gemini North. At Gemini South the Near Infrared Coronagraphic Imager (NICI), Gemini South Adaptive Optics Imager (GSAOI) and FLAMINGOS-2 will all soon be available with AO modes and the Gemini Planet Imager (GPI) will follow with delivery in 2010.

Context and Development History

Adaptive optics usage at Gemini started in an unusual way. In 1999, an AO imager helped finish the integration of the Gemini North Telescope. NIRI, our planned commissioning imager at Gemini North was very late in development and delivery, and we badly needed an imager to efficiently complete the commissioning of the telescope. Almost desperately, we bet on the Hokupa'a-36/QUIRC AO and imager pair, an experimental curvature-sensing system built by a team at the University of Hawaii's Institute for Astronomy (IfA), originally for use on the CFHT 3.6-meter telescope.

It is remarkable and significant that we employed an AO system to execute several core commissioning tasks at Gemini North. This turned out to be very challenging, but also ended up being very productive. We proceeded to move daringly into the first science observations with this AO system. In hindsight and with the pain forgotten, this arrangement allowed us to learn some important early lessons about science operations with the innovative Gemini telescopes systems. In addition, we were able to quickly explore areas of science that benefited directly from the use of AO on such a large telescope.

Clouds on Titan

By exploiting the multi-instrument queue-observing mode to monitor Saturn's moon Titan for several months with ALTAIR/NIRI, Henry Roe (University of California-Berkeley) and colleagues found short-lived temperate-level clouds never before seen. These observations, made in collaboration with the W.M. Keck Observatory, point to evidence of a giant active methane "slush" geyser or a geological warm spot on Titan. (For more details see paper by H.G. Roe et al., 2005, ApJ, 618, L49-L52.)

The ALTAIR AO project was approved by the Gemini Board in 1997 as our first facility AO system. It was designed and built by a team at the Herzberg Institute of Astrophysics (HIA) in Canada, arrived at Gemini North on October 11, 2002, and was mounted on the telescope on November 5, 2002. Most of its commissioning took place in 2003, although we suffered from several delays due to extended periods of poor weather. We also had to deal with various performance issues like vibrations (an AO system is unforgiving, as the smallest vibrations are obvious, but it offers a frustrating but powerful way to track them down). ALTAIR (in the natural guide star mode) was first offered for science in semester 2003B, or one year after Hokupa'a-36 was de-commissioned. In retrospect, this was probably too long a gap without AO. Unfortunately, the components of Hokupa'a-36 were needed for the new Hokupa'a-85 that the University of Hawai'i was developing. Note: Hokupa'a-85 was funded by the National Science Foundation (NSF). It was tested on Gemini South for a few nights in early 2005. Its performance turned out to be limited, but Hokupa'a-85 was a very useful test bed and pathfinder for NICI which uses a very similar AO system.

ALTAIR is now in regular use at Gemini North and is delivering excellent science. Six years after the first AO observations at Gemini it is rewarding to realize that close to 20% of the 300 refereed papers based on Gemini data involved the use of AO (Hokupa'a-36 and ALTAIR) on the Gemini North telescope.

Brown Dwarf Companions at Solar System Scales

In their Hokupa'a-36 study "Crossing the Brown Dwarf Desert Using Adaptive Optics: A very Close L-Dwarf Companion to the Nearby Solar Analog HR 7672", Michael Liu (University of Hawai'i) and his team showed that brown dwarf companions do exist at separations comparable to those of the giant planets in our solar system. (For more details see paper by M. Liu et al., 2002, ApJ, 571, 519-527.)

In order to take advantage of the laser guide star (LGS) mode of ALTAIR, Gemini's solid-state sodium-line laser arrived in Hawai'i in February 2005, and was first successfully propagated on the sky on May 2, 2005. It turns out that attaching the laser to the telescope and shining it on the sky was the "easy" part. We then spent more than a year solving several complex issues related mainly to the laser launch telescope and the ALTAIR LGS subsystems. As this issue of *GeminiFocus* goes to press, we are in the final stage of commissioning the combined ALTAIR LGS system and its integration with NIRI and NIFS. We are now ready for science with ALTAIR in both the LGS and natural guide star (NGS) modes. With ALTAIR we have demonstrated, as was previously done at the W.M. Keck Observatory, that transforming an AO NGS system into an LGS system is achievable. ALTAIR can be switched quickly between its NGS or LGS modes on demand during the course of nightly queue-scheduled operations.

We are currently taking the next steps in transforming the Gemini South telescope into a powerful AO facility. Early in semester 2007A, we will complete the commissioning of NICI on the Gemini South telescope. This specialized AO system was built by Mauna Kea Infrared in Hilo, Hawai'i, and includes its own 85-element curvature-sensing AO system which has evolved from the successful Hokupa'a-36 system. Funded by NASA, the NICI instrument will be devoted to the search for large Jovian planets around nearby stars in the southern hemisphere.

Almost in parallel with NICI, the integration of the Multi-Conjugate Adaptive Optics (MCAO) system (CANOPUS) is now underway at Gemini South. Instead of one deformable mirror and one laser guide star, as in the ALTAIR LGS system, CANOPUS will deploy three deformable mirrors and five laser beams. This will enable an AO-corrected field of 80 arcseconds (four-times what is currently available). A new 50-watt solid-state laser is being procured from Lockheed Martin Coherent Technologies (LMCT), and will be delivered to our Chile facilities in mid-2007. All of this development means that the year 2007 at Gemini South will be dominated by CANOPUS integration and commissioning. Our current schedule is to offer CANOPUS for general science use with the 4 x 4K near-infrared imager Gemini South adaptive optics imager (GSAOI), followed by the near infrared cryogenic multi-object spectrograph FLAMINGOS-2 in 2008.

Low Mass Binary Companions

In searching for giant planets around nearby stars with Hokupa'a-36, Laird Close (University of Arizona) and his collaborators discovered a population of brown dwarfs as binary companions to low-mass stars, changing our view of the formation mechanism of such objects. Low-mass stars and brown dwarfs come in pairs more often than their more massive cousins, and they form much tighter orbiting systems. (For more details see paper by L. Close et al., 2004, ApJ, 587, 407-422.)

Amidst all of this we have also moved into the "extreme adaptive optics" front. Our first Aspen instrument, the Gemini Planet Imager (GPI), is being built by a large consortium led by Bruce Macintosh at Lawrence Livermore National Laboratory. We are fully aware that we are pioneering MCAO and extreme AO (with GPI), and remain keenly aware of the uncertainties and risks.

Beyond the current horizon, and not yet funded for development, is a ground-layer adaptive optics (GLAO) system for Gemini North. This AO system would deliver low-order correction (corresponding to an continuous delivery of the current 20% image quartile) for imaging over fields as large as 7 x 7 arcminutes. To prepare for this instrument's development, we are now conducting a one-year survey on Mauna Kea to characterize the turbulence profile of the lower atmosphere.

The Gemini AO program was developed and designed based on the experience acquired with earlier systems built in several Gemini partner countries (U.S., UK and Canada) and elsewhere in Europe. In particular the PUEO system at the Canada-France-Hawai'i Telescope and the Come-On systems at the European Southern Observatory (ESO) have provided not only useful lessons for designing ALTAIR as a general user system for Gemini, but they also created the know-how and justification for a push-button, point-and-shoot AO system ready to go at a moment's notice. The multi-instrument queue observing approach at Gemini has (as expected) proven to be extremely effective and powerful at integrating AO into normal science operations.

Approach and Strategies

The Gemini AO system suite is broad and comprehensive. We have developed and exploited a Shack-Hartmann system (ALTAIR), curvature sensing systems (Hokupa'a-36, NICI), multi-conjugate adaptive optics (MCAO-CANOPUS), extreme adaptive optics (GPI), and we are exploring ground-layer adaptive optics (GLAO). In all, this is a unique and very competitive program that allows us to be among the most technologically advanced telescopes in the world.

M-Type Stars Favor Closer Relationships than G-Types

Sebastian Daemgen and his collaborators have conducted a survey of 41 nearby, young (300 million years) M stars with ALTAIR/NIRI. Twelve objects are binaries, seven of which are reported for the first time. The binaries seem to occur in tighter systems than G binaries. They exclude the existence of companions with masses greater than ten Jupiter masses at separation of › 40 astronomical units and masses greater than 24 Jupiter masses at more than ten astronomical units. (For more details see paper by S. Daemgen et al., 2007, ApJ, in press.)

To realize the aggressive goals of Gemini's AO program an approach was implemented that required good planning and tight project, risk and budgetary management.

The Project Approach

Gemini does not build instruments. We contract them out and manage the programs. This outsourcing philosophy applies to the AO program as well, with the exception of some subsystems that are very closely related to the telescope and its operation. For example, the laser beam transfer optics design and development were done in house because they involve complex interfaces to the telescopes and require minimal impact on the ongoing science operations,

We contracted ALTAIR to the Herzberg Institute of Astrophysics in Victoria BC, Canada, and the lasers to Coherent Technologies Inc., in Colorado (Coherent Technologies was merged into Lockheed Martin Coherent Technologies (LMCT) at the end of September 2005). For MCAO, we divided the key components into different key packages that were contracted out. For example, the MCAO instrument, CANOPUS, (the functional equivalent of ALTAIR) is being built by EOS Technologies Inc. in Tucson; the Real Time Controller (RTC) is built by the Optical Sciences Company (TOSC) and the MCAO deformable mirrors by CILAS in France. We manage the entire MCAO program at Gemini, but about 85% of the project costs are associated with

Companion Black Hole at Milky Way's Center

The Gemini Hokupa'a AO imaging of the center of the Milky Way Galaxy has produced an important 2000 epoch imaging data set. Several papers have been published using these data. For example, a new, second black hole of 1,300 solar masses was found orbiting around the center of our galaxy. It appears to hold together seven massive stars in the well-know infrared source IRS-13 that are probably the wreckage of a previously much-larger star cluster (For more details see paper by J.-P. Maillard et al., 204, Astronomy & Astrophysics 423, 155-167.)

outside contracts. All contracts and internal work undergo a strict set of reviews at the conceptual, preliminary and critical design phases. This is a well-proven management approach for our current instrumentation program and we are using this for the AO program as well.

Commonalities

In order to avoid "reinventing the wheel," we design and construct common subsystems for both Gemini North and South telescopes whenever possible. At Gemini North, the laser and its enclosure are mounted on the side of the telescope (Figure 1); they are installed on one of the "Nasmyth" platforms at Gemini South. This allows most of the laser beam transfer optics and launch telescopes to be identical. The NIRI dewar design was also re-used for NIFS and GSAOI.

Risk Management

Any AO program, especially an LGS system, has a high degree of risk. At Gemini we manage these risks in two ways. First, we are continuously and periodically identifying and assessing their impact on cost, schedule and technical implications, based on probability of a risk's occurrence and its impact on the project. Second, in the case of more risky items—such as the deformable mirrors and lasers—we have taken a proactive approach by having small demonstration contracts (e.g. for the deformable mirrors (DM) and the LGS wavefront sensors). We also conducted a sodium layer measurement campaign to refine the power requirements of the Gemini South laser.

Five years ago, high-power sodium-line-lasers were based on challenging technologies, and they were big, expensive and dangerous. We endeavored to change this. We enrolled the AO community and industry to manage the risk of new laser technologies by coming up with a simpler, but sophisticated, laser based on solid-state technology. In a successful venture with Coherent Technologies Inc., we took delivery of a 12-watt laser in early 2005 for the Gemini North ALTAIR/LGS system.

The Gemini North laser system is compact (the size of a moderately sized household appliance) and is

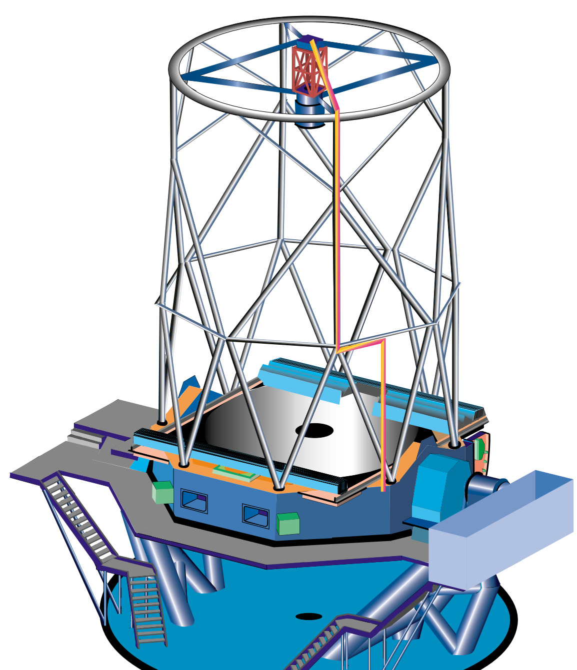


Figure 1.
Gemini telescope structure, highlighting the laser beam transfer optics path (in orange). Identical paths and systems are used for both telescopes. At Gemini South, the laser enclosure structure is mounted on the altitude platform as shown here (large blue rectangular box at right).

mounted at the side of the mirror cell. This location makes it easily accessible and capable of operating at angles from 0 to 90 degrees (during observations it can be used from the zenith down to elevations of 45 degrees above the horizon due to airmass constraints).

To secure the more powerful laser (50-watt) required by MCAO at Gemini South, we funded risk reduction programs with the help of several sources. We raised almost $10 million (US) for sodium laser research and development by effectively leveraging the Gemini investment with virtually all other sodium laser program spending in the world. This initiative involved working with the United States Air Force at the Starfire Optical Range, the National Science Foundation, US, European and Japanese observatories, as well internal programs at laser companies. This effort culminated in the contract that Gemini (and Keck) signed in September, 2005 for the building of two new solid-state lasers by LMCT; a 20-watt laser for Keck I and a 50-watt laser for MCAO at Gemini South. We estimate that the cost per watt diminished by a factor of almost five over the last six years, from about $500,000 per watt in 2000 to about $100,000 per watt in 2006-2007.

Our MCAO management approach and integration plan have been developed based heavily on the lessons learned with the Gemini North system. A thorough structuring of MCAO efforts using a rigorous project management and systems engineering plan, together with the involvement of the entire Gemini engineering team is key to this success and in maintaining our ambitious schedules.

Collaborations

Crucial to our efforts and successes have been our close collaborations with other observatories with strong AO programs. We have engaged in extensive exchanges of expertise and equipment with the W.M. Keck and Subaru observatories, also on Mauna Kea. Our operational efforts are coordinated by exchanging technical expertise on laser maintenance and operation and by sharing our pool of aircraft spotters (who monitor for aircraft while the lasers are propagating). We are working closely to design and install a better aircraft monitoring system, crucial for the effective and smooth science operation of our complex LGS AO systems.

We are also deeply indebted to our colleagues at the Lick Observatory, W.M. Keck Observatory and Starfire Optical Range for their pioneering work in the design, construction and operation of powerful sodium-line lasers for astronomical use. We are the fortunate beneficiaries of an enormous amount of effort and investment that paved the way for the powerful AO systems now in operation at several Mauna Kea observatories and around the world.

Budgetary Considerations

AO facilities obviously cost money, and an overview of costs is useful in understanding the program,

Instrument	Telescope	Cost in U.S. dollars
NIRI	Gemini North	2,500,000
NIFS	Gemini North	2,461,240*
NICI	Gemini South	4,209,300*
GSAOI	Gemini South	3,179,211*
GPI	Gemini South	24,847,533 (with contingency)

Table 1. Cost of Gemini's instruments that use AO (NICI, NIFS and NIRI) or exploit AO exclusively (GSAOI and GPI). Note: asterisk indicates that costs do not include detector cost, nor on-site integration and commissioning.

(see article by Jay Frogel on AO funding in the U.S. starting on page 82 of this issue.) Hokupa'a-36/QUIRC which was used on Gemini North from late 2000 until July, 2002 cost Gemini $50,000 in enabling modifications, although its construction was funded by the NSF and built by the University of Hawai'i.

An overview of the cost of the Gemini instruments that use AO (NICI, NIRI) or exploit AO exclusively

Bow Shock Star Reveals Secrets Near Galactic Center

Tom Geballe and collaborators used ALTAIR/NIRI spectroscopy to show that the star driving the bow shock of IRS-8 (near the center of the Milky Way Galaxy) is an O5-O6 giant or supergiant. It is the hottest, most massive and youngest found in the core of our galaxy. (For more details see paper by T. Geballe et al., 2006, ApJ, in press.)

(NIFS, GSAOI, GPI) is shown in Table 1. The total cost of ALTAIR including its LGS system is about $7.7 million. This is the amount paid by the Gemini partnership. If we include internal design and development cost at HIA for ALTAIR, the total ALTAIR + LGS cost is $12.2 million. In comparison, the total cost of MCAO is about $17.5 million.
Our successful venture with commercial technology firms for procuring the Gemini North lasers is worth emphasizing. The solid-state sodium laser for Gemini North was built by Coherent Technologies Inc. (before it became LMCT) under a fixed price contract. The laser was delivered in February, 2005, first light occurred in May, 2005 and its commissioning as part of the ALTAIR LGS system is near completion as this issue goes to press.

Challenges and Lessons Learned

AO is deeply interconnected with multiple telescope systems. We regularly use ALTAIR to tune the primary mirror at the beginning of the night as its active interfaces are very quick and they do a great job. Most of the Gemini AO systems are interfaced between the telescopes and the instruments, and in principle we can feed all of the instruments mounted on the telescope with an AO beam.

Table 2.
Number of staff per night needed to support LGS science operation at Gemini

Task	*Current LGS Operations*	*Goal for LGS Operations*
Summit crew (SSA, astronomer, eng.)	2.5	2.5
Laser support (technician)	2	1
Aircraft traffic monitoring (spotters)	4	1
Engineering oversight (SW, systems)	2.5	0.5
TOTAL	**11**	5

Although the first images obtained with ALTAIR were very good, two issues immediately stood out. First, we could barely reach the required Strehl ratio of 0.45 in the H band due to a print-through pattern in the Gemini North secondary mirror. This pattern is due to the way the mirror was mounted to the secondary tip-tilt platform. The effect does not prevent high-quality science, but it does limit the potential performance. We expect delivery of a new secondary mirror to be installed at Gemini North in early 2007, and this print-through problem should be eliminated.

Second, the size of the corrected field (defined as the isoplanatic patch, or the distance from the guide source where the full-width-half-maximum drops by 50%) turned out to be disappointingly small: 7-10 arcseconds. Paradoxically, in order to have a large isoplanatic patch, ALTAIR was designed and built to have its deformable mirror (DM) conjugated at an altitude of 6.5 kilometers above Mauna Kea, where the dominant layer of turbulence was thought to be. Clearly this did not work. To correct this, in early 2005 François Rigaut (Gemini) and Jean-Pierre Véran (HIA) designed a simple but clever solution by introducing a lens into the WFS path (called a field lens) that conjugates the DM closer to the ground. The results were immediate and spectacular. ALTAIR now delivers outstanding images over fields as large as 40 arcseconds across, and it is still possible to conjugate to the higher altitude with a remote switch of the lens from the control room.

LGS science operation is complex and challenging, as astronomers have learned with the system at the W.M. Keck Observatory. We are experiencing the same complexities at Gemini. Running an LGS system for AO requires resources and people well beyond our regular operations. In Table 2, we compare the number of people required for an LGS night, as currently deployed, versus our goal for a more streamlined model. Regular night-time operations at Gemini require a minimum of two people at the telescope (one System Support Associate (SSA) who controls all telescope systems including AO, and one astronomer who operates all instruments to execute the science programs in the queue). Some science and engineering staff may be present at the Hilo Base Facility control room for a fraction of the night, and on average this represents 0.5 person per full night. However, the demand on staff for running LGS at night is four to five times higher, with a total of up to 10 or 11 persons involved. Our goal is to reduce this number to five people before the end of 2007, and this will require efforts to make the LGS systems more robust and provide deeper training of the involved staff. The use and deployment of human spotters to monitor local aircraft traffic must also be streamlined.

The current spotter system at Gemini North costs about $1,100 (U.S.) per night. We are working in collaboration with the W.M. Keck and Subaru observatories toward a more automated system where monitoring of the whole Mauna Kea sky down to the horizon could be done with a sophisticated camera system. This could be operated by a single well-trained individual, but in reality it would likely be a team of two. Such a system will need to be approved by the Federal Aviation Administration (FAA) as well. We believe that a centralized system will be more efficient and less costly than the current one.

The Mauna Kea observatories already have a laser traffic control system in place. The pointing and movement of each telescope on the mountain is continuously monitored, following an agreed-upon set of rules, which are; the first telescope on target has priority, whether it is projecting a laser or not. Any subsequent telescope, if projecting a laser, must shutter at this location. If the subsequent telescope is not projecting a laser, then it may proceed at its own risk.

At times, it has been challenging for the observatory and our user community to support the efforts and directions of the Gemini AO program. Some of this resistance may have been driven by conservatism, but probably was due more to a desire to avoid undue risk in order to make sure the telescopes produce good, solid initial science results. Some of our user communities, like the U.S., had little experience with AO, and tended at first to be more resistant to the more ambitious parts of the AO program. We took this as an opportunity, i.e. an invitation to the observatory and to the National Gemini Offices, to be more active at promoting AO and explaining how it works to the broad Gemini user community. We also doubled our efforts to make sure that the integration and commissioning of AO systems would have minimal impact on regular science operations. We believe that we have been successful on both fronts.

Finally, the Gemini Board has always strongly promoted and supported the Gemini AO program, in particular the MCAO initiative. The national agencies made it clear that without the ambitious scope and promising science of our AO program the funding would not have been so generous. In addition, it was clear that these resources for AO could not have been re-directed into other areas such as less risky instruments or projects.

Stellar Evolution in the Bulge of the Andromeda Galaxy

AO ALTAIR/NIRI imaging of the bulge of our neighbor galaxy in Andromeda, M31, by Knut Olsen (CTIO) and his team allowed them to determine the age and the metal abundances of individual stars in the central bulge and inner disk. Reconstructing the star formation history, the team shows that most stars are relatively old, with heavy element composition similar to our Sun. The disk we currently see in M31 has been around for at least 6 billion years, or roughly half the age of the universe. It could have existed relatively undisturbed at even older ages. (For more details see paper by K. Olsen et al., 2006, AJ, 132, 171-289.)

The Gemini AO program is now at a mature stage. As reported in this special issue of *GeminiFocus*, many great science results have already been realized from our commitment to AO. We believe that even more spectacular findings will be revealed over the next several years as a result of the a ten-fold increase in sky coverage provided by the LGS and the dramatic increase in fully-corrected AO fields that will be delivered by MCAO.

Jean-René Roy is Deputy Director and Head of Science at Gemini Observatory and can be reached at: jrroy@gemini.edu

François Rigaut is a senior scientist at Gemini Observatory and can be reached at: frigaut@gemini.edu

Michael Sheehan is Deputy Chief Engineer and Mechanical Engineering Group Manager at Gemini Observatory and can be reached at: msheehan@gemini.edu

by Thomas R. Geballe

IRS-8: Black Sheep of the GC's Massive Stars?

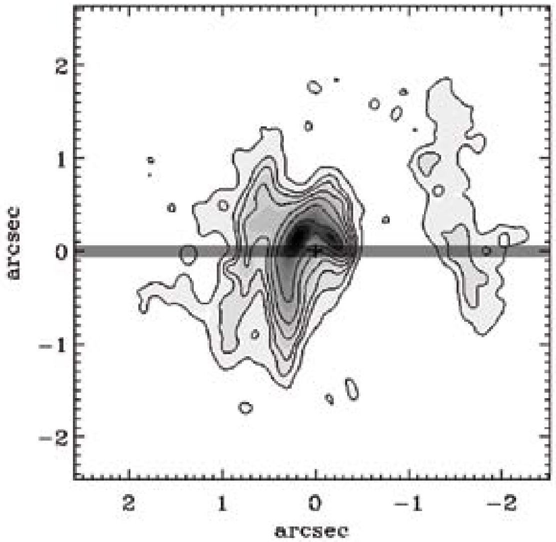
The centers of large galaxies are likely to contain veritable zoos of astronomical objects and phenomena. This is not surprising because gravitational forces, combined with inelastic interactions between objects, ensure that material makes its way into galactic centers. The nuclei of galaxies contain the densest known clusters of stars, probably host large numbers of white dwarfs and neutron stars, often shroud supermassive black holes, and often there are immense clouds of gas and dust within them as well.

Only a limited number of the individual objects in the central few parsecs of distant galaxies can be easily distinguished from our viewpoint, millions of light years away. However, by comparison, the center of our Milky Way Galaxy lies a mere 8,000 parsecs (25,000 light years) from Earth. This is close enough that the detailed distribution of the gas and dust in the central few parsecs has been mapped and astronomers have determined the natures of its brightest stars, which are mostly well resolved from one another. This has been done almost entirely using radio and infrared observations, because dust in the spiral arms between Earth and the center of the Milky Way absorbs all of the visible and ultraviolet radiation emitted in our direction.

Figure 1.
H and K color composite image of the IRS-8 region made at Gemini North with Hokupa'a and QUIRC in 2000.

The advent of adaptive optics on 8- to 10-meter-class telescopes effectively brought infrared astronomers 10 times closer to the Milky Way's center, compared to the views they had before the 1990s. This advance has led to the spectacular precision measurements of the mass of Sgr A*, the supermassive black hole at the very center of our galaxy, using accurate determinations of the orbits of many of the stars within one to two arcseconds (0.1 parsec, about a third of a light-year) of Sgr A*. It also has allowed highly detailed studies of the massive, hot, and windy stars clustered around Sgr A* at slightly larger distances.

Still, many prominent objects in the Galaxy's center have remained unexplained. Until recently, one group of mystery objects was a number of bright and compact mid-infrared sources whose near-infrared spectra showed no stellar photospheric features. Most are embedded in what is known as the "Northern Arm" of gas and dust, an arc-like



structure of mid-infrared and radio continuum radiation extending in a curved path from within 0.2 parsec (more than half a light-year) of the black hole generally northward out to about 1 parsec (3.2 light-years) from it.

Near the northern end of Northern Arm lies one of the brightest of these mystery sources, IRS-8, which was discovered in the mid 1970s by Eric Becklin and Gary Neugebauer. Until it was examined with adaptive optics, IRS-8 appeared to observers as a fuzzy blob between one and two arcseconds in size. Its structure finally was revealed at Gemini North during an early Demonstration Science program of adaptive optics imaging of the region around the Galactic Center in 2000 that used the University of Hawaii's Hokupa'a and QUIRC instruments. The images clearly show bright 2-micron radiation coming from an arc-like structure surrounding a relatively fainter star (Figure 1). The distance from the star to the apex of the bow is about 0.2 arc-seconds or 0.01 parsec. The arc-like structure clearly indicates a bow shock (created when the outflowing gas from a rapidly moving object piles up nearby interstellar material in front and to the sides of it). Fortuitously, it appears in the plane of the sky and its structure is clearly visible from our viewpoint.

In a paper published in 2004, three Gemini staff members—François Rigaut, Jean-René Roy, and the author, working with Bruce Draine at Princeton University—quantitatively showed that a bow shock of the observed size would be a straightforward consequence of the interaction of a dense and high velocity wind from a "typical" massive and windy hot star traversing the moderately dense interstellar gas (with associated dust) in the Northern Arm region. The point-like object seen at the center of the bow shock, now known as IRS-8* was the obvious candidate for the perpetrating star. But no detailed information was available about IRS-8*.

To test if IRS-8* is indeed a hot, massive and windy star, the Gemini team used the adaptive optics system ALTAIR with the near infrared spectrograph NIRI on Gemini North in the summer of 2005 to separate the spectrum of IRS-8* from the much brighter surrounding bow shock (as shown in Figure 2). We then joined forces with

Figure 2. Contour image of the bow shock obtained through a narrow-band 2.3-micron filter, with the point source removed (the cross indicates the location of the star). The location of the 0.1 arcsecond wide NIRI slit is denoted by the narrow shaded rectangle.

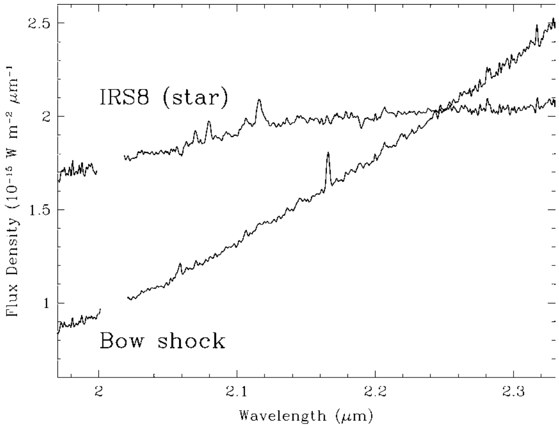


Figure 3. Spectrum of the central star of IRS-8 and of a small portion of the bow shock 0.24 arcsecond east of the star.

Francisco Najarro of the Instituto de Estructura de la Materia in Madrid to interpret the data. The data are shown in Figure 3. IRS-8* has a flat continuum consistent with a hot stellar photosphere reddened by the known extinction to the center of the galaxy, and a number of weak emission and absorption lines. The bow shock, on the other hand, has a steeply rising continuum consistent with warm dust, and recombination lines of helium and hydrogen in emission that originate in ionized interstellar gas.

As demonstrated in Figure 4, the lines seen in IRS-8* are characteristic of a normal O5-O6 giant or supergiant star. Such an object has an effective temperature of roughly 36,000 K, a luminosity more than 350,000 times that of the Sun, and a mass about 45 times that of the Sun. The age of an isolated star with these properties is about 3.5 million years. Optical spectra of stars with these properties show that they also have powerful winds with speeds of 2,500 kilometers (about 1,553 miles)

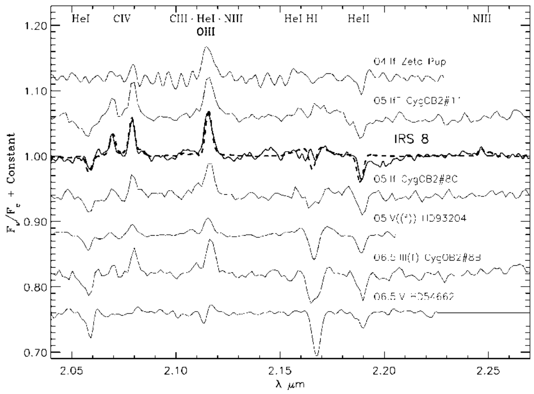


Figure 4. Comparison of the normalized and modeled spectrum of IRS 8 with K-band spectra of other OB stars from Hanson, Conti, and Rieke (1996). The identities of the lines are given at the top of the figure.

per second, and mass loss rates of about 5 to 10 solar masses per year. A wind of this strength from IRS-8* could easily power the observed bow shock.

None of the above properties are unusual for a hot and massive star. However, within the central parsec of our galaxy, all of the other hot stars that have been identified to date are believed to be approximately six million years old. Apparently IRS-8* is much younger. If so, its age conflicts with the generally accepted picture in which all of the massive stars in the central cluster formed in a single burst. IRS-8* differs somewhat from the other massive stars in that its distance from Sgr A*, while only about 1 parsec (3.2 light-years), is considerably greater than theirs. This could be because IRS-8* did not form in the same location as the other massive stars. On the other hand, the direction of IRS-8*'s proper motion, revealed by the orientation of the bow shock, is almost directly away from Sgr A*, about which the other massive stars are roughly centered. That suggests that IRS-8* was once a member of the massive cluster but was ejected. If so, then the age discrepancy remains and is a challenge to our understanding of the history of massive star formation in the center of our galaxy.

If IRS-8* is a close binary system however, exotic evolutionary scenarios involving mass exchange between the star pair could give it the appearance of being a younger star than the other cluster members, even though it is actually the same age. In the near future, the Gemini team intends to obtain more detailed spectra of IRS-8*, which should allow a more accurate determination of the properties of the stellar wind and this also might reveal if the star is single or part of a massive binary system.

This tale is an excellent example of how answering one question leads to another unanticipated question, which itself urgently demands an answer. At the same time, the discovery of the nature of IRS-8 has helped produce a breakthrough in our understanding of the Northern Arm mid-infrared sources. The idea that stars undergoing mass loss within the interstellar medium in the center of our galaxy produce bow shock-like structures of swept-up gas had already been suggested by Angelle Tanner, then a graduate student at UCLA, and her colleagues. That suggestion was based on W.M. Keck Observatory AO observations of another Northern Arm source, IRS-21. Tanner and her team have now used adaptive optics imaging at Keck to infer bow-like morphologies for IRS-21 and several other Northern Arm sources, although in none of these cases is the obvious arc-like structure of IRS-8 seen, nor are the central stars apparent. A few additional examples of the phenomenon have been found elsewhere in the Milky Way's center and it also has been suggested as the explanation for the unusual mid-infrared brightnesses of a large number of lower luminosity sources, which presumably have less energetic winds. Thus, rather than being unique, IRS-8 appears to be the most graphic example of a common phenomenon in the center of the Milky Way Galaxy.

For more information see:

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Thomas R. Geballe is a tenured staff astronomer at Gemini North and can be reached at: tgeballe@gemini.edu

by Knut Olsen

Star-formation Histories of the Bulge and Disk of the Andromeda Galaxy

Behind their façade of invariability, as astronomers often explain, galaxies are in the process of continuous and often violent activity. This statement is decidedly true in the case of the well-known nearby irregular galaxy known as the Large Magellanic Cloud (LMC). At the same time our solar system was forming, the LMC was transitioning from a state of relative slumber to one of frenzied star-formation activity, and possibly creating its characteristic bar structure. Just a few millions of years ago our earliest human ancestors (among the first upright-walking primates on the planet) would have seen a very different LMC from the one we see in the southern hemisphere today. This is because the main engine of star birth in the LMC, the core of the great star-forming complex 30 Doradus, had not yet been born.

By contrast, the Andromeda Galaxy, more famous than the LMC and known to most astronomers simply as M31, tells a very different evolutionary story. Our team (Robert Blum, Andrew Stephens, Tim Davidge, Philip Massey, Steve Strom, François Rigaut, and the author) has used near-infrared images of M31's bulge and inner disk to make a partial map of the star-formation history of M31 in order to help tell its evolutionary story. We have measured, to within a certain precision, the ages and approximate chemical abundances of all past star-formation events in representative portions of M31.

The images were obtained with the ALTAIR adaptive optics system plus the Near-Infrared Imager (NIRI) camera on Gemini North, and with the Hubble Space Telescope's Near Infrared Camera and Multi-Object Spectrograph (NICMOS) instrument. The NIRI+ALTAIR images, as shown in Figure 1, are the deepest near-infrared observations ever obtained of these dense regions in M31. Our measurements show that, to within the limits of our precision, the star formation history of M31's bulge is basically indistinguishable from that of its inner disk. Both regions appear to consist mostly of old (about six billion years or older) stars with chemical abundances similar to that of our Sun, as seen in Figure 2. The uniformity of these stellar populations suggest that most of M31, its prominent bulge and disk included, were built long ago, and that M31 has not actually changed very much for a long time.

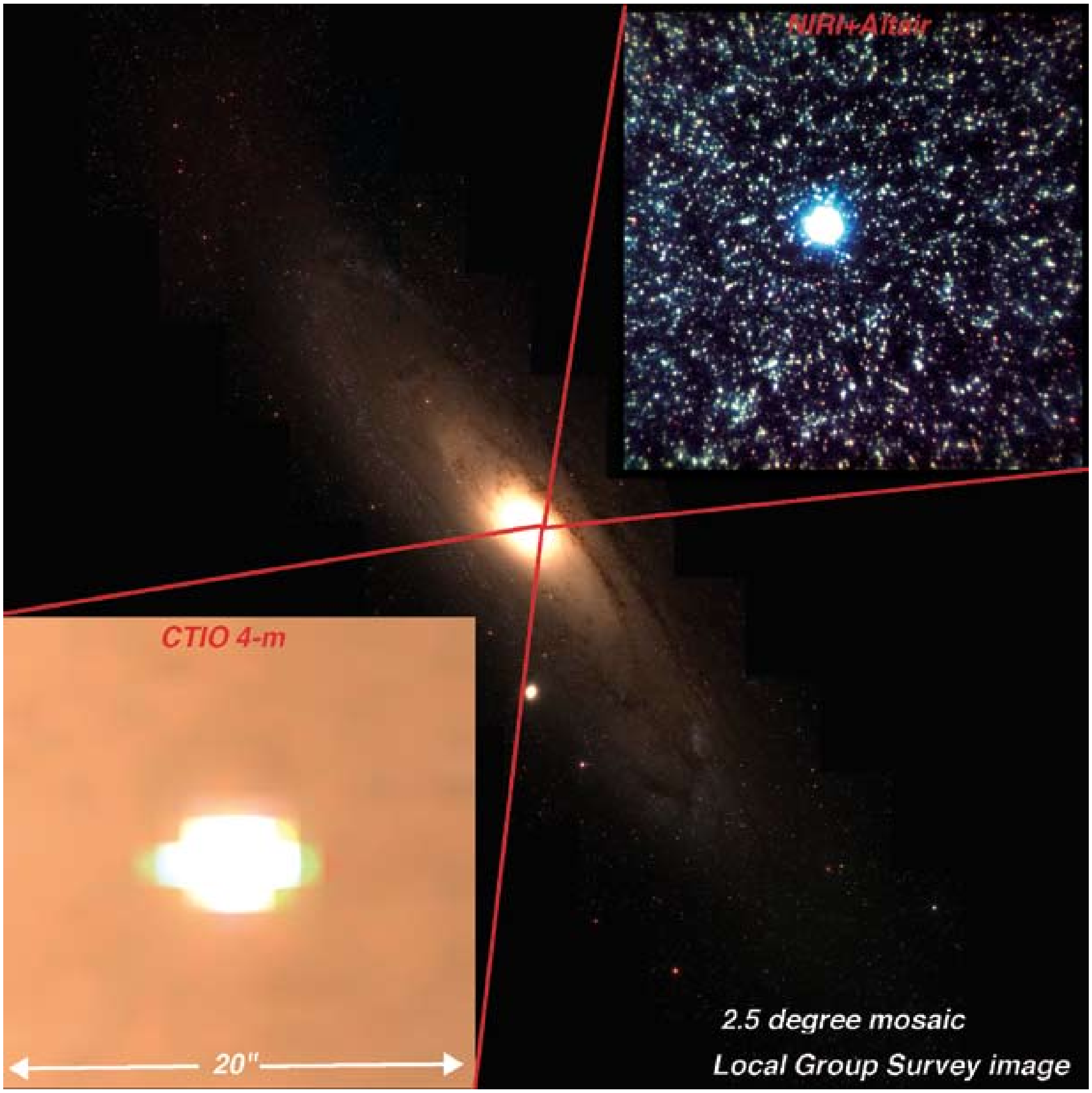

Figure 1. M31, the Andromeda Galaxy. The background image is a mosaic of images taken with the CTIO 4-meter telescope and Mosaic II camera as part of the Local Group Survey; it is 2.5 degrees on a side and has a resolution of ~1 arcsecond, limited by the ground-based seeing. The image at upper right shows one of our NIRI+ALTAIR images of a 20 arcsecond-wide field in the M31 bulge; the adaptive optics correction provides resolution of ~0.1 arcsecond. The bright central source is the Milky Way foreground star used to perform the AO correction. The ten-times higher resolution makes a substantial difference, as seen in the image at lower left, which shows the same bulge field but with the one arcsecond resolution of the CTIO 4-meter image. The only star visible is the bright foreground star, which has an elongated shape because it is saturated.

The star-formation history of a galaxy is recorded in the stars that it contains today. To see how, we need to consider the stellar life cycle. Stars spend the vast majority of their lifetimes burning hydrogen in their cores. During this time, their luminosities and surface temperatures change very little, as these are set by the mass and initial chemical compositions of the stars. The rate at which the core hydrogen burns is strongly dependent on the mass of the star. Massive stars burn hydrogen quickly (making the stars hot and luminous) and low-mass stars are more frugal, consuming their fuel more slowly (resulting in lower luminosity and temperature). Once the hydrogen fuel in the core is exhausted, the pressure exerted by gravity drives the star to evolve quickly, with accompanying large changes in its luminosity and surface temperature.

If we consider only the core hydrogen-burning stars, also known as main sequence stars, then clearly we will only be able to observe the stars if they were born at times no earlier than their hydrogen-burning lifetimes. Assuming that stars form with the same range of initial masses at all times, then a basic way to measure a galaxy's star-formation history is to measure the distribution of stars with the luminosities and temperatures characteristic of the main sequence, and deduce the unique star-formation history needed to produce what we see. Such analysis can also yield the rough chemical compositions of the stars, which affect the observed temperatures and luminosities.

Unfortunately it's currently impossible to observe the faint low-mass main sequence stars that would be needed to probe the complete star-formation history at early times in the dense bulge and disk of a galaxy as distant as M31. There are large numbers of such stars present, but their images overlap and produce a hopeless mess, even at the very highest spatial resolutions available with adaptive optics or from space-based telescopes. In our work, we relied instead on the stars that have evolved away from the main sequence. They are much brighter than main-sequence stars, and hence can be singled out even in dense regions. Because stellar evolution after the main sequence happens very quickly, evolved stars are rare compared to main sequence stars. The M31 bulge and inner disk are so densely populated however that our NIRI+ALTAIR images contain large numbers of such stars. We used them as transitory probes of the much fainter main-sequence stars. However, even with these brighter stars, our study depended critically on the high spatial resolution delivered by NIRI+ALTAIR and HST/NICMOS. In natural ground-based seeing conditions, the large numbers of stars present in M31's dense bulge and inner disk overlap and produce a smear of light, precluding the detection and measurement of any individual stars, as seen in Figure 1.

Given the measured brightnesses of the evolved stars in our fields, we developed a model that included the star-formation history needed to produce the observed brightness distribution, which we illustrate in Figure 2. The use of evolved stars to deduce the star-formation history is more uncertain than for main-sequence stars, so we could only measure the history in fairly coarse bins of age and chemical composition. For example, all stars with the same composition older than about six billion years are indistinguishable with our methods. Nevertheless, we arrived at an interesting result: both the bulge and disk appear dominated by old stars that are as rich in heavy elements as the Sun. This implies intense star formation at early times in both the bulge and disk, which was needed both to produce a large number of stars in a short time and to enrich the chemical abundances up to the solar level.

To appreciate this result more deeply, it's important to understand what we expected to find. In the most-accepted current model of galaxy formation, galaxies begin their growth through the settling of principally hydrogen gas onto dark matter halo "seeds." These (in sum) outweigh the normal (baryonic) matter by about a factor of five. The gas, preserving angular momentum, collapses into disks, within which the cascade of collapse continues as stars form from the gas. The growth of galaxies proceeds through continued accretion of gas from the surroundings and through the violent merger of smaller galaxy-bearing dark matter halos into larger ones.

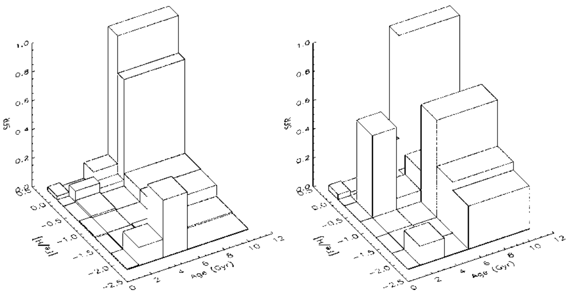

Figure 2. A graphical representation of the star-formation histories of M31's bulge (left) and disk (right). The three axes in the plots are age in billions of years, chemical abundance, and relative star-formation rate. The chemical abundance is expressed as [Fe/H], the logarithmic ratio of the abundance of iron with respect to hydrogen compared to the same ratio in the Sun; hence [Fe/H]=0 is the solar chemical abundance, while [Fe/H]=-2 means that iron is deficient compared to the Sun by a factor of 100. The star-formation rate measures the mass in stars formed in each bin of age and chemical abundance. While there are small differences in detail, both the bulge and the disk star-formation histories are dominated by the oldest stars with roughly solar chemical abundances.

The presence of these two processes means that galaxy disks are continually growing through gas accretion and small mergers, and being disrupted by large mergers. Merging is expected to be very active at early times, but to decrease in frequency at later times, as the number of galaxy fragments available for merging decreases. Thus, the oldest stars—those that originally formed in disks but whose orbits were long ago disrupted by mergers—are expected to be found in the bulges of spiral galaxies and in elliptical galaxies. The galaxy disks we see today should contain mainly stars that formed after the heaviest merger activity ceased.

The random nature of mergers and the differences in the environments that galaxies inhabit means that some disk galaxies will have experienced large mergers late in their lives, making their disks young, while for other galaxies the last merger happened long ago. In the Milky Way Galaxy, the bulge is, as expected, dominated by old stars with chemical abundances similar to the Sun, in agreement with our result for the M31 bulge. The Milky Way also has a thick disk containing stars with ages of 10-12 billion years, which likely marks the time of the last significant merger and suggests a quiet merger history. The star-formation history we measured for the M31 disk is in concordance with a generally

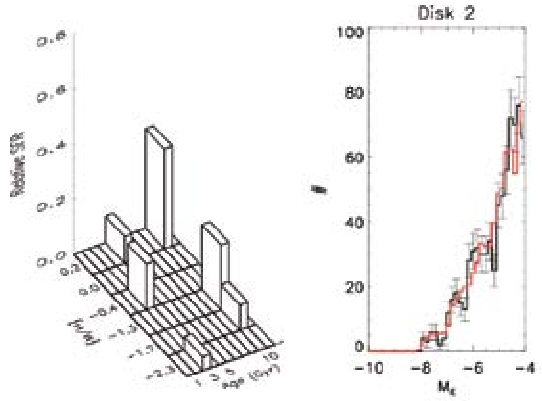

Figure 3. Measuring the star formation history from a distribution of stars. The model star formation history, as in Figure 2, of one of our fields is shown on the left. On the right, the black line with error bars shows the distribution of K-band infrared luminosities of all stars detected in that field; the luminosities are expressed as absolute K-band magnitudes, such that bright stars lie at left, fainter stars at right. The red line shows the K-band luminosity distribution corresponding to the model star formation history on the left, as fit to the data.

quiet merger history within the entire Local Group. The big difference between the Milky Way and M31, however, is that the Milky Way's old thick disk represents only a few percent of the stellar mass of the younger thin disk, whereas in M31, the oldest populations contain the majority of the stellar mass of the disk. This leads to the next question for investigation: why are the Milky Way and M31 disk star-formation histories so different? Stay tuned...

For more information see:

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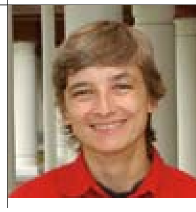
Knut Olsen is an astronomer at NOAO in La Serena Chile and can be reached at: kolsen@ctio.noao.edu



by Inger Jørgensen

MCAO and the Study of Galaxies at z > 1

One of the large ongoing research projects at Gemini is known as the Gemini/HST Galaxy Cluster Project. A bold undertaking that uses imaging from the Hubble Space Telescope and multi-object spectroscopy from both GMOS North and South, this project has the primary goal of mapping the star formation history of galaxy clusters between redshift one and the present.

The most recent results from the project are described in this article, a study of two clusters at redshifts of 0.8 to 0.9. When observing targets at these relatively "modest" distances, the instrument of choice is GMOS, since the diagnostic features used in the project lie in the optical at these redshifts. However, there is a very compelling reason for expanding this project to use MCAO. Namely, by studying clusters in the near-infrared we can reach targets at higher redshifts (and therefore larger distances). In particular, we want to extend the project to redshifts between $z = 1$ to 2 where it appears that large changes in the amount of star formation occurred.

The results presented in this article show that these changes are strongly correlated with galaxy mass. In the intermediate redshift clusters described here, we find that the low-mass galaxies ($M \sim 10^{10.3}\ M_{sun}$) experienced a star-formation episode as recently as $z \sim 1$ (only one billion years prior to their lookback time) while the higher-mass cluster members had their last star formation take place at $z > 1.6$ (> 2.4 billion years before their lookback time). In this article we delve into the details of how that mass dependence was discovered using GMOS spectroscopy in conjunction with HST imaging.

It is known that global parameters for elliptical galaxies are strongly related. The tightest relation is the Fundamental Plane (FP) which is a relation between the size (half-light radius), the surface brightness, and the central velocity dispersion of an elliptical or lenticular galaxy. In short, the FP is a relation between galaxy masses and their mass-to-light (M/L) ratios. As an example, for the nearby Coma cluster, the mass vs. mass-to-light ratio relation is measured to have a slope of 0.24 and a scatter of only 0.09 in log (M/L), illustrating the tight correlation.

Because the scatter of the FP is very low it is a powerful tool for studying how the mass-to-light ratios of the galaxies evolve with redshift. The mass-to-light ratios of observed galaxies reflect the mix of stellar populations within the galaxies and can be related to the star formation history of the galaxy through stellar population models. However, the predictions based on stellar population models are degenerate in metallicities and ages, in the sense that a change in a given parameter may be due to either a change in age or metallicity, or a combination of both. For example, the mass-to-light ratios of galaxies increase with increasing age, but also with increasing metallicity. Only through the use of parameters that have different dependencies on ages and metallicities is it possible to disentangle these two effects.

As part of the Gemini/HST Galaxy Cluster Project we used GMOS North spectroscopy and HST imaging to analyze the FP of two galaxy clusters at redshifts of 0.8 to 0.9. The clusters are part of our sample of 15 rich clusters with z = 0.15 - 1.0 which were selected based on their x-ray luminosity. Figure 1 shows the FP "edge-on" for the two rich clusters RXJ0152.7-1357 at z = 0.835 and RXJ1226.9+3332 at z = 0.892 together with the FP for the Coma cluster. In Figure 2 we show the same FP data, but here it is plotted in terms of mass vs. mass-to-light ratio. Figures 1 and 2 show a larger offset between the Coma cluster FP and the FP for the two z = 0.8 - 0.9 clusters than the result presented in our published paper. This is due to a recalibration of the photometry to rest-frame B band that was performed to obtain a calibration consistent with calibrations use by other research groups. This recalibration does not affect the slope of the FP.

The most important result from the observation and analysis of these two clusters is that both the FP and the mass vs. mass-to-light ratio relation have a significantly steeper slope than found for the Coma cluster. We interpret this difference as a mass dependency of the star formation history.

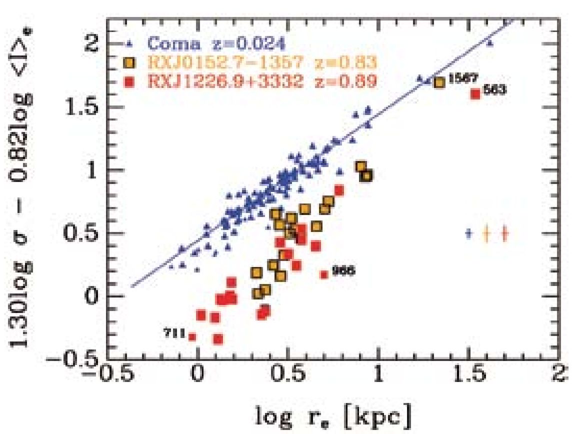


Figure 1.
The Fundamental Plane (FP) for the Coma cluster and the two high-redshift clusters. The solid line is the relation for the Coma cluster. The FP for the two high-redshift clusters is significantly steeper than that found for the Coma cluster.

That is, the fact that the FP of Coma and these two higher-redshift clusters are different implies that galaxies of different masses experienced their last episodes of star formation at different times in the past. From these observations we conclude that the low-mass galaxies in these clusters (masses of $10^{10.3}$ solar masses) experienced a star formation episode as recently as z ~ 1 (only about one billion years prior to their lookback time). Conversely, the galaxies with masses larger than $10^{11.3}$ solar masses had their last star formation episode at z › 1.6. This is a surprising result, but it is consistent to the "downsizing" found by other studies of galaxies at redshifts between about 0.5 and 1.5 (e.g., by the Gemini Deep Deep Survey). Moreover, the effect is predicted from modeling of the properties of nearby E and SO galaxies. The green dashed line on Figure 2 shows such a prediction by Thomas and collaborators who analyzed the strength of absorption lines to establish the star formation histories of the galaxies as a function of the galaxy masses. The prediction agrees surprisingly well with our data at z = 0.8 - 0.9.

Many observational studies support the view that major changes in galaxy evolution take place at redshifts between one and two. Indeed, it seems that sometime during the period corresponding to this redshift interval, a large fraction of the galaxies stopped having significant star formation. Support for this idea comes from several observing projects including the Gemini Deep Deep Survey as well as FP studies at redshifts from 0.5 to 1.2.

To further constrain the galaxy evolution in this critical redshift interval, it is desirable to apply one of the best empirical tools, the FP. However, to do so requires high spatial resolution imaging in the near-infrared (in order to match rest-frame B-band) over a sufficiently large field of view to cover typical cluster angular sizes in a manageable amount of observing time. Further, very deep high signal-to-noise spectroscopy is needed in the near-infrared to measure the spectral properties of the galaxies in the rest-frame optical. The instrumentation for pursuing such observations is just now becoming available as ground based facilities. Multi-conjugate Adaptive Optics (MCAO) will give the high spatial resolution and the field

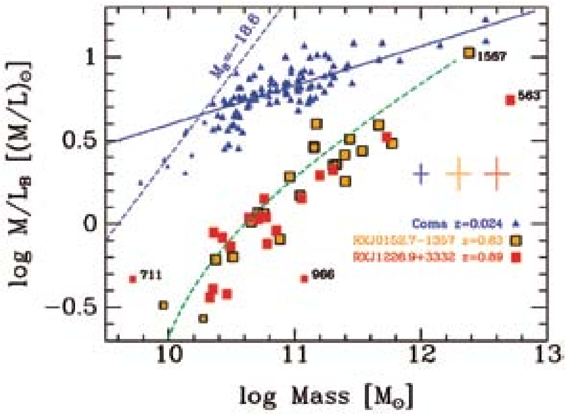


Figure 2. The mass vs. mass-to-light ratio relation for the Coma cluster and the two high redshift clusters. The solid line is the relation for the Coma cluster. The dashed blue line is the magnitude limit for the Coma cluster sample. The green line shows the model prediction discussed in the text.

of view that needed for the imaging. Due to the radial gradients in the spectral properties of E and SO galaxies, it is also desirable to obtain the near-infrared spectroscopy using MCAO to obtain high spatial resolution for these observations. To build significant sample sizes it is preferable to have MCAO feed a multi-object near-infrared spectrograph.

As part of the science justification for MCAO at Gemini, we assessed whether the stability of the point-spread function (PSF) obtainable with MCAO would be sufficient to pursue the determination of two-dimensional surface photometry for high-redshift galaxies needed to establish the FP and to study the morphology for these galaxies. We compared the expected performance of MCAO with classical (non-conjugated) AO for which it is known that PSF variations over the field represent a major challenge to 2-dimensional photometry.

We constructed a simulated galaxy field in which the galaxy sizes and luminosities match observed properties of galaxies at a redshift of 0.6. The galaxy field covers 65 x 65 arcseconds. The galaxies have either $r^{1/4}$ or exponential luminosity profiles, but not combinations of the two types. The results from these simulations are also applicable to higher redshift galaxies, since the typical angular sizes of the galaxies at z = 0.6 and z = 1.5 are 0.6 arcsecond and 0.45 arcsecond, respectively, and these sizes are fully covered by the simulations. Of course, the galaxies at z = 1.5 have fainter apparent magnitudes and in practice longer exposure times are needed than for z = 0.6 galaxies.

We concentrate on two subfields, each 16.25 x 16.25 arcseconds. The central subfield covers from -4 arcseconds to 12.25 arcseconds relative to the optical axis, while the outer subfield covers from 13.65 to 29.9 arcseconds. Thus, the outer-most corner is 42.3 arcseconds from the optical axis. Each subfield contains three stars. Simulations were made for the classical AO (one 17^{th} magnitude NGS and one LGS, both located in the center of the field) and for the baseline MCAO system (five LGSs and three 17^{th} magnitude NGSs). Sky background and noise were added equivalent to an exposure time of six hours in the H band.

Figure 3 shows the simulated fields for the seeing limited case, for classical AO and for MCAO. Figure 4 shows a smaller area of the outer field

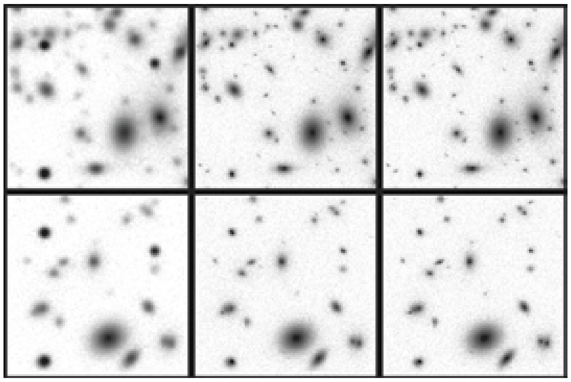


Figure 3. Simulated galaxy field at z = 0.6. Top row: central subfield. Bottom row: outer subfield. Left: seeing-limited case, fwhm = 0.5 arcsecond. Center: classical AO. Right: MCAO. The subfields cover 16.25 x 16.25 arcseconds.

located approximately 30 arcseconds from the optical axis, illustrating the gains in resolution for MCAO compared to classical AO. The subfield contains eight faint galaxies, one close to the bright star in the lower left. All eight galaxies can easily be identified in the MCAO simulation, while in the simulation of classical AO only five of the galaxies can be identified due to the degradation of the PSF far from the optical axis.

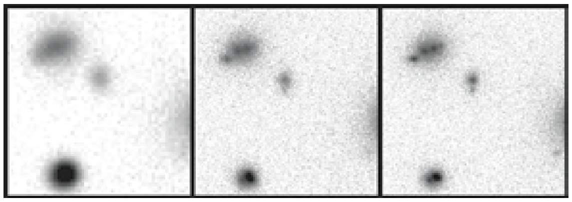


Figure 4. A 7 x 7 arcsecond subfield of the simulation, approximately 30 arcseconds from the optical axis. Left: seeing-limited case. Center: classical AO. Right: MCAO.

The simulated data were processed similarly to what would be done for observational data. The half-light radii, total magnitudes, and mean surface brightnesses were derived by fitting the images

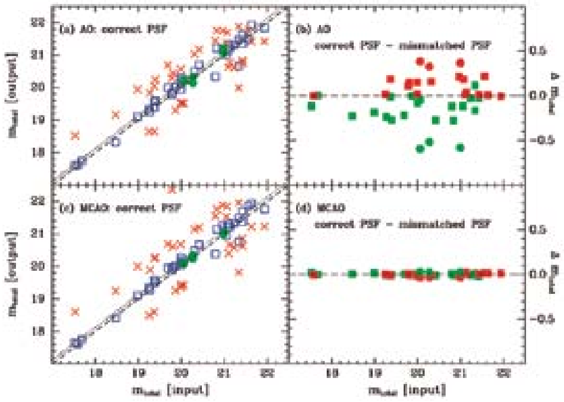


Figure 5. Comparison of input and output total magnitudes for the simulated galaxies and stars. (a) and (c): Results for fits with different profile types. Blue boxes: the galaxies were fitted with the correct profile type. Red crosses: the galaxies were fitted with the incorrect profile type. Green hexagons: results for the stars (b) and (d): The difference between the result when the correct PSF is used and when the mismatched PSF is used. Red: the outer field. Light green: the central field. Boxes: galaxies. Hexagons: stars. See text for details.

with two-dimensional models convolved with a two-dimensional PSF. Each simulated galaxy was fitted twice, with an $r^{1/4}$ and with an exponential profile. The three stars in the fields were fitted by scaling of the constructed PSF. All objects in a field are fitted simultaneously. Pixels containing signal from the objects that are not fitted are omitted from the fit. A residual image with the fitted models subtracted aids in the evaluation of the derived fits. The PSFs were constructed from two or all three stars in each of the simulated fields. There are large PSF variations with distance from the center of the field for the classical AO case. For real observations stars may not be conveniently located in the field. Thus, to illustrate a worst case scenario we also mismatched the PSFs, fitting the outer field using the PSF for the central field and visa versa.

Before discussing the results for the total magnitudes and the half-light radii, it is worth keeping in mind that even for nearby bright galaxies, e.g., galaxies in the Coma Cluster, the typical random uncertainties on the total magnitudes are of the order 0.1 magnitude, while the uncertainties on the half-light radii are about 10%. These uncertainties are due to the large (infinite) angular extent of galaxies which means that the total magnitudes and half-light radii must be measured by fitting models to the brighter parts of the galaxies, or alternatively attempt to estimate the parameters from the asymptotic behavior of the enclosed luminosity as a function of aperture size.

Figures 5 and 6 show the results from the fitting versus the input parameters for the total magnitudes and the half-light radii, respectively. We show the results from fitting the correct profiles (blue boxes) as well as incorrect profiles (red crosses). For real data the best fitting profile would be determined from the χ^2 of the fit. The results for the stars are shown as green hexagons. The one-to-one relations are shown as dashed lines on Figures 5 (a,c) and 6 (a,c). The small offsets between these relations and the location of most of the points are due to the limited size of the PSFs used for the fitting. The PSFs include about 88% of the total signal in the stars. The fitting cannot be done with larger PSFs, due to the low signal-to-noise of the stars. For real observations this is a common problem if the available stars in a field are faint as those included in the present simulations. The small size of the PSFs causes the magnitudes for the galaxies to be determined 0.12 mag too faint, and correspondingly the half-light radii is determined too small. For $r^{1/4}$ and exponential profiles an offset of 0.12 magnitude in the total luminosity corresponds to an offset in the logarithm of the half-light radius of about 0.075. The dotted lines on Figures 5 (a,c) and 6 (a,c) show the expected relations when the systematic effects due to the small PSF size have been taken into account. The derived total magnitudes and half-light radii follow these expected relations, with some scatter, as expected.

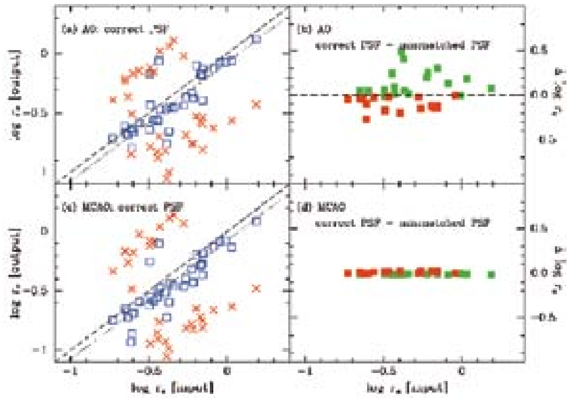


Figure 6. Comparison of input and output half-light radii of the simulated galaxies. Symbols are as in Figure 5. See text for details.

For classical AO, the PSF variation over the field will in general not be fully mapped. It can easily be the case that the PSF is known only from the central NGS. Figures 5 (b,d) and 6 (b,d) show the effect of using the mismatched PSFs. For the classical AO, this results in systematic errors in the total magnitudes of 0.2 - 0.3 magnitude for the galaxies (and 0.4 - 0.5 magnitude for the stars), and systematic errors in the half-light radii of 25 - 50%. For the MCAO simulation no systematic effects result from mismatching the PSFs.

Classical AO can only successfully be used for reliable measurements of half-light radii and total magnitudes of distant galaxies if the PSF is known as a function of position in the field. A field of view of 1 x 1 arcminute at a high Galactic latitude (where we are most likely to pursue studies of high redshift galaxies) will contain less than five stars bright enough to use for reconstruction of the PSF variation over the field. Thus, in most cases we will have insufficient knowledge of the PSF variation over the field of view. The very small variation of the PSF over the field that is the result of the MCAO is essential for the ability to measure half-light radii and total magnitudes of distant galaxies. The presented simulations show that with MCAO we will be able to study galaxy morphology with quantitative methods and derive 2-dimensional surface photometry over the size field of view (1 x 1 arcminute or larger) that is needed in order to study the FP for z › 1 galaxy clusters.

The number of known galaxy clusters at z › 1 is still quite small, but several efforts are underway that are expected to lead to the discovery of additional z › 1 clusters. Among these are the wide-field deep infrared surveys carried out by Spitzer/IRAC and by UKIRT/WFCAM, both of which have follow up spectroscopy scheduled on Gemini to confirm cluster redshifts. Once we have confirmed (equatorial) clusters from these efforts, it will be possible to target those clusters with MCAO for detailed studies of the stellar populations using both the FP and other scaling relations.

The discussion of the Fundamental Plane for RXJ0152.7-1357 and RXJ1226.9+3332 is presented in Jørgensen et al., 2006, ApJ, 639, L9.

The Gemini/HST Galaxy Cluster Project team members are Inger Jørgensen, Marcel Bergmann, Jordi Barr, Kristin Chiboucas, Katy Flint, Roger Davies, David Crampton, Maela Collobert, and Marianne Takamiya. The team includes Gemini staff as well as researchers from the UK, the U.S. and Canada.

The simulations for the MCAO science case were carried out by François Rigaut and Inger Jørgensen.

Inger Jørgensen is Head of Science Operations at Gemini North. She can be reached at: ijorgensen@gemini.edu

by Laird M. Close

Nature's Tiniest Twins

The Strange New Population of Very Low-mass Binaries

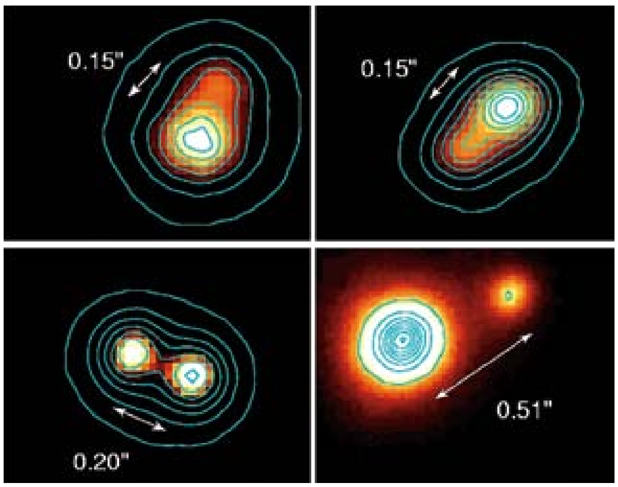


Figure 1. An example of four very low mass (VLM) binaries discovered by Hokupa'a at Gemini. These are H band (1.6 micron) images, and were obtained with AO by guiding directly on the very faint (m_V~20; m_I~16-18) late M stars themselves (Close et al., 2003).

Brown dwarfs are low-mass objects that were definitively detected for the first time just over ten years ago. They were the first self-luminous objects found that were too small to shine like normal stars. Little was known about them at the time, other than that they were too low in mass (less than 72 Jupiter masses) to fuse hydrogen. Our understanding of the formation process of such low-mass objects was mainly speculation: they were too massive to form like planets from a circumstellar disk around a star, yet perhaps they were also too low in mass to form from the collapse of an isolated cloud core.

Today we know that brown dwarfs can have temperatures and radii similar to those of giant extrasolar planets (many have radii similar to that of Jupiter), and so the detailed study of these objects informs our models of extrasolar planets. Indeed, such extrasolar planets are the primary targets of the next generation of high-contrast imagers (such as the Gemini Planet Imager (GPI), and NASA's Terrestrial Planet Finder).

The First Adaptive Optics Survey for Very Low Mass Binaries

As was true in the case of stars, it is mainly through the study of binaries that we can best determine the precise astrophysical properties of brown dwarfs. Recent results from the study of pairs of very low-mass (VLM) stars and brown dwarfs has truly allowed astronomers to better define the nature of these enigmatic objects.

Gemini has played a significant role in this work (an example is discussed in the article by Keivan Stassun starting on page 25 of the June 2006 issue of *GeminiFocus*). After the first few (~4) VLM binaries were discovered by HST (and were defined as L dwarfs with temperatures between 1200 to 2000 K), a large Gemini adaptive optics (AO) program to image › 70 VLM (less than 0.1 solar mass) objects in the field was undertaken. At that time it was impossible to carry out an AO survey of VLM stars/brown dwarfs due to the very faint fluxes (visual magnitudes fainter than 20) of these objects.

However, a combination of the photon-counting wavefront sensor (WFS) in the original Hokupa'a 36 curvature AO system, and Gemini's 8-meter aperture, allowed a uniquely sensitive natural guide star AO survey of very faint VLM stars and brown dwarfs. Indeed, in the course of this survey over 14 new VLM binaries were discovered using Gemini.

The results of this Hokupa'a survey (which, in many ways, was Gemini's first significant moderate-sized AO survey) showed for the first time that VLM binaries were significantly different from just slightly more massive (M0-M4) dwarf binaries in the solar neighborhood. While much more massive G- and early M-star binaries have a range of separations (with a broad peak at about 30-60 astronomical units), we found that the separations between nearby (old) VLM binaries were almost never greater than 16 astronomical units. This was quite a surprise since both M and G star binaries appeared to have roughly similar separations despite a factor of more than two in mass. Similar conclusions were found in HST optical surveys. In addition to being much more tightly bound than $M_{total} > 0.5\ M_{sun}$ binaries (binaries with a total mass of greater than half the mass of the Sun), the Gemini survey found that VLM binaries are less common (with a binary frequency of about 15%) than their higher-mass counterparts (about 30% for M0-M4 binaries over the same separation range).

These results spurred a significant "rush" of similar observations with HST and curvature AO at Gemini, as well as infrared-WFS AO at the European Very Large Telescope. Today more than 80 VLM binaries have been detected. (For a complete list see Nick Siegler's "VLM binary" web page at: http://paperclip.as.arizona.edu/~nsiegler/VLM_binaries/) Hence, the study of VLM binaries, which simply did not exist in 2000, has blossomed into a very active field of astronomy. In lockstep with this rise in observations, theoretical models of brown dwarf binary formation began tackling the difficult problem of how to form these unusual binaries. For example, it was found by using 3-D simulations that forming brown dwarfs binaries was not trivial. In particular, it proved difficult to produce 10-15% of these objects in pairs with detailed formation models. However, the "ejection" class of brown dwarf formation models (where the low mass of brown dwarfs is explained by their being ejected from their stellar nurseries before they can accrete enough matter to become full hydrogen burning stars), first put forth by Reipurth and Clarke in 2001, could explain the lack of "wide" VLM binaries (binaries with large separations) since the ejection process would dissolve any weakly bound systems. However, the velocities and distribution of brown dwarfs do not clearly show the characteristics predicted by some ejection theories.

The trends gleaned from the Gemini/Hokupa'a survey have been confirmed by the increasing number of detected field (old) VLM binaries in the past few years. While there is only one possible wide (two objects separated by 220 astronomical units) VLM binary candidate, all other old field VLM binaries have separations less than 30 astronomical units (and more than 95% have separations less than 15 AU). Moreover, they have a sharp peak in their separation distribution at about four astronomical units and tend to be nearly-equal mass systems (with mass ratio (q) greater than 0.7). Figure 2 shows a graphical description of where old and young VLM binaries can be found in mass vs. separation space.

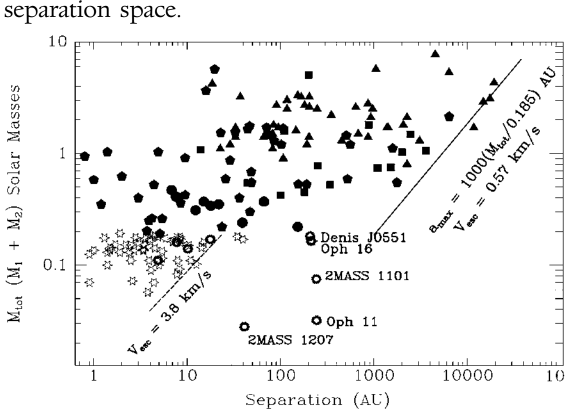


Figure 2. Known stellar-mass binaries (solid symbols), very low mass (VLM) field (old) binaries (open stars), and young VLM binaries (open circles). Note how all the field VLM systems are very tight, yet younger VLM systems (circles) have much wider separations (figure reproduced from Close et al. 2006).

A New Population of Young, Very Wide, VLM Binaries

In certain young associations of stars there have been recent exciting discoveries of very wide, very young, VLM binaries that have no analogs in the older field population of stars. In fact, all wide systems (greater than 50 AU, except for one, Denis 0551) have ages of less than ten million years. They also have nearly equal masses and very low binding energies.

An extreme example of these young, wide, brown dwarf binaries is that of Oph 11AB from the survey taken by Allers et al. (It is also called Oph 162225-240515AB). Each member of this binary has a very low mass (about 17 and 15 Jupiter masses respectively), are about five million years old, and have a very wide separation of 243 astronomical units. This makes Oph 11AB the most weakly bound binary known.

The lack of objects like Oph 11 in the older field studies suggests that wide VLM binaries are only observed when they are young since they have not been dissolved yet by random three-body encounters. Such encounters will steadily increase the binding energy until the VLM system dissolves. Objects like Oph 11 with an escape velocity of less than 0.5 kilometers (0.3 miles) per second will likely become unbound in the future. Also, such brown dwarf binaries cannot form through a disruptive "ejection." Yet, it is also a challenge to understand how an isolated cloud core could fragment into such a widely separated, weakly bound, low-mass binary.

The Future: Laser Guide Star AO

The recent detection of this new young and wide VLM population is challenging our concepts of how brown dwarfs form. How common are these wide young VLM binaries? Young VLM objects are typically more than 100 parsecs (326 light-years) distant, therefore making them too faint to guide on with conventional AO. One solution is to guide on artificial "laser guide stars" projected near the science target. In the very small survey of Close et al. (2006) of the young Ophiuchus association using the Keck Laser Guide Star (LGS) AO system, two very wide binaries were found out of six candidates (~30% binarity). This hints that perhaps such systems are not as rare as once assumed from older field studies. If these systems are common, it implies that very low-mass cores can often fragment into very wide systems.

It is clear that larger surveys (using Gemini's new LGS facility) will be required to better define the binarity of these wide systems. Moreover, such LGS AO surveys will help us determine the minimum mass object produced by fragmentation. Other questions that may be posed: how do the environments of these young associations affect the VLM binary properties? Can wide VLM systems exist in denser star formation regions? Answers to these questions will help shape our concept of how brown dwarfs and planetary-mass objects form and what their fundamental properties are as a function of age, mass, and environment. Whatever the answers, it is likely that AO and Gemini will continue to play an important role.

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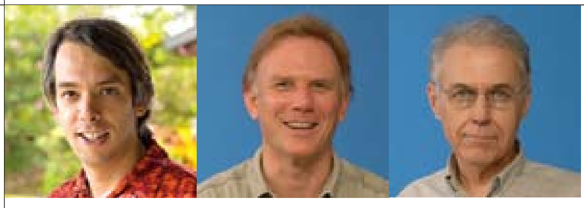
Laird M. Close is an associate professor of astronomy at the University of Arizona and is supported by an NSF CAREER award. He can be reached at: lclose@as.arizona.edu



by Olivier Guyon, David Sanders and Alan Stockton

AO Imaging of Quasar Host Galaxies with Gemini & Subaru

Quasar host galaxies are challenging objects to observe due to their small angular size (a few arcseconds for the closest quasars), small apparent luminosity, and the unfavorable contrast between the galaxy and the quasar. Yet, they hold an important clue to understanding quasar formation and evolution: their study is essential to understand why, how and for how long the central black hole is fed material. Quasars are also relevant to galaxy evolution since their existences may be short-duration events in the long lives of galaxies, possibly triggered by galaxy mergers.

The host galaxies of quasars can be directly imaged with adaptive optics (AO) in the near-infrared for the following reasons:

- most nearby quasars are bright enough (with visual magnitudes of about 16) to serve as natural guide stars;
- the galaxy vs. quasar contrast is most favorable in the near-infrared, where ground-based AO systems operate;
- near-infrared images of a galaxy provide good tracers of stellar mass (less extinction due to absorption of light than in the visible), therefore providing "clean" images for morphological studies of the host galaxies.

Using the Gemini North and Subaru telescopes we have conducted an AO imaging survey of a representative sample of 32 nearby ($z < 0.3$) quasars. They were selected from the Palomar-Green (PG) Bright Quasar Survey (BQS), in order to investigate the properties of quasar host galaxies. Our survey observations spanned from November 2000 to February 2003. The B band absolute magnitudes of our quasar targets span a factor of ~23, from $\sim M_B = -22.12$ (the minimum threshold for "*bona fide* quasars") to $M_B = -25.53$. Three sources have absolute luminosities slightly below the minimum threshold and are traditionally classified as "Seyfert 1 nuclei." Given that this threshold is somewhat arbitrary, we have included these three objects in the current study. Of the sources we selected, 27 were radio quiet and five were radio-loud.

Observations were performed using the 36-actuator curvature adaptive optics system Hokupa'a and the QUIRC near-infrared camera on Gemini North. On the Subaru telescope, the 36-actuator curvature AO system was used with the Infrared Camera and Spectrograph (IRCS) system. Such relatively low-order curvature AO systems are well matched to this project, thanks to their good sensitivity. Each object was observed for typically one hour of open shutter time with a 0.15 arcsecond angular resolution. In order to obtain a homogenous image quality through our sample, fainter quasars were observed under the best

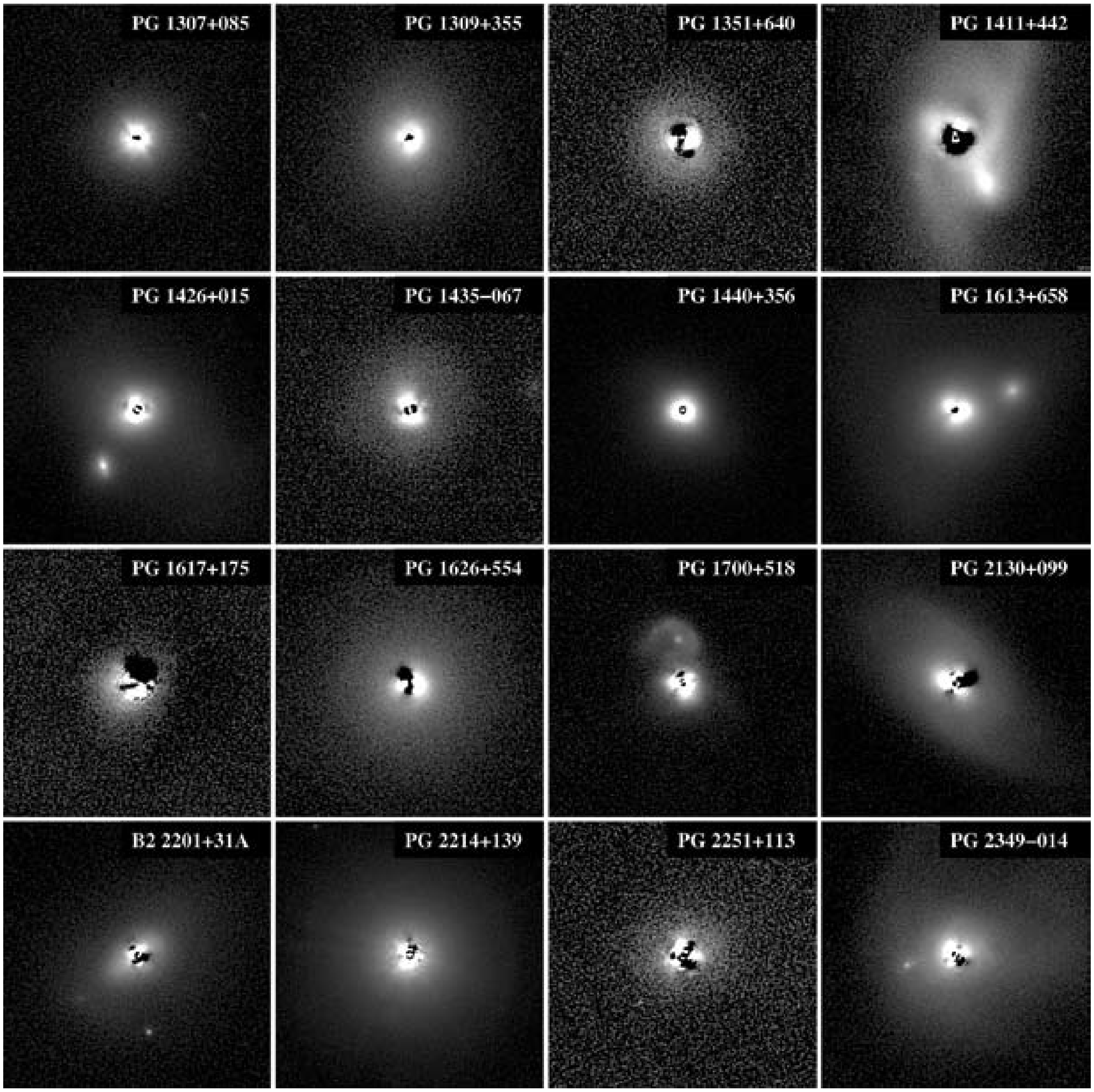


Figure 1. PSF-subtracted images of 16 quasar (QSO) host galaxies (half of our sample). Each image is 10 x 10 arcseconds. Many features can be seen in these sharp (~0.15 arcsecond resolution) AO images: spiral arms (PG2130+099), tidal arms/debris from mergers (PG1411+442, PG1700+518 and others), close companions (PG1426+015 for example). Some host galaxies, usually ellipticals, also appear very smooth. PSF subtraction artifacts can be seen at small radius.

seeing conditions, while easier targets were observed during less-favorable conditions.

The most challenging part of the project was to properly subtract the image of the central quasar to reveal the usually much-fainter host galaxy. Reference stars, in the vicinity of (and with the same visible brightness as) the quasar, were observed at least every 20 minutes. Almost all of our observations were performed with no rotation of the cassegrain instrument port relative to the telescope. Although that resulted in a field rotation on the imaging array, this observation mode greatly helps with point spread function (PSF) subtraction because:

(1) field rotation helps to decouple PSF features from true image features (the PSF does not rotate, the object does);

(2) maintaining the telescope and instrument fixed one to another improves PSF stability.

PSF-subtracted images of half of our sample can be seen in Figure 1.

Analysis

Despite these precautions, variations in the PSF are unavoidable due to changes in atmospheric conditions (wind speed, seeing), and these variations need to be properly understood. While sharp adaptive optics images are extremely sensitive to morphological features (such as spiral arms) in the host galaxies, we found that radial surface brightness profiles are only reliable beyond about one arcsecond. Closer in, PSF subtraction errors are comparable to the host galaxy's surface brightness.

Therefore, our data analysis relies on both visual inspection of the images (looking for morphological features revealed by sharp AO images) and two-dimensional (2-D) surface brightness modeling. Host galaxy types were classified as either "Disk present (Dp)" (hosts for which a large disk is present), "Elliptical (E)", "Bulge + Disk (B+D)" or "Unknown (U)." Among the host galaxies of "Unknown" type are also strongly disturbed host galaxies (almost certainly undergoing major merger activity), and objects with insufficient or ambiguous 2-D fitting information.

We chose to give priority to the features visible in the image rather than the results of the 2-D model fitting, primarily because the 2-D fitting is more prone to errors. For example, if the host galaxy image shows prominent spiral arms, it will be classified as Dp, regardless of the results of the 2-D fitting. If no obvious feature is visible in the images, 2-D fitting is used to classify the host. In most, but not all, cases, both approaches gave consistent results.

Results

Our imaging campaign was generally quite successful, given that we were able to detect and characterize the host type for 28 of our sources. Two host galaxies were too faint to be classified, and our host classification scheme gave ambiguous results for an additional two objects. Our sharp AO images revealed morphological features (spiral arms, bars, tidal arms, close companions) on many of the targets.

Host Types and Photometry

We found no clear evidence that quasar host galaxies are predominantly either spirals or ellipticals, as both types were well represented in our sample. We also found a large number of host galaxies with distributed morphologies, almost certainly due to collisions between two galaxies.

As shown in Figure 2, for the sample of 28 classified hosts, the distribution of host types was 10 (36%) ellipticals ("E"), 3 (11%) bulge+disk ("B+D"), 8 (29%) disk dominated ("Dp"), and 7 (25%) of indeterminate type. Photometry shows that the mean H-band magnitude (and corresponding LH*) of the host galaxies for our sample of quasars was $M_{H(host)}$ = -24.82 (~2.1 LH*), with

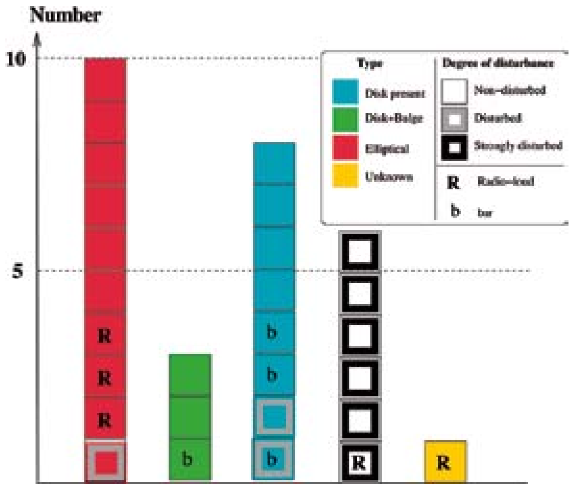


Figure 2. Distribution of "host type", and "degree of disturbance" within each "host type" for 28 out of the 32 objects (28 = 32 - 2 non detections; 2 "bad PSF subtractions").

a range of -23.5 to -26.5 (~0.63 - 10.0 LH*).

There appears to be a strong correlation between host type and the H-band absolute magnitude of the host (see Figure 3). Sub-LH* hosts all have a dominant ("Dp") or strong disk component ("B+D"); 1-2 LH* hosts appear to be equally divided between ellipticals ("E") and disks ("Dp" or "B+D"); >2 LH* hosts are mostly ellipticals ("E"). A similar, but somewhat weaker trend is found for the B-band absolute magnitude of the quasar.

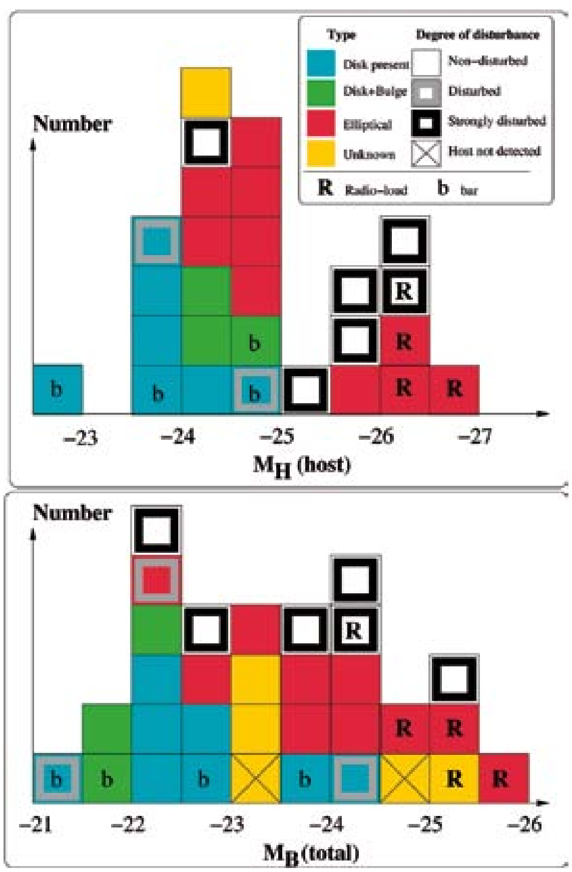


Figure 3. (Top) Distribution of host types as a function of the absolute H-band magnitude of the host. Only those 27 objects with hosts well characterized are included in the histogram.

(Bottom) Distribution of host types as a function of the absolute total B-band magnitude for all 32 quasars. As described in the text, host types (disk present, bulge+disk or elliptical) are not assigned to strongly disturbed hosts.

For the subsample of 18 quasars with redshifts $z < 0.13$, which is the redshift completeness limit corresponding to the M_B(lim)~16.2 limit of the Palomar-Green Bright Quasar Survey, we find no obvious correlation between the absolute magnitude of the quasar, $M_{B(total)}$, and the absolute magnitude of the host galaxy, $M_{H(host)}$ (see Figure 4).

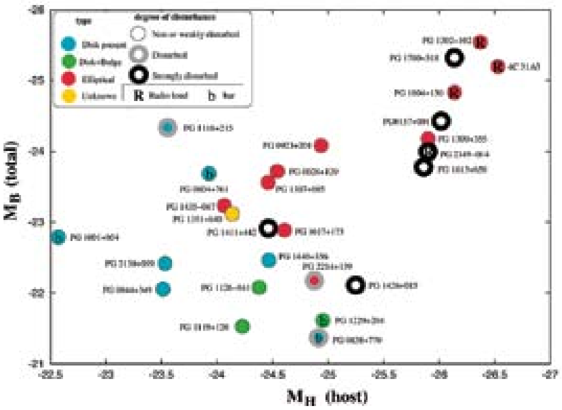


Figure 4. Absolute total B-band magnitude of the quasar versus the absolute H-band magnitude of the quasar host galaxy. Only those 27 objects with hosts detected and characterized are shown (same sub-sample as top panel in Fig. 3). Radio-loud objects are labeled in bold red.

However, at $z > 0.15$, all eight sources in our sample have the largest host luminosities, $M_{H(host)} < -25.5$ (> 4LH*), and the largest quasar luminosities, $M_{B(total)} < -23.8$, suggesting that the most luminous quasars are found among the most luminous hosts.

The mean properties of the hosts of radio-loud quasars (RLQs) are clearly different from the mean properties of the hosts of radio-quiet quasars (RQQs). All five of the RLQs are among the 10 sources in our sample at $z > 0.17$. All five RLQs are among the 10 most luminous QSOs (i.e. $M_B < -24$), and for the four RLQs where we were able to reliably measure the host, all are among the five most luminous hosts (i.e. > 6 LH*), as shown in Figure 4. Three of the five RLQ hosts are classified as ellipticals, one host suffers from a bad PSF, but otherwise shows no visible sign of disk structure, and one is strongly disturbed and cannot be classified. These results are in keeping with the paradigm which suggests that RLQs are preferentially found in giant elliptical hosts with the most luminous quasars.

Strong Evidence for a Connection Between QSOs, Mergers and Ultra-luminous Infrared Galaxies (ULIRGs)

One of the important findings of our survey is that many quasar host galaxies are not peaceful and isolated. A large fraction (nine out of 30) of our detected hosts were classified as either being "disturbed" (three) or "strongly disturbed" (six). Another three objects were found to have strong, well-defined bars, bringing the total fraction of objects with obvious disturbed and/or non-axisymmetric structure up to 40% (12 out of 30). In many cases, close apparent companions are visible within a ten-kiloparsec projected separation. These companions are both more likely and more asymmetric (elongated) around "strongly disturbed" hosts and a statistical argument can therefore be made that they are associated with mergers.

In total, these "disturbed" objects are relatively equally distributed over all values of $M_{H(host)}$, and $M_{B(total)}$, although in detail, the "strongly disturbed" objects are much more likely to be found among the most luminous hosts (i.e. > 2 LH*), with "disturbed" and "well-defined bars" more likely to be associated with less-luminous hosts (i.e., < 2 LH*).

Interest in the infrared properties of quasars has been fueled by suggestions of an evolutionary connection between quasars and ultraluminous infrared galaxies (ULIRGs), where both types of objects represent different phases in the end stage of the merger of two relatively equal-mass gas-rich spirals. Key to such a connection has been the suggestion that those quasars with the strongest mid/far-"infrared excess" emission seem to have "disturbed" hosts, whose properties are somewhat similar to the hosts of "warm" ULIRGs.

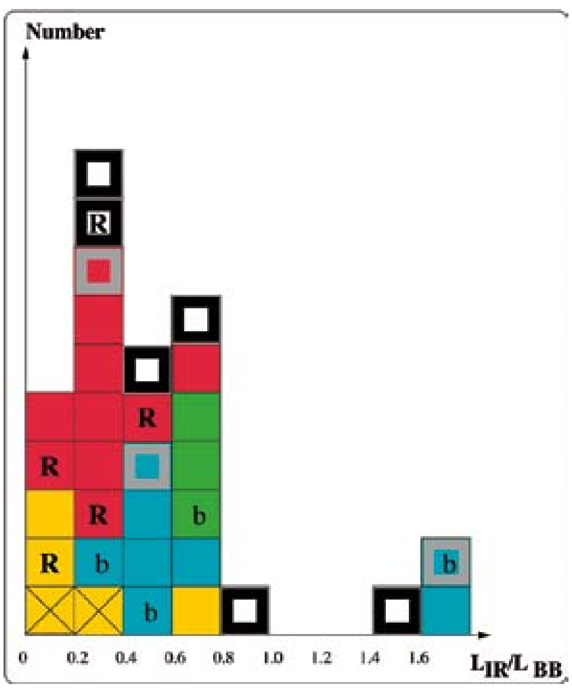


Figure 5. Distribution of host types as a function of "infrared" (LIR) to "optical/UV" (LBB) luminosity ratio of the quasar, where LIR and LBB are meant to represent the total far-infrared luminosity and the luminosity of the "blue-bump" in the spectral energy distributions of quasars. As described in the text, host types (disk present, bulge+disk or elliptical) are not assigned to strongly disturbed hosts.

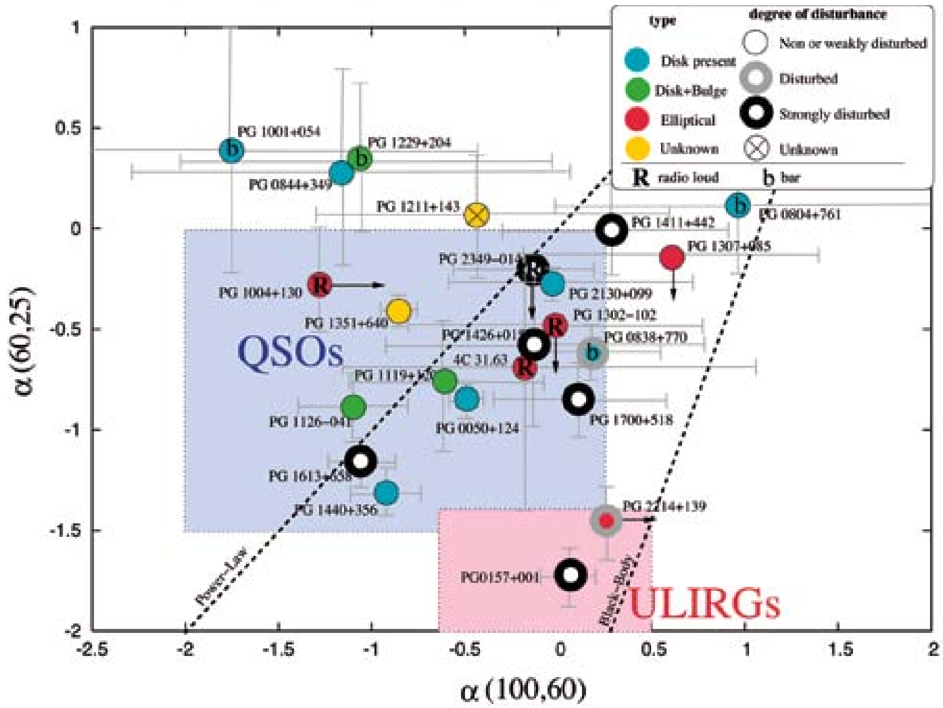


Figure 6. Infrared color-color diagram. Spectral indexes are defined as $\alpha(100,60) = \log(100\ \mu m/f60\ \mu m)/\log(100\ \mu m/60\ \mu m)$ and $\alpha(60,25) = \log(60\ \mu m/f25\ \mu m)/\log(60\ \mu m/25\ \mu m)$. The light blue and light red areas show the approximate empirical locations of quasars (close to a power law SED) and ULIRGs (dominated by thermal black body emission peaking in the mid-infrared). Objects not detected (upper limit) in only one of the three infrared wavelengths are shown, with a black arrow indicating possible positions on this figure. Lines corresponding to power-law emission and single temperature black body emission are also shown. Radio-loud objects are labeled in bold red.

Using previously published photometry, we have quantified for each quasar in our sample the “infrared excess.” For the quasars, “infrared excess” has been defined using the mean radio-to-x-ray spectral energy distributions (SEDs) of quasars. The data have been interpreted to show that the SED is dominated by two thermal emission “bumps.” In addition to the well-known “blue bump” (BB) of optical/ultraviolet emission at wavelengths between about 0.01 - 1.0 micron (thought to be associated with thermal emission from an accretion disk), there also exists an “infrared/submillimeter bump” at wavelengths between about 1.0 - 500 microns, which is interpreted as being primarily due to dust re-radiation of emission from either the accretion disk or from embedded circumnuclear star formation. The “infrared excess” is then defined to be the ratio of luminosities in the two “bumps”, LIR/LBB.

We find a strong correlation between the infrared excess, L_{IR}/L_{BB}, of the quasar and its host type and host degree of disturbance (Figure 5). This ratio is twice as large, on average, in hosts with strong disk components as in elliptical hosts, and likewise is twice as large, on average, in “disturbed” + “strongly disturbed” hosts as in “non-disturbed” hosts. We also find that “disturbed” and “strongly disturbed” hosts have mid/far-infrared colors that place them in a region of the far-infrared color-color plane in between the power-law that is characteristic of the majority of quasars, and the black-body that is characteristic of the majority of ULIRGs (Figure 6).

The paper with the results of this survey appeared in ApJ Suppl.: Guyon, O., Sanders, D. B., Stockton, A., 2006, ApJ Suppl., 166, 89.

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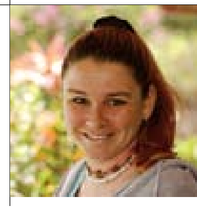
Olivier Guyon is an astronomer at the Subaru Telescope, National Astronomical Observatory of Japan, he can be reached at: guyon@subaru.naoj.org

David B. Sanders is a professor at the Department of Physics & Astronomy and an astronomer at the Institute for Astronomy, University of Hawai'i at Manoa, he can be reached at: sanders@ifa.hawaii.edu

Alan Stockton is an astronomer at the Institute for Astronomy at the University of Hawai'i at Manoa, he can be reached at: stockton@ifa.hawaii.edu



by Tracy Beck

Science Highlights: System Verification of NIFS

NIFS, the near-infrared integral field spectrograph, is the latest addition to Gemini North's facility instrumentation. It is an adaptive optics-fed IFU spectrograph that delivers imaging spectroscopy at R~5000 in the 1 - 2.4 micron region of the spectrum at tenth of an arcsecond spatial resolutions. After a short commissioning period in late 2005 (See Gemini North's Near-Infrared Integral Field Spectrograph (NIFS) on page 60 of this issue for commissioning and characteristics), NIFS was ready for system verification observations of its science performance. Six nights of NIFS science verification time were available in three different modes: (1) NIFS + ALTAIR AO-fed IFU spectroscopy (3 nights), (2) NIFS+ALTAIR coronagraphy (2 nights) and (3) NIFS non-AO seeing-limited observations (1 night). To demonstrate the performance of NIFS in each of these modes, observations of a wide range of science programs were carried out in January and February of 2006, from high-redshift galaxies to young binary stars in nearby star forming regions. This article presents a subset of the science highlights from the NIFS science verification.

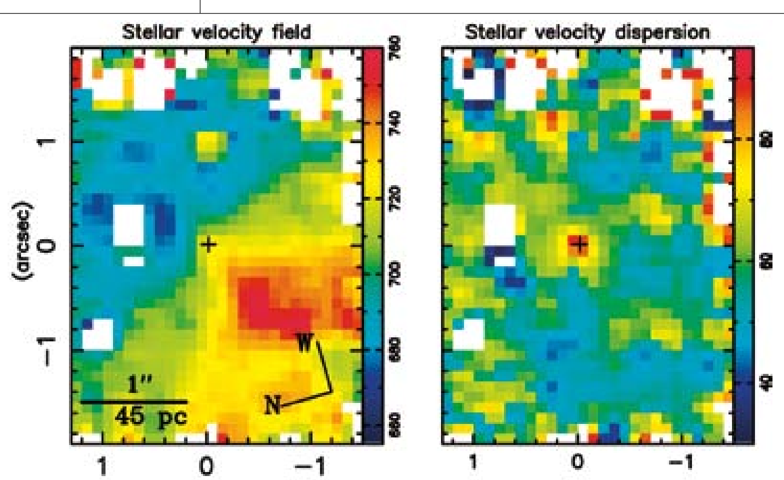


Figure 1. The stellar kinematics of NGC 4051 obtained by direct fit of stellar templates. Left panel: radial velocity field. Right panel: stellar velocity dispersion showing the higher values at the four central pixels.

NIFS Peers into the Nuclei of Active Galaxies

One of the primary science goals of NIFS is to understand the kinematics of the nuclear emitting regions of active galaxies. Particularly, NIFS can measure the velocity kinematics and dispersions in the inner nucleus, resolving the sphere of influence of the central black hole for the closest active galaxies. This allows us to estimate the black hole mass. Additionally, resolved integral field unit (IFU) spectra at high spatial resolution can be used to measure the excitation and dynamics of gas in active galactic nuclei to reveal how radiation and mass outflows interact with the circumnuclear environments.

A team led by Thaisa Storchi-Bergmann (Universidade Federal do Rio Grande do Sul, Brazil) and her graduate student Rogemar Riffel used NIFS in the 2.0- 2.45-micron wavelength region to study the active nucleus of the galaxy NGC 4051. Thaisa chose this object for investigation with NIFS because it was bright, with a resolved nucleus that could be used with the ALTAIR natural guide star system. NGC 4051 has strong line emissions to allow for measurements of gas kinematics, and it is nearby and could be well sampled using 0.1 arcsecond spatial pixels. "The observations allowed us to map the stellar kinematics at a sampling of 4.5 x 4.5 square parsecs," Thaisa explained.

Figure 1 presents the stellar velocity field and velocity dispersion maps of the NGC 4051 nucleus determined by fitting stellar templates to the NIFS data. The right panel shows the stellar radial velocity field with blue and redshifted kinematics centered around the position of the nucleus (which is delineated by a "+" sign). The left panel shows the stellar velocity dispersion, Thaisa states: "The main result is the finding of an increase in the velocity dispersion in the inner four pixels, suggesting that we are resolving the radius of influence of the

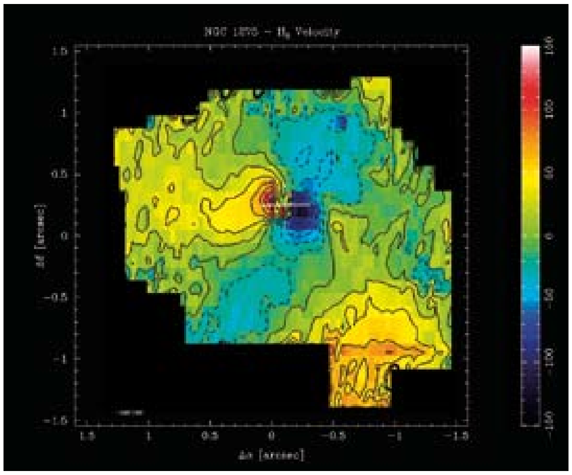


Figure 2. Fitted central velocity of the H_2 1-0 S(1) line in NGC 1275 for velocities in the range +/-150 km/s (scale at right). The white cross locates the continuum peak. The kinematics indicate the presence of a rotating Keplerian disk of molecular hydrogen.

nuclear supermassive black hole. We have calculated a value of 7 x 10^6 solar masses using the measured velocity dispersion in the inner four pixels of 85 kilometers per second (about 53 miles per second) and a radius of 4.5 parsecs (about 15 light-years)."

Further modeling and investigation of the data by Thaisa and her team is underway, but she says, "The results we are getting are great!"

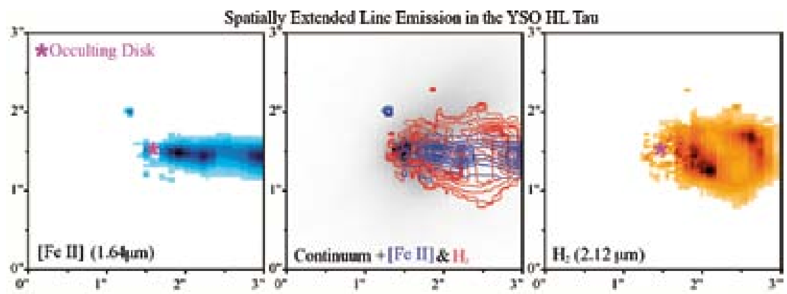
Observations of the active galaxy NGC 1275 (Perseus A) in the K-band 2.0- 2.4-micron region were also carried out during system verification of NIFS+ALTAIR (by principal investigator Peter McGregor of the Research School of Astronomy and Astrophysics, Australian National University). The goal for this work was to investigate the nuclear region of the galaxy and determine the structure and kinematics of the disk of molecular hydrogen around the central black hole. Figure 2 presents the spatially resolved velocities detected by NIFS in 2.12-micron molecular hydrogen emission. "There is a clear velocity shear about the nucleus indicating the presence of a resolved circumnuclear disk on 0.2 arcsecond scales," Peter said. "The kinematics of this H_2 torus imply that about 700 million solar masses of material resides in the central region of NGC 1275. A large fraction of this mass is from the nuclear supermassive black hole in NGC 1275.

NIFS Investigates an Outflow from a Young Star

The coronagraphic mode in NIFS provides the ability to study faint emission in the vicinity of a bright object. For system verification using the 0.2-arcsecond diameter occulting disk, observations of the outflow from the young star HL Tau were carried out (by the author as principal investigator). HL Tau, and a small subset of other young stars, are known to possess well-collimated outflows seen in the emission lines of shock-excited forbidden species (e.g. [Fe II] (ionized iron) at 1.64 microns) and molecular hydrogen (2.12 microns). The NIFS spectra of HL Tau in the H and K band reveals the morphologies of the [Fe II] and H_2 (molecular hydrogen) emission with spatial resolution of about 14 AU (one AU is the distance between Earth and the Sun).

Figure 3 shows images of the iron (left panel) and molecular hydrogen emission (right panel), also included is the position of the 0.2 arcsecond occulting disk used for the study. In the center is an image of the continuum emission in the K band with the contours of [Fe II] (blue) and H_2 (red) overplotted. The iron emission traces shocks in multiple knots along a collimated region of the outflow axis, and the knots of H_2 emission are spatially offset from the jet axis. Analysis of the 3-D datacubes using the kinematics of the material is

Figure 3. NIFS images of the 1.64 micron [Fe II] emission (left) and 2.12 micron H_2 (right) in the inner 200 AU of the young star HL Tau. In the central panel is an image of the continuum emission with overlaid contours of iron and molecular hydrogen emission.



currently underway. The dynamics and morphology of material in the inner 200 AU of HL Tau will be used to infer information about the structure of the accretion envelope of the star and the mechanisms controlling mass inflow and jet collimation.

NIFS Observes Clouds and Surface Features On Titan

For NIFS SV, three proposals were submitted to observe surface features and cloud structures on Saturn's moon, Titan. These three projects were subtly different but complementary, and as a result they were merged into one project for Titan. The primary investigators for the NIFS Titan project were Laurence Trafton (University of Texas), Henry Roe (Lowell Observatory) and Jeremy Bailey (Macquarie University, Australia).

Observations with NIFS allow for resolved imaging spectroscopy of the 0.9-arcsecond spatial extent of Titan's disk. Trafton and his team are using NIFS K-band spectra to investigate phenomena related to low-altitude weather patterns and dynamics in Titan's atmosphere using narrow absorption lines of molecular dimers (van der Waals-bound associations of two molecules). Jeremy Bailey and collaborators acquired data in the J, H, and K infrared bands where the spectra are dominated by methane absorption in Titan's atmosphere. "The different wavelengths probe different levels in the atmosphere from the surface to the stratospheric photochemical haze. We are using the data to study the structure and distribution of the transient methane clouds," Jeremy stated.

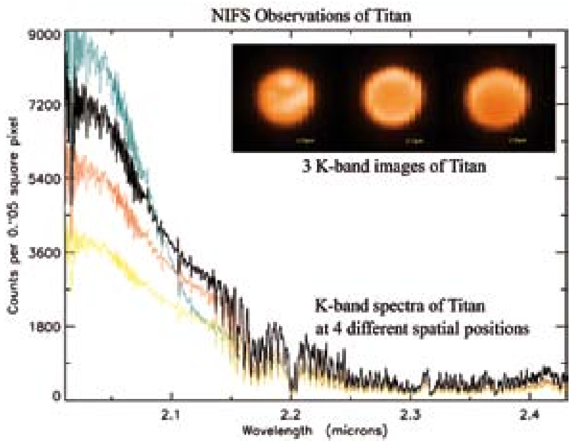


Figure 4. Four 2.0- to 2.4-micron spectra of Titan at different locations over its disk are plotted with an inset of three K-band images constructed at wavelengths of 2.03, 2.12 and 2.30 microns.

Previous imaging observations of Titan's disk allowed only for classification of the methane hazes as "trophospheric" or "stratospheric," and precise altitudes were not possible to determine. Henry Roe and his team used NIFS to monitor weather patterns from K-band spectra of Titan spread out over three nights. Their team has also observed Titan using Gemini with NIRI+ALTAIR imaging. Henry says, "The big advance of using NIFS over NIRI is that the spectroscopy allows us to get much more precise cloud altitudes, e.g., 10 +/- 1 kilometers (about six miles). It's a huge advance to be able to narrow down the altitude of a cloud to a few kilometers, instead of nearly 50 kilometers (about 30 miles). This is the key to distinguishing formation and dissipation mechanisms".

Figure 4 presents the K-band spectra of Titan at four different locations, as well as images of Titan at different K-band wavelengths. Shortward of 2.1 microns, the spectra and images reveal surface features on Titan in a region where the atmosphere is not completely opaque. Trafton points out that "the main atmospheric opacity is the pressure-induced absorption of H_2-N_2, which peaks near the H_2 S(1) line at 2.121 microns. Titan's ground is not visible at longer wavelengths due both to pressure-induced and methane absorption."

Images of Titan's disk at 2.12 and 2.30 microns show atmospheric haze in different levels of the atmosphere. Trafton and the team presented their initial NIFS results on their search for the H_2-N_2 dimer in Titan's atmosphere at the October, 2006 meeting of the Division of Planetary Sciences held in Pasadena, CA.

Special thanks to Peter McGregor of the Research School of Astronomy and Astrophysics, Australian National University, for his input on this article.

Tracy Beck is a Gemini science fellow at Gemini North and can be reached at: tbeck@gemini.edu

by Mark Chun

Hokupa'a: Gemini's First Adaptive Optics System

A driving mission for the Gemini telescopes has always been to deliver the finest image quality possible from each site. Adaptive optics and diffraction-limited images were an integral part of Gemini's vision from the start, and early in the design process planners recognized that all aspects of the observatory had to be tuned in order to achieve the ultimate resolution possible with the telescopes. The seeds of a unique collaboration between Gemini and the University of Hawaii's Institute for Astronomy (IfA) sprang from these early planning efforts, and led to the use of IfA's adaptive optics system Hokupa'a and the QUIRC near-infrared camera system on Gemini North.

From the observatory's initial conception, subsystems were designed to control the telescope optics, the telescope structure, the dome environment, and the instruments to ensure the best possible image quality. Each of the subsystems had to be held to an accounting system that tracked all possible sources of image quality degradation. Even with this planning, few could imagine that diffraction-limited imaging would be possible during the early commissioning of the Gemini North telescope. With the many challenges facing the young observatory, major subsystems that are now taken for granted, such as the primary mirror active control, were not fully available. Function rather than performance was the priority at that time.

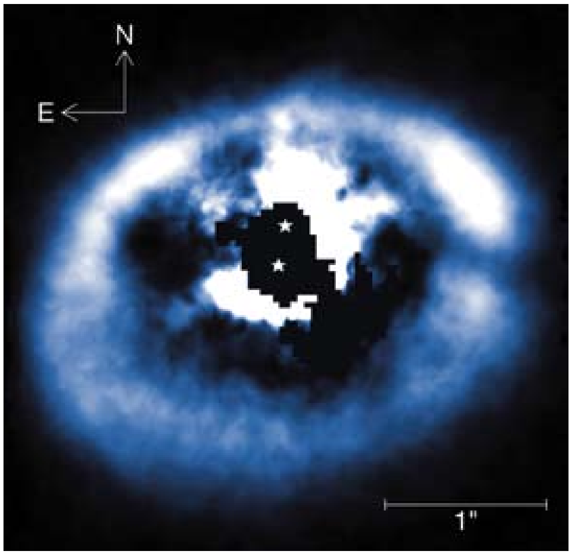


Figure 1. This is a Hokupa'a/ Gemini image of GG Tau and its circumbinary disk. GG Tau is a young binary star system (separation of 0.25 arcsecond shown by the two star symbols) with a disk of circumstellar material. The morphology of the circumstellar material gives clues to the processes during star and planet formation. Image courtesy of Dan Potter (University of Arizona) and the IfA AO group.

Amazingly, after some fortuitous meetings, a coming together of a number of factions, (and more than a little hard work), diffraction-limited images were achieved on the Gemini North telescope prior to its dedication in 1999 and provided to its users during its first two years of community science access (2000B-2002A). This achievement is even more remarkable when you consider that Hokupa'a and the near-infrared camera QUIRC was delivered to Gemini only a month prior to the telescope's dedication. The unique collaboration between IfA and Gemini made this accomplishment possible.

The IfA Hokupa'a team was led by Malcolm Northcott and Elon (Buzz) Graves and was an adaptive optics system based on curvature wavefront sensor. This technique was pioneered by François Roddier, a recognized pioneer in astronomical adaptive optics systems. The name Hokupa'a stems from the Hawaiian word for Polaris, the star that does not move. The instrument's creation was the culmination of several years of development by the team and was previously used on telescopes such as the University of Hawai'i 2.2-meter and Canada-France-Hawai'i telescopes on Mauna Kea. The system was a research instrument based on a wavefront sensor that measures the optical wavefront's second-derivative (curvature) and a deformable curvature mirror with only 36 correcting elements. While not designed for Gemini's large 8-meter aperture, Hokupa'a routinely provided near diffraction-limited images on the Gemini North telescope. Importantly, the instrument coupled with the large aperture of the Gemini telescope, provided an adaptive optics system that worked with guide stars fainter than previously achieved anywhere else.

In the early commissioning and first four semesters of community access to the Gemini North telescope, Hokupa'a amassed a number of outstanding achievements. In addition to providing diffraction-limited images on a newly commissioned telescope for its dedication, it was an extremely productive scientific instrument. Hokupa'a still has the distinction of producing the most papers per hour of observation of any instrument offered at the Gemini Observatory. Its 40 peer-reviewed science papers span the full breadth of astronomical topics, including low-mass stars, circumstellar disks, and the structure and nature of objects at and around the center of the Milky Way Galaxy. Also, in the era before laser guide star adaptive optics systems became functional on large telescopes, Hokupa'a on Gemini made significant contributions to extragalactic astronomy. The first Gemini queue observations were made with Hokupa'a and, in fact, all of the four Hokupa'a/Gemini semesters were entirely queue-scheduled.

What makes these achievements so remarkable is that nature is a wonderful, but unforgiving accountant. All unaccounted-for errors manifest themselves in the final image, and with such a young observatory it is amazing (1) that the observatory subsystems worked sufficiently well at the early stages to put diffraction-limited images within reach, and (2) that Hokupa'a, a system not originally conceived to work on an 8-meter telescope, quickly achieved and maintained such a high level of consistent science productivity. These achievements clearly reflect the hard work and talent of those who took part in the collaboration. Hokupa'a, as the forerunner for the facility adaptive optics systems on Gemini, set a high standard for such systems, and indeed all instruments, to follow. However, what I will remember most about Hokupa'a is that it was a remarkable coming together of a group of talented people that together fought and overcame the teething pains of a young telescope.

Mark Chun is an assistant astronomer at the University of Hawai'i. He is a member of the team building NICI for Gemini South and the PI for the GLAO Site testing on Mauna Kea for Gemini North. He can be reached at: mchun@ifa.hawaii.edu.


by Jean-Pierre Véran
and Chad Trujillo

Adaptive Optics With ALTAIR

ALTAIR, the Gemini North facility adaptive optics system, has been in full science operation since early 2004. In its original version, ALTAIR used the light of a natural guide star (NGS) to sense atmospheric turbulence and drive a deformable mirror (DM) to compensate for the distortions to starlight imparted by this turbulence. Because this guide star has to be bright (red magnitude, (m_R)) and fairly close to the science target of interest, ALTAIR's sky coverage is quite limited. Recently, two major upgrades have been implemented that greatly relieve this limitation.

The first upgrade is the addition of a field lens at the ALTAIR entrance focus. This lens optically re-conjugates the DM to the ground level. In the initial design, the DM was conjugated to 6.5 kilometers (about four miles) above the ground level. However, it turned out that, on average, the turbulence at Mauna Kea is closer to the ground than expected, so that a ground-level conjugation is more optimal. With the field lens, a significant increase in the size of the corrected field was demonstrated in most conditions. This not only enables the acquisition of wider fields, but also increases the sky coverage, since the guide star can be farther away to achieve the same level of correction. A science-grade field lens has now been manufactured and will be implemented soon.

The second upgrade is the installation of a sodium laser on the Gemini North telescope. The 12-watt laser beam is generated inside an enclosure attached to the telescope structure. From there the beam is carried to the secondary mirror by a complex set of mirrors (called the "beam transfer optics,") and launched by a 50-centimeter (20-inch) off-axis telescope (called the "launch telescope") that lies just behind the secondary mirror. The laser light is tuned to a wavelength of

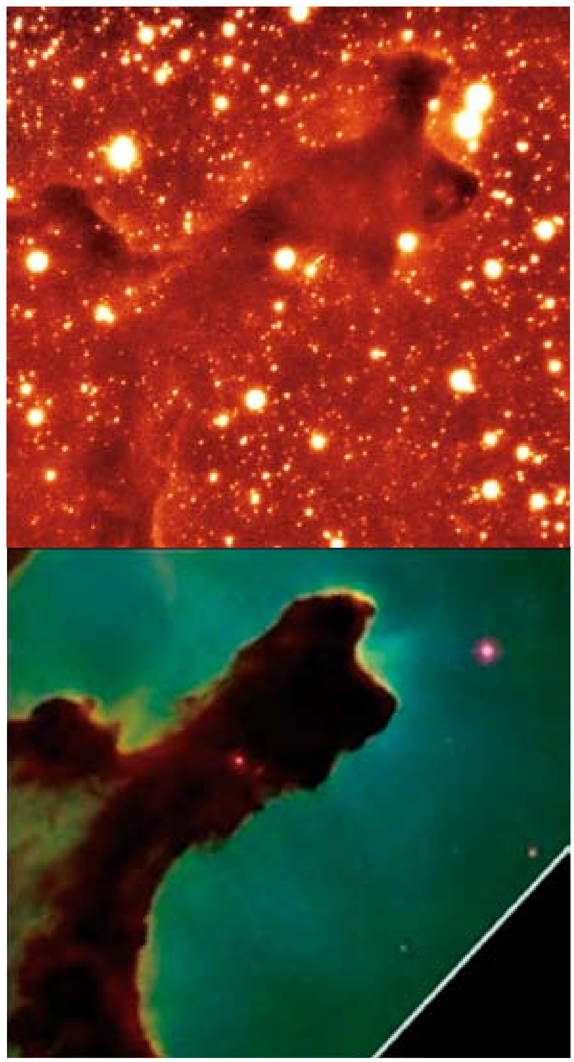


Figure 1. The Eagle Nebula (ALTAIR/LGS K-band, at top) shows that using the LGS system in the near-infrared allows one to probe dusty regions that are largely opaque in the visible (HST, bottom). ALTAIR/LGS resolution in the near-infrared compares favorably to HST resolution in the visible.

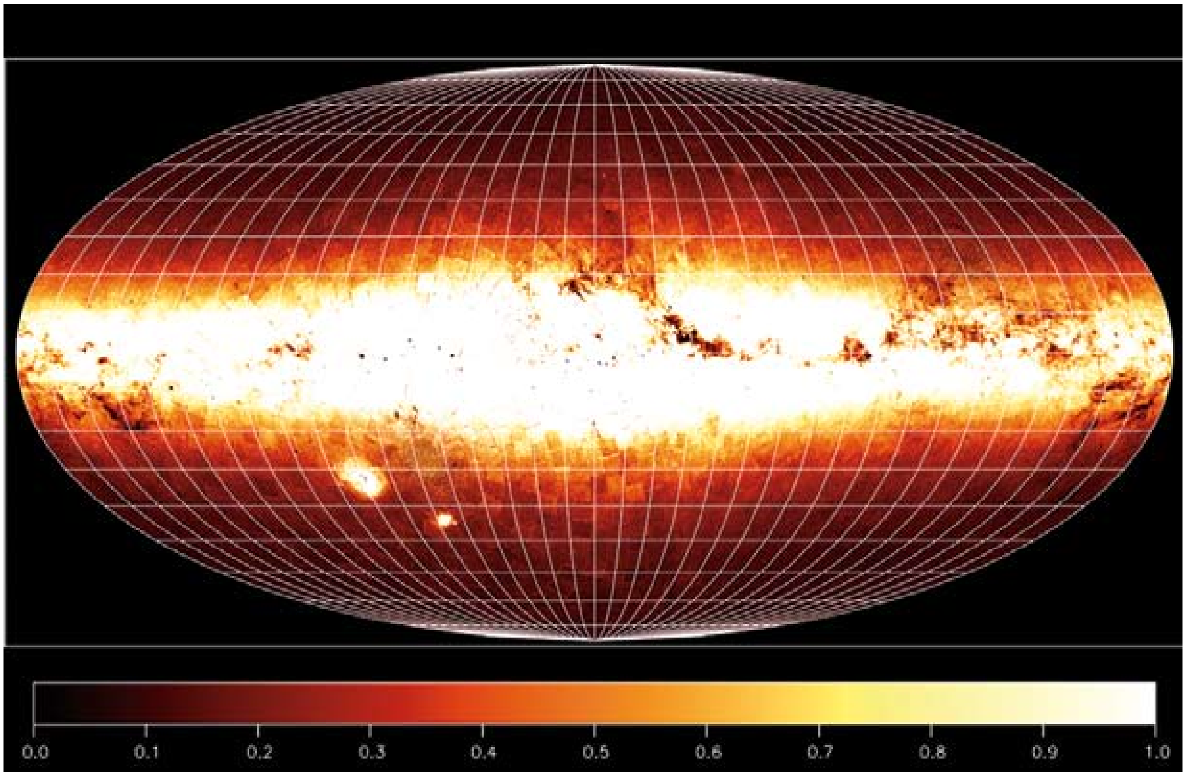


Figure 2. LGS sky coverage is not only a function of galactic latitude, as shown in the above map of sky coverage for m_R = 17 tip-tilt guide stars. White regions correspond to areas of 100% sky coverage and black regions are 0% sky coverage. Note that this plot was generated from the USNO-A2.0 catalog, thus there are plate-to-plate photometric calibration variations in the southern hemisphere as well as sampling errors near the celestial poles.

589 nanometers, which corresponds to one of the excitation lines of the sodium atom. These atoms are plentiful in a thin layer of the mesosphere approximately 90 kilometers (about 55 miles) above ground level. They are scattered in the atmosphere by the disintegration of meteors entering the Earth's upper atmosphere. The laser beam excites these sodium atoms above the telescope and creates an artificial beacon roughly equivalent to a 9th magnitude (visual) star. This excited sodium "star" is called a laser guide star (LGS). The advantage of a laser guide star is, of course, that it can be created at any location in the sky. This does not completely solve the sky coverage problem however, because the LGS is unable to provide any tip-tilt information (data that allows the mirror to be tipped or tilted to correct for image motion). Therefore a natural guide star is still needed, but since it is only used to sense for tip-tilt, it can be much fainter (as dim as 18th magnitude ($m_R < 18$) and farther away (up to 25 arcseconds away from the science target). Overall, it is estimated that the sky coverage is increased by a factor of ten in LGS mode, compared to the NGS mode (Figure 2).

The LGS mode does complicate operations. Beside the technical feat of creating such a powerful laser beam at exactly 589 nanometers, each position in the sky where the LGS is to be created must be cleared with the U.S. Space Command to avoid any risk of damaging sensitive instruments on a satellite overhead. Also, when the laser beam is active, a pair of human spotters is continuously watching the sky for cirrus clouds (which would increase the light backscattered towards the ground) and for airplanes (the Federal Aviation Administration requires this so that the laser doesn't potentially interfere or distract airline pilots). And finally, a computer-controlled system monitors the pointing of all the telescopes on Mauna Kea and shutters the laser in case of a "collision," that is when the laser beam intercepts the line of sight of another telescope. In spite of these potential restrictions, the operation remains quite smooth: satellite or plane conflicts have been essentially non-existent so far, and "collisions" with other telescopes have been limited to between one and three per night, with an average duration of 15 minutes each.

The LGS laser facility was commissioned in spring of 2005. The first LGS light delivered to ALTAIR was in June, 2005. The original ALTAIR had an LGS wavefront sensor (WFS) but an NGS WFS was added to measure tip-tilt from the NGS in LGS mode. This was a major retrofit. Technical commissioning proceeded through the summer of 2005, but then had to be interrupted because it turned out that the laser launch telescope had been

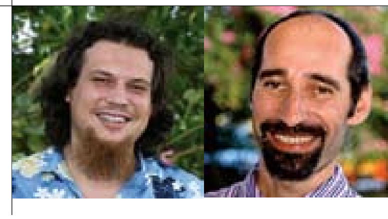
Figure 3. Gemini North laser propagation during LGS commissioning in October, 2006. The full-moon provides illumination inside the dome.

damaged and was producing too large an LGS. The launch telescope was fixed and re-installed in spring of 2006 so commissioning could proceed.

The control system of ALTAIR LGS is very complex. It has many different opto-mechanical devices inside and outside the system that are in constant interaction with each other through no fewer than seven feedback loops. Each loop needs to be carefully optimized so that the system can deliver the best image quality in all conditions and be fully automated. At the time of this writing the technical commissioning of ALTAIR LGS is almost complete, and is expected to move into the system verification phase shortly thereafter. Performance characterization is still an ongoing process. The performance will be a function of the brightness of the tip-tilt NGS and its distance from the science target. High Strehl performance is expected to be obtained for tip-tilt NGSs brighter than $m_R = 15$ and within 15 arcseconds of the science targets. Under these conditions, the Strehl ratio is expected to be about 75% of that seen in NGS mode; which represents 20% in H band and up to 35% in the K band. The Strehl ratio in LGS mode is less than the Strehl ratio in NGS mode because the LGS is at a finite distance and thus only probes a cone of turbulence that originates from the LGS. A natural guide star would probe the full cylinder of turbulence that would distort the science image. When the tip-tilt NGS is fainter than $m_R = 15$ or further than 15 arcseconds in angular distance from the science target, only low Strehl ratios will be achieved, ranging from a few percent in the J band to up to 10% in H and K. Again, a full performance optimization and characterization will be carried out at the end of the commissioning phase. In the meantime, some excellent science images have already been obtained, including the one shown in figure 1.

Jean-Pierre Véran is Head of Adaptive Optics at the Herzberg Institute of Astrophysics in Victoria British Columbia, Canada. He can be reached at: Jean-Pierre.Veran@nrc-cnrc.gc.ca

Chad Trujillo is an assistant astronomer at the Gemini Observatory and can be reached at: ctrujillo@gemini.edu



by Damien Gratadour
and François Rigaut

Gemini's Multi-Conjugate Adaptive Optics System

Since the early 1990s the emergence of adaptive optics systems has allowed large telescopes (8- to 10-meter-class) to scan both northern and southern skies with the sharpest possible views in the near-infrared. However, the scientific exploitation of such systems is still limited to small regions (10 to 20 arcseconds) around a relatively bright reference source (with visual magnitudes brighter than about 17). Now, imagine an enhanced adaptive optics system that covers a much larger fraction of the sky and provides uniform image compensation over fields significantly larger than the natural isoplanatic patch. This is the aim of the multi-conjugate adaptive optics (MCAO) project that is nearing completion at Gemini South.

The advent of MCAO is recent. New adaptive optics system designs were introduced at the beginning of the 21st century to mitigate both the limited sky coverage and the limited field of view. Initially, laser guide star systems (still limited by the so-called "cone effect") were implemented on large telescopes (Lick Observatory, Starfire, Gemini, and Keck for instance). More recently, MCAO emerged, with only a few systems currently under development (Gemini, the Very Large Telescope, and the Large Binocular Telescope, for example). The evolution of adaptive optics systems, as well as a comparative case for MCAO are presented in "From Adaptive Optics to Multi-conjugate Adaptive Optics" starting on page 7 of this special issue of *GeminiFocus*.

Intensive end-to-end adaptive optics simulations have been completed to prove the concept of MCAO and select the most efficient possible configuration. This work has led to the final design of the Gemini MCAO system.

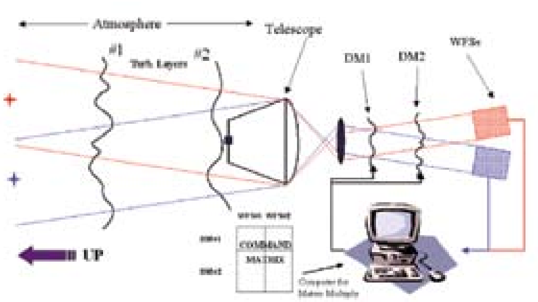


Figure 1. Schematic drawing of MCAO concept.

The MCAO Design

The MCAO concept addresses and corrects the three major limitations of existing adaptive optics systems. These are: limited sky coverage, restricted field of view, and the negative impact of the cone effect. To do this, Gemini's MCAO design uses five laser guide stars and three natural guide stars as reference sources whose light is analyzed by eight wavefront sensors. The use of multiple guide stars allows the system to probe multiple equivalent turbulent layers in the atmosphere, i.e., to characterize a three-dimensional volume of turbulence (using tomography). This capability is the key for increasing the size of the corrected field of view. Moreover, the use of multiple laser guide stars allows us to achieve substantial sky coverage and minimize the impact of the cone effect. The resulting tomographic measurements are then used by a real-time controller to reconstruct the shape of the wavefront corresponding to three equivalent turbulent layers. The calculated distortions are then used to send the corresponding commands to three deformable mirrors which are conjugated to the corresponding altitudes. Hence, MCAO, which is not an instrument in itself, but an interface between the telescope and the scientific instruments, can be divided into four main subsystems as shown in Figure 5 (next page) and described as follows:

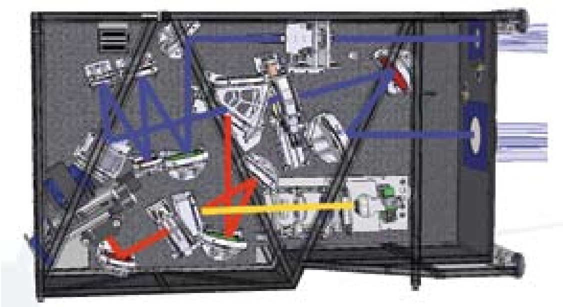


Figure 2. Schematic of the AO module (AOM). In blue, the science path, in red, the LGS path and in yellow the NGS path.

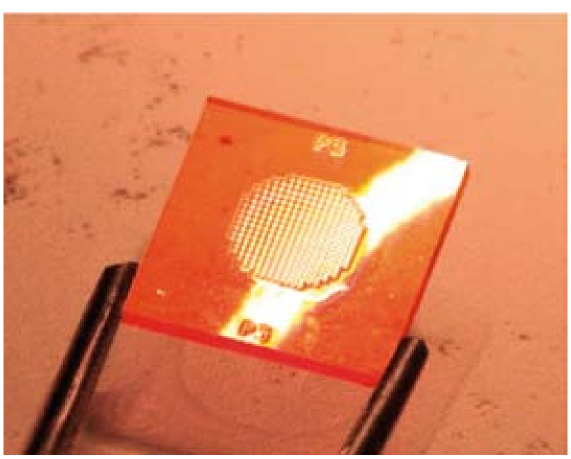


Figure 3. The lenslet array of one of the LGS WFS. The whole optical element is only a few millimeters wide.

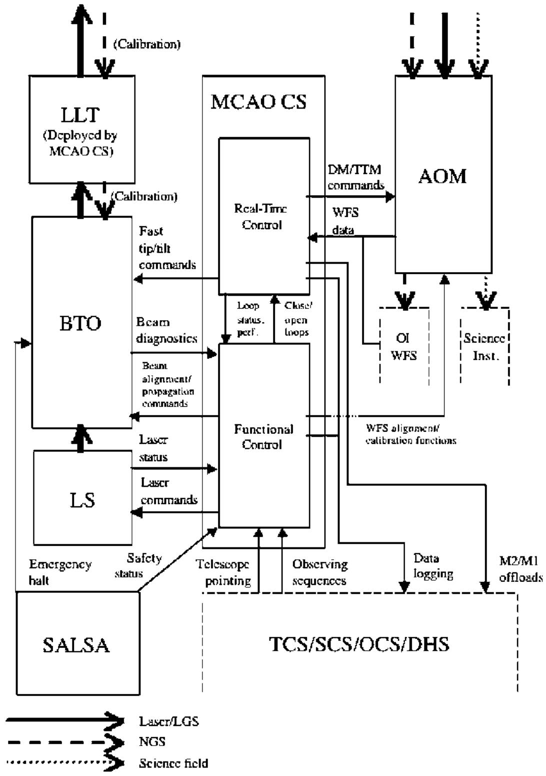
First, the adaptive optics module (Figure 2, and called CANOPUS at Gemini South) includes all of the optics, sensors and diagnostic elements needed to compensate the f/16 science beam and relay the beam to a science instrument. The major components of the adaptive optics module include three deformable mirrors, one tip/tilt mirror, five high-order laser guide star wavefront sensors and three tip/tilt natural guide star wavefront sensors. The three continuous face-sheet stacked actuator deformable mirrors will be optically conjugated to ranges of 0 (ground), 4.5 (2.8 miles) and 9 kilometers (5.6 miles) respectively, and are composed of 349, 468 and 241 actuators respectively, (using 2, 2.65 and 1.4 times the number of actuators in the ALTAIR deformable mirrors). The laser guide star sensors consist of five 16 x 16 sub-pupil Shack-Hartmann wavefront sensors. Sub-pupils will image the spots at the vertices of quad cells composed of 2 x 2 pixels each on the CCD array, with an additional guard row of pixels between the sub-apertures.

The sensitivity of the laser guide star wavefront sensors is not a significant issue since the constant power delivered by the laser will suffice to provide bright-enough artificial stars resulting in reasonable signal to noise for each sub-pupil at a sampling rate of 800 Hz. On the other hand, to ensure substantial sky coverage, the natural guide star sensors should be able to analyze the light of stars as dim as 18th magnitude. For this reason, the design concept for the three natural guide star wavefront sensors is a quadrant detector with four fiber-fed avalanche photodiode photon-counting detectors. An optical pyramid in the focal plane of the natural guide star path defines the quadrant detector, and a lens located immediately before the pyramids forms images of the pupil on the entrance of each fiber leading to the avalanche photodiodes. The field of view of these sensors is limited to one square arcsecond in order to minimize sky background noise. Additional components of the adaptive optics module include the atmospheric dispersion corrector and the calibration unit. The module, (CANOPUS), will be mounted to the Gemini instrument support structure and weighs about 900 kilograms (about 1,984 pounds).

Figure 4. The MCAO corrected field of view superimposed on an HST mosaic of the Antennae galaxy. The five LGS "constellation" is displayed in orange. For reference, the corrected field of view of a classical AO system is about half of the diameter of the LGS constellation.

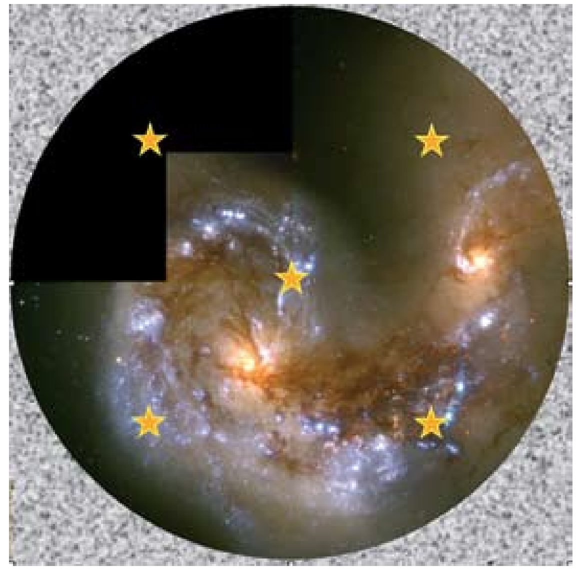
Figure 5. Schematic summarization of the different subsystems of MCAO.

Second, the laser system (which is also a subsystem of the laser guide star system) includes all hardware and software necessary to produce and maintain five laser beams tuned at the sodium spectral-line wavelength of 589 nanometers. These components include the following: one laser head and laser enclosure, optics to split the primary beam into a "constellation" of five laser beams (Figure 4), the laser electronics, a control system, cooling systems and any diagnostic elements that are needed to maintain the production of the sodium light. The primary beam will be provided by a continuous-



wave mode-locked laser. It will deliver a total power of 50-watts so that after splitting, each laser beacon will have a power of approximately 10 watts (i.e. comparable to the laser guide star system on ALTAIR). Additional details on the solid-state laser currently in use at Gemini North are in the article starting on page 54 of this issue.

Third, the laser launch telescope (LLT) and beam transfer optics (BTO) (which together form the second subsystem of the laser guide star system) are used to deliver the laser's light to the sky. The BTO delivers the five laser beams from the laser system to the LLT which is mounted behind the telescope's secondary mirror. The LLT is basically



a beam expander that creates the smallest possible laser guide star spots on the sky. The MCAO laser launch telescope and beam transfer optics designs for Gemini South are nearly identical to those developed for the ALTAIR laser guide star system on Gemini North. The BTO system also includes a shutter controlled by the safety system (called SALSA, for Safe Aircraft Localization and Satellite Avoidance) to enable laser shutdown to avoid possible collisions between the laser and an airplane or a spacecraft. This safety shutter includes a "power shutter" functionality as well, and can dump the full laser power for any length of time.

Finally, the fourth main subsystem of Gemini's MCAO system is the real-time control system. It controls the adaptive optics module as well as the laser system, the beam transfer optics, the laser launch telescope and the laser safety system. Due to its high level of complexity in terms of real-time performance and the number of hardware interfaces it must control, the MCAO control system will be split into two main functions: the control of the various opto-mechanical assemblies and that of the adaptive optics system itself. The control system will be able to analyze measurements of the five laser guide star wavefront sensors as well as the three natural guide star wavefront sensors. It will send commands to the three deformable mirrors, as well as the tip-tilt mirror at a rate of 800 Hz.

The Expected Performance

Thanks to the design described above, MCAO will

Performance of LGS AO, MCAO and HST		
Sky Coverage @ b=90°	LGS AO	MCAO
J band	7%	12%
K band	35%	24%
Sky Coverage @ b=30°		
J band	21%	67%
K band	74%	82%
Field of view diameter		
J band	90”	120”
K band	40”	80”
Sensitivities	HST	MCAO
J band	26.0	28.6
K band	23.7	28.0

Table 1. A comparison of sky coverage with Classical AO vs. MCAO.

offer unique advantages in terms of astronomical capability. Complete end-to-end adaptive optics simulations have allowed us to assess MCAO performance for the current design.

The first gain to be realized by using MCAO will be in the increased sensitivities of observations. In the case of broadband imaging at 2.2 microns, and for point sources, MCAO has a 1.2- to 1.7-magnitude advantage over NICMOS (the near-infrared camera onboard HST) and classical, natural guide star adaptive optics systems.

Second, MCAO generally offers moderately better sky coverage performance than LGS AO (Table 1). The fact that MCAO is less wavelength-dependent enables better multi-wavelength imaging, a necessity for programs requiring color-color diagnostics.

The third major advantage brought by MCAO is a gain in the corrected field of view. For programs that need enhanced fields of view, MCAO provides a 10 to 20 multiplex gain, which enables new science and also increases efficiency.

Finally, a uniform point-spread function (PSF) over a wide field of view is a key feature that is unique to MCAO. Although a 0.1-magnitude error can be achieved in some cases on fields of 10-30 arcseconds with classical adaptive optics, a uniform point-spread function with MCAO will vastly improve the accuracy of the image/spectra analysis. More generally, it is the experience of adaptive optics users that data reduction is a critical problem because of the lack of proper and simultaneous point-spread function calibration which adds to the spatial variability of the point-spread function over the field. Having a large uniform field goes a long way toward solving this problem; if a star is present in the field of view, it can be used as a PSF reference for the whole one by one square arcminute uniform field. Since, by definition, there are three stars brighter than 18th magnitude needed as tip/tilt guide stars in a 2-degree diameter field, the probability of having a least one in the central 1 square arcminute is high (~60%).

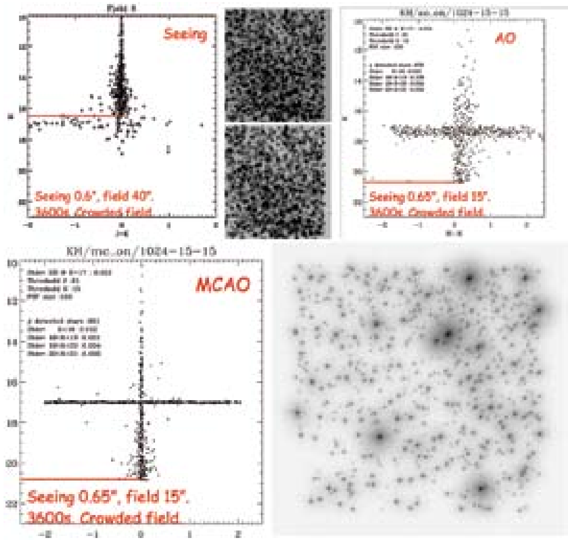


Figure 6. Simulations result showing the power of MCAO for the study of stellar populations. A color-color diagram (K/[J-K]) obtained on a crowded stellar field is shown for each case (seeing limited, AO and MCAO observations). The simulated image of the stellar field is shown on the bottom right (the same field observed under seeing limited conditions is shown on the top left).

The MCAO Science Case

Now that we've presented a full picture of the capabilities and limitations of the MCAO system undergoing construction for Gemini South, we can explore the science programs that will be enabled by MCAO. The science goals are divided into three themes that benefit from MCAO's specific capabilities: the global mass distribution of stars, the evolution of galaxies through stellar population studies, and the evolution of distant field and clusters of galaxies. More details can be found in the *MCAO Science Case* document that resulted from the Santa Cruz MCAO Science Workshop in October, 2000. The examples below were extracted from that document at: http://www.gemini.edu/sciops/instruments/adaptiveOptics/AOIndex.html

MCAO will provide dramatic new opportunities to probe the stellar mass function in star clusters, ranging from sites of current star formation to old globular clusters. With MCAO, it becomes possible to explore the behavior of the global mass distribution of stars in relatively dense environments of the Milky Way Galaxy and the Magellanic Clouds. The prime observations will require deep imaging in the J, H, and K bands and in some narrow near-infrared bands, followed up with multi-slit (with FLAMINGOS-2) and integral field unit spectroscopy (with the Gemini Near-infrared Spectrograph (GNIRS), for example). Near-infrared photometry is ideal for probing the substellar mass function. MCAO on Gemini South will permit the determination of the populations of brown dwarf and planetary-mass objects in young, nearby clusters.

A particularly exciting aspect of MCAO is its potential use for high precision astrometric measurements (at milli-arcsecond levels) on relatively nearby galactic star clusters to ascertain cluster membership and to infer kinematic and dynamic properties (five kilometers per second at one kiloparsec is about 1.0 milliarcseconds per year). This capability is unique to MCAO and is a powerful new weapon for studies of our galaxy and its associated clusters. This astrometric precision, at least for relative measurements, remains to be confirmed once MCAO has been tested on the sky.

With its field size, an MCAO system on an 8-meter telescope offers an unprecedented means for studying nearby galaxies. The first program proposed in this quest is the calibration of the supernova Ia zero point. These observations require accurate photometry of thousands of stars packed into very crowded fields in their host galaxies. The advantage of MCAO versus conventional adaptive optics for this work lies in the ability to extract accurate photometric measures over as wide a field as possible.

Table 2. Specification of Gemini's MCAO system (CANOPUS) currently being built for Gemini South.

A summary of MCAO's characteristics	
DM conjugate ranges	0, 4.5 and 9 km
DM orders	16, 16 and 8 actuators across the pupil
WFS orders	16x16 (LGS) / Tip/tilt (NGS)
LGS laser power	50 W split into 5 laser beams
Launch Telescope	50 cm (behind the telescope secondary)
NGS magnitudes	up to 19 (for 50% Strehl at H)
Sampling rate	800 Hz
Control algorithms	Decoupled control of the LGS and NGS modes

A second program aims at investigating the stellar populations in massive star-forming regions located in nearby galaxies; in particular, the interplay between high- and low-mass star formation, and the processes and time scales for triggered star formation. This program requires a wide field of view and is mainly based on deep J, H, and K broadband imaging to explore the stellar super-clusters of starburst regions in nearby galaxies by determining their ages and metallicity. This would allow us to separate the several possible distinct populations of star clusters.

A third program concerns the evolution of dwarf irregular versus elliptical galaxies. Small galaxies come in two species: dwarf ellipticals and dwarf irregulars. Not only their appearances, but some of their fundamental properties (such as their gas content, star formation history and mass-to-light ratios) are dramatically different.

With MCAO we should be able to study dwarf ellipticals out to larger distances, and thus in a greater variety of environments—from loose and low-density groups to more compact denser groups. It also becomes possible to image (resolve) all dwarf ellipticals up to 10 megaparsecs away from Earth. In addition, MCAO will provide a stable point-spread function for accurate photometry over a field as wide as 1.5 arcminutes with appropriate pixel scale. It will be possible to obtain deep J and K images with MCAO that sample the red giant branch tips of spheroidal systems and spiral galaxy disks out to distances that include the Virgo Cluster. Additionally, metallicity distribution functions could be constructed for systems spanning a range of masses, environments, and morphologies.

All of these observations require diffraction-limited image quality to resolve individual objects in very crowded environments and to obtain reliable photometric measurements of stars that are, by traditional standards, extremely faint. The enhanced field of view is also of great importance, as large numbers of stars must be surveyed to properly sample the entire range of metallicities in a system. A moderately stable point-spread function across the field is essential.

Finally, the study of intergalactic stars as well as extragalactic globular clusters will also benefit from the capabilities of MCAO and are key programs to understand the metallicity distribution functions of galaxies. For these programs, diffraction-limited observations at H band with a stable point-spread function over a 1- to 2-arcminute field of view is a requisite and [J-K] colors at high angular resolution over the same field would provide a key diagnostic on age and metal content of the stars in such environments.

The last theme of the MCAO science case is the evolution of distant field and clusters of galaxies. During the past decade, considerable effort has been dedicated to studies of galaxies at intermediate and high redshifts (z = 0.4 to > 2), with the main goal to study galaxy evolution directly and even to see galaxy formation. Such studies have often been limited to the bulk properties of these objects, limiting our physical insight. MCAO, coupled with the increased light gathering of the Gemini South telescope, will allow us to study individual systems with high spatial resolution, and therefore, to determine the spatial distribution and dynamics of star-forming material and stellar populations. The goal is to delve into the physics of the evolution of individual galaxies and to understand how they evolve on their own and as a function of their environment. MCAO provides a time savings of about a factor of 10 over conventional adaptive optics because of its ability to observe 10-20 galaxies simultaneously. Single galaxies could be studied with conventional adaptive optics (e.g., the Near-Infrared Integral-field Spectrograph (NIFS)), but MCAO provides a multiplexing advantage by a factor of 10-20 due to its field of view.

Timeline

All the main components of the MCAO system are presently being delivered and their integration should begin shortly. Some components currently are being installed on the Gemini South telescope. The last major component to be delivered will be the laser system, with delivery expected in mid-2007. After the integration and tests in the lab, integration and commissioning on the telescope are expected to begin a month later. MCAO should be operational on Gemini South by the end of 2007. If the delivery and integration of the key components of MCAO proceed as planned, we expect to be in a position to execute System Verification programs sometimes in early 2008A using the Gemini South near-infrared imager (GSAOI) and FLAMINGOS-2 in 2008A (see "The Gemini South Adaptive Optics Imager" and "FLAMINGOS-2: the New Multi-object Spectrograph on the Block" on pages 67 and 69 of this issue.).

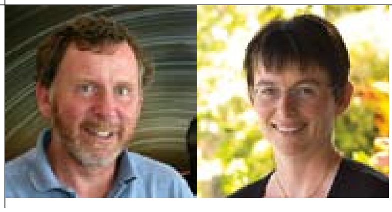
MCAO Project milestones	
Laser system design completion	August 2006
BTO design completion	September 2006
CANOPUS delivery	October 2006
BTO installation	December 2006
Laser delivery	Mid-2007
CANOPUS installation on tele-scope	June 2007
MCAO technical commissioning	November 2007

Table 3. Milestones in the development of Gemini South's MCAO system (CANOPUS).

Once fully delivered and implemented at Gemini South, MCAO will give the Gemini user community a unique capability for exploring the universe. Many individuals have played a part in this effort and their hard work will soon pay off with a powerful new tool.

Damien Gratadour is a Gemini adaptive optics science fellow at Gemini South and can be reached at: dgratado@gemini.edu

François Rigaut is a senior scientist at Gemini Observatory and can be reached at: frigaut@gemini.edu



by Michael Sheehan
and Celine d'Orgeville

AO Laser Guide Star Facility

Figure 1. Laser propagation from Gemini North in July, 2006 from the Canada-France-Hawai'i Telescope catwalk.

The Gemini laser guide star facility is a cutting-edge addition to the observatory's adaptive optics systems. It consists of a laser system and all subsystems necessary to project a laser beam into the sky to create a simulated guide star that will help astronomers deal with the effects of atmospheric aberration during observations. The facility has been in operation (commissioning) at Gemini North since May 2005 and components for the Gemini South laser guide star facility are now in various stages of development for deployment in 2007.

The Gemini North laser guide star system is attached to the elevation structure of the telescope, housed inside an environmentally controlled clean room. The laser system operates equally well in changing gravity orientations as the telescope moves from the zenith to a minimum altitude of 30 degrees. At Gemini South, the five-beam multi-conjugate adaptive optics (MCAO) laser system is significantly larger and more complex than at Gemini North. To accommodate the bigger Gemini South laser system, a new support structure and a much larger clean room is being designed and will be located near one of the mount access platforms. For both facilities, the beam is transported from the laser exit window to the telescope top-end through a series of static and articulating optics, where it is expanded and launched along the telescope's optical axis.

The History of Laser Guide Stars at Gemini

The Gemini North laser guide star facility achieved its first light during the early morning of May 2, 2005 (Gemini's laser propagation is shown in Figure 1). This major milestone was preceded by years of engineering design and development by dedicated teams of Gemini engineers and scientists, as well as several outside contractors.

Options for laser procurement and concepts for beam transfer optics systems matured following, and as a result of, the MCAO conceptual design review in mid-2000. A year later, at the MCAO preliminary design review, the concepts were developed to the level where the program could launch into the detailed design stage. An early decision was made to do the opto-mechanical design, fabrication, installation, integration and testing of the beam transfer optics system in-house with our own staff. This decision was based on the complexity of the physical interface of the beam transfer optics to the telescope and the need to minimize the impact on ongoing telescope operations during the integration and testing phases of the project.

The parts of the laser guide star facility contracted to outside vendors include the laser system, laser launch telescope and much of the software and control systems. From the beginning of our adaptive optics work, the laser system development was highlighted as a major technological and budgetary risk. We began risk reduction activities immediately by bringing the adaptive optics community and industry together (where appropriate) to develop the technology necessary for the production of efficient and economical astronomical lasers. Approximately $10 million was raised for sodium laser research and development which resulted in collaborations between Gemini and virtually all other sodium laser guide star programs in astronomy and industry. In late 2002, Coherent Technologies, Inc. (CTI, now Lockheed Martin Coherent Technologies, LMCT) signed a firm, fixed-price contract to produce a 12-watt solid-state sodium laser guide star system for Gemini North.

The Gemini North Laser Guide Star Facility

The heart of the laser guide star facility is the laser system. The Gemini North laser is a diode pumped, solid-state system using sum frequency laser technology to produce a 5-millimeter diameter, 12-watt beam at the yellow-orange wavelength of 589 nanometers. It was delivered as an "operational breadboard," meaning that a limited amount of alignment and tuning was to be expected prior to normal operation.

The laser system (shown in Figure 2) consists of the laser optical bench (visible) and the laser electronics (not visible in Figure 2). Both are housed within an environmentally controlled clean-room known as the laser service enclosure (shown in Figure 3, next page). The laser bench subsystem contains the 1064-nanometer and 1319-nanometer oscillators, a 1319-nanometer doublepass amplifier, a 589-nanometer sum frequency generator (SFG) crystal, a wavelength lock and diagnostics system and a beam diagnostics section.

Figure 2.
The Gemini North laser system shortly after delivery at the Hilo Base Facility.

Both oscillators consist of Nd:YAG (neodymium-doped yttrium aluminum garnet) rods, double end-pumped by fiber-optic-coupled 806-nanometer diode arrays. The lasers are mode locked at 76 MHz with a pulse width of 800 picoseconds. The wavelength in each laser cavity is maintained by using a temperature-controlled etalon (a type of interferometer). The sum frequency generator stage consists of a single-pass, periodically-poled stoichiometric lithium tantalate (PPSLT) crystal mounted in a temperature-controlled oven. The wavelength lock and diagnostics system monitors the 589-nanometer absorption in a sodium cell. This produces an error signal that is used to change the etalon temperature (and wavelength) of the 1319 laser thereby altering the wavelength of the 589-nanometer beam.

The laser electronics enclosure contains all control and diagnostic electronics, two Windows®-based

Figure 3. The Gemini North laser guide star facility with the laser service enclosure (light blue structure in front) and the laser beam path (shown by the dashed orange line).

computers, the 12 laser pump diodes, and the thermal management system.

Beam Transfer Optics

On its path to the sky, the laser beam passes through six major areas of the beam transfer optics system (Figure 3). This system contains relay optics that include both fast and slow articulating mirrors, static fold mirrors and beam conditioning lenses. Several camera systems are used for diagnostic purposes and laser beam alignment. The beam transfer optics system also includes laser safety shutters that are necessary to protect people and equipment if the system enters into any of a number of fault states. The entire beam path is enclosed in a slightly positive-pressure duct system. The beam transfer optics provide a circularly polarized laser beam with high throughput and excellent beam quality while maintaining correct beam pointing on the sky.

As the beam leaves the exit window of the laser bench enclosure, it is first projected to the truss pointing mirror assembly located just outside of the laser service enclosure. This assembly includes a laser safety shutter, quarter-wave plate and a position controlled tip-tilt mirror. It also has provisions for attaching a surrogate laser, used for beam transfer optics optical alignment in the absence of the laser system. Next, the beam encounters the truss centering mirror assembly, midway up the main truss. This system includes a second position-controlled tip-tilt mirror and one of several pre-alignment cameras. Tip-tilt motions of the truss pointing mirror and truss centering mirror are used to redirect the laser beam to compensate for telescope flexure as it moves in elevation, and for differential thermal expansion as the ambient temperature changes during the night. The pre-alignment cameras view the position of the laser beam on several mirrors along the beam transfer optics path to aid in gross alignment of the beam transfer optics.

From the truss centering mirror assembly, the beam is sent to the truss fold mirror assembly. This is a static fold mirror that directs the beam toward the telescope top end, and also includes two of the three relay lenses used to compensate for laser beam divergence along its path to the launch telescope. From there, the beam enters the top-end ring mirror assembly. At that point, a static mirror folds the beam through a 14-millimeter-wide duct positioned above one of the 10-millimeter-wide secondary support structure vanes to the central portion of the secondary support structure; the area occupied by the beam transfer optics optical bench assembly. The top-end ring mirror assembly also includes the third relay lens, a pre-alignment camera and a pressurized air input port.

The beam transfer optics optical bench assembly consists of a fast steering mirror, a pre-alignment camera, a beam diagnostics system, two tip-tilt mirrors, a beam dump and the entrance window to the laser launch telescope. The bench is attached to the top plate of the laser launch telescope, which is then attached firmly to the telescope secondary mirror support structure. The bench includes a cover as well as a remotely controlled exit aperture.

As the laser beam exits the laser vane duct, it enters the beam transfer optics optical bench assembly and reflects off the fast steering mirror. The fast steering mirror is controlled by feedback from the laser guide star wavefront sensor in ALTAIR and compensates for beam jitter due to wind shake and atmospheric turbulence. The beam then proceeds to the two tip-tilt mirrors, past the beam dump and then to the laser launch telescope. A small amount of the laser light is also diverted to the beam transfer optics diagnostics system. This diagnostics system consists of near- and far-field cameras that are used to calculate the pointing and centering errors of the laser beam accumulated along its path due to telescope flexure and thermal distortion.

The beam transfer optics diagnostics system drives the truss pointing mirror and truss centering mirror to point and steer the beam to compensate for these errors. It also includes features for beam quality measurement. The two tip-tilt mirrors are used primarily to realign the output beam to the telescope's optical axis using look-up tables. A fold mirror diverts the beam to a beam dump when it is necessary to stop projection of the laser beam on the sky under normal operation for events such as when slewing to a new target or for aircraft avoidance.

The laser launch telescope expands the laser beam from 5 to 300 millimeters and projects it to the sky centered along the telescope's optical axis. The laser launch telescope consists of a diverging lens assembly and an off-axis parabolic primary mirror housed in an aluminum tubular structure that resides within the secondary support structure of the Gemini telescope. The laser launch telescope was designed and built by EOS Technologies of Tucson Arizona.

Gemini South Laser Guide Star Facility

In many respects, the Gemini South laser guide star facility is identical to the one at Gemini North. There are two significant differences, however. First, the MCAO laser system has five laser beams, rather than the one beam at Gemini North. Second, the laser system is attached to the mount column instead of the telescope elevation structure. Most of the beam transfer optics hardware was designed to accommodate either one or five beams. This design decision was made to have as much common hardware as possible for both the Gemini North and Gemini South systems and to reduce the design and development work and costs.

Gemini South Laser System

The Gemini South MCAO laser system consists of the laser bench and laser electronics subsystems. As with the Gemini North laser system, these are housed inside an environmentally controlled clean room. The Gemini South laser service enclosure is fixed to one of the telescope mount access platforms, and unlike its counterpart at Gemini North, it does not move with the telescope in elevation. The entire Gemini South laser guide star facility work is currently in the detailed design phase. A sketch of the current laser service enclosure design for Gemini South is shown in Figure 4.

The laser bench subsystem is shown in computer-aided design form in Figure 5 (next page). It consists of four major modules: the oscillators

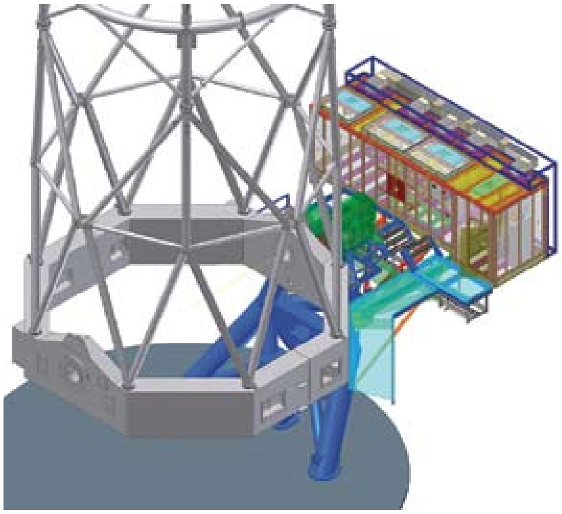


Figure 4. Gemini South laser service enclosure, currently in the final stages of design.

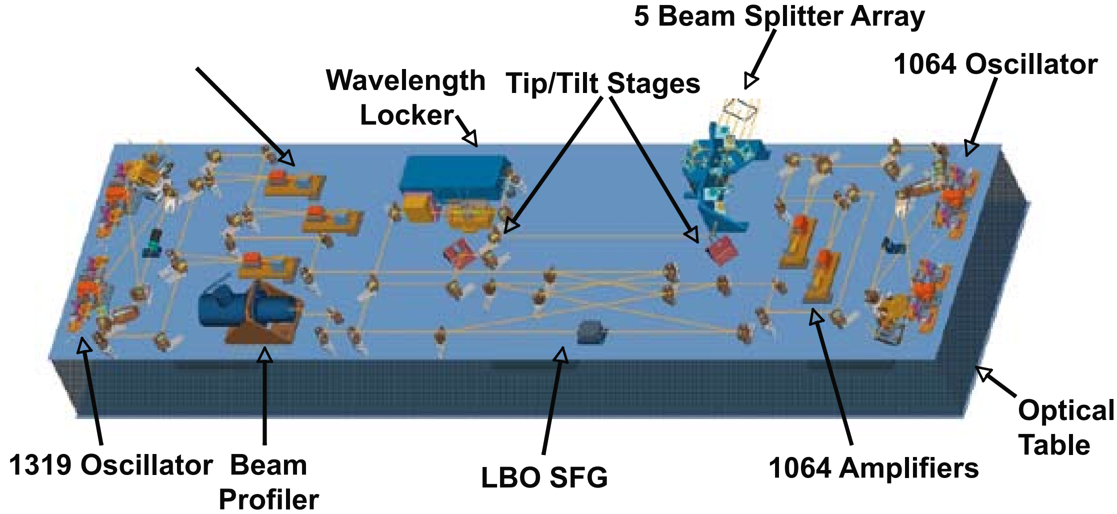


Figure 5. The Gemini South laser system optical layout. The oscillators and wavelength locker are based on the proven technology from the Gemini North laser system. The amplifiers and Sum Frequency Generator (SFG) are new to the system but based on existing technologies from Coherent Technology Inc. (CTI).

(one at 1064 nanometers and the other at 1319 nanometers), the amplifiers (one each for 1064 nanometers and 1319 nanometers), the sum frequency generator, and the diagnostics (power, wavelength, and beam quality).

The oscillators and wavelength locker are based on the proven technology from the Gemini North laser system. The amplifiers and sum frequency generator are new to the system but based on existing technologies from Coherent Technology Inc. (CTI).

The oscillators for the Gemini South laser are upgraded versions of those proven on the Gemini North laser system. The 1064 oscillator is a 1.8-meter-long cavity, resulting in a round-trip time of 12 nanoseconds. Pulses of the correct duration and bandwidth are produced by mode-locking the resonator using an acousto-optic modelocker. Two Nd:YAG laser rods, each pumped with two fiber-coupled 805-nanometer laser diodes, provide the gain medium for the oscillator. An intra-cavity etalon gives further control over the pulsewidth and serves to stabilize the exact wavelength of the oscillator. The 1319-nanometer oscillator is substantially the same as the 1064-nanometer oscillator with the exception of the optical coatings which enable lasing at 1319 rather than 1064 nanometers.

The output of each oscillator is directed to its respective amplifier. The 1064 amplifier consists of two gain modules that amplify the pulse train up to the power required by the sum frequency generator. Each gain module consists of LMCT's patented planar waveguide technology, which enables high-power amplification without incurring spatial or polarization distortions. The 1319-nanometer amplifier is the same as the 1064-nanometer amplifier except for coatings and the additional gain module to account for the lower gain of Nd:YAG at 1319 nanometers

Sum frequency generation is a non-linear optical process where the two input frequencies (in this case the frequencies correspond to wavelengths of 1064 and 1319 nanometers) are combined, or summed, to generate a third frequency (corresponding to 589 nanometers). The efficiency of this process increases with increasing input intensity. Thus, in addition to producing the bandwidth needed for efficient interaction with sodium, mode-locking the oscillators also results in short, high-intensity pulses which then ease the constraints on the nonlinear optic. Lithium triborate, chosen for its high-power handling capabilities and field-proven reliability, will be used as the nonlinear optical crystal in contrast to the PPSLT crystal at Gemini North due to the lower power of the laser.

From the sum frequency generation stage, the 50-watt beam is then split into five beams of equal power and directed through the laser bench exit aperture to the Gemini South beam transfer optics.

Gemini South Beam Transfer Optics

The constellation of five laser beams is projected directly down the elevation axis of the telescope. Figure 6 illustrates the current design for this path. After exiting the laser service enclosure, it immediately goes into the laser exit housing. This area includes the laser safety shutter, bench transfer optics shutters for each beam, quarter wave plates and a mount for a surrogate laser system. From there the beams continue toward the telescope through a K-mirror (used to de-rotate the constellation with telescope elevation axis moves) to the elevation fold mirror and then on to the truss pointing array.

The elevation fold mirror includes slow tip and tilt motion control to compensate for telescope flexure. Jittering of the laser beams due to motion of the laser bench on its vibration isolation system is also a problem. To compensate for jitter, this portion of the path also has a fast beam steering system used to maintain precise pointing angle and centering distance of the laser beams on the truss pointing array mirrors. Position-sensing devices located just ahead of the array sense the motion of the laser

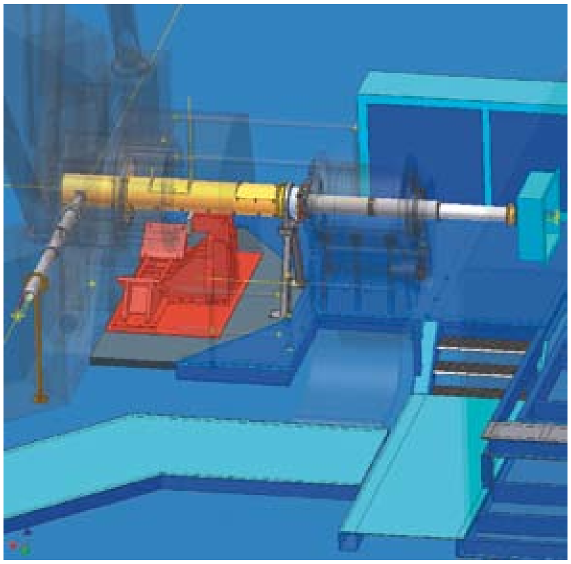


Figure 6. The Gemini South bench transfer optics path between the laser service enclosure and the telescope. This addition is the major difference between the Gemini North and Gemini South bench transfer optics systems.

beam constellation. This sensor data is processed to send tip and tilt motion commands to two fast tip-tilt platforms on the laser bench to stabilize the beams at the truss pointing array.

Laser Safety Systems

Laser safety considerations have been the top priority throughout the entire design and development of the laser guide star facility. For the laser itself, we chose to use a solid-state system largely because of the risks associated with chemicals and fire inherent in dye laser systems. The bench transfer optics system was designed to be enclosed throughout its entire path to eliminate accidental human interaction with the laser beam(s), and a safety shutter is placed as close as possible to the laser exit window. Interlocks are placed on all access doors that will shutter the laser when any door is opened.

Close communication with the Federal Aviation Administration for aircraft pilot notification and with the U.S. Space Command for satellite avoidance is an essential part of every laser run. Currently we employ aircraft spotters to search the sky for aircraft around the observatory during all laser propagations. If an aircraft is detected in the area, the spotters simply press a button and a laser shutter is deployed. A passive camera based system, with both wide angle visible and boresighted infrared cameras to automatically detect aircraft, is currently under development.

The Gemini laser development program is a core element of the observatory's forward-looking instrument program. The use of laser guide stars has become an essential part of most large observatory operations due to the remarkable scientific potential that it enables. From an engineering point of view, this technology provides our technical staff with an exciting and challenging opportunity to combine science and engineering while making Gemini a leader in laser guide star development and high-resolution infrared astronomy.

The authors would like to thank Lockheed Martin Coherent Technologies for their descriptions of the Gemini North and South laser systems.

Michael Sheehan is Deputy Chief Engineer and Mechanical Engineering Group Manager at Gemini Observatory and can be reached at: msheehan@gemini.edu.

Celine d'Orgeville is the Deputy Adaptive Optics Program Manager at Gemini Observatory and she can be reached at: celine@gemini.edu

by Tracy Beck

Gemini North's Near Infrared Integral Field Spectrograph (NIFS)

In March 1999 Gemini Observatory held a meeting to discuss ways to "fill the gaps" in its suite of optical and infrared instrumentation. From this meeting came the concept of the Near Infrared Integral Field Spectrograph (NIFS). Near-infrared imaging spectroscopy was identified as the primary role of NIFS. From the start, it was characterized as a fast-track niche instrument that could provide resolved near-infrared spectroscopy of astronomical targets at adaptive optics-fed spatial resolutions of about a tenth of an arcsecond. Peter McGregor (NIFS principal investigator (PI)) and the instrumentation team at the Research School of Astronomy and Astrophysics (RSAA) at the Australian National University (ANU) in Canberra, Australia was selected to build NIFS.

NIFS was designed to be used primarily with Gemini North's facility adaptive optics (AO) system, ALTAIR. Its key capabilities are the high spatial resolution IFU covering a 3 x 3 arcsecond square field, with a moderate-resolution (R~5000) spectrograph in the 0.95-2.4 micron wavelength range. NIFS was designed to excel at high angular resolution observations of spatially extended targets, particularly complex regions that have a high surface brightness, extended narrow emission line regions, or spatially extended emission components. Thus, a core science goal for NIFS is to study the demographics of massive black holes in nearby galactic nuclei, and discern the structure and kinematics of the inner narrow-line regions of nearby Seyfert galaxies. Additionally, NIFS has several occulting disks in the focal plane unit that permit high contrast observations to search for faint companions or spatially extended structure in the vicinity of very bright targets. (See the companion article: *Science Highlights from the Science Verification of NIFS* on page 40 of this issue for more information on NIFS's science performance).

Figure 1.
Gemini North showing the propagation of the laser guide star with NIFS mounted on the up-looking port of the instrument cluster.

Figure 2.
An Image of the NIFS cryostat after the fire in Australia in January 2003.

On January 18, 2003, when it was mere months away from completion and delivery to Gemini North, NIFS was destroyed by the bush fires that devastated the Mount Stromlo Observatory and surrounding communities in Canberra (Figure 2). The rebuild of NIFS started a few months after the fire, and ANU outsourced some of the reconstruction efforts to the Australian aerospace company, Auspace. After a tireless effort by the group at ANU and Auspace, NIFS-2 was delivered to Hawai'i in August, 2005 only two and a half years after its predecessor was ruined. The team earned the "ACT Government Innovation and New Technology Award" for engineering excellence for the rebuild of NIFS.

On October 19, 2005, NIFS had first light at Gemini North. The instrument commissioning took place over the course of the next month in a commissioning-and-queue observing philosophy. If there were times when the weather deteriorated to the point where NIFS commissioning tests could not be carried out, then observations switched to queue mode to make better use of the conditions. The commissioning tasks were completed on November 20, 2005, after a span of great weather on Mauna Kea and a total of about 18 full nights on the sky. Observations with NIFS were tested both with AO correction using ALTAIR, as well as with the peripheral wavefront sensor (PWFS2) for cases where adaptive optics guide stars were not obtainable. In the latter case—non-AO mode—NIFS serves as a sensitive R~5000 spectrograph "light bucket." Based on the system's flux throughput calculations (~28% at K, ~20% at H), NIFS AO-fed spectroscopy is competitive with the Near Infrared Imager (NIRI) for point-source sensitivity.

The On-Instrument Wavefront Sensors (OIWFS) inherent in the Gemini infrared instruments can provide guide corrections that cannot be properly compensated for using the facility wavefront sensors. Particularly, the OIWFS allows for flexure compensation to keep the position of an object stable in the observing field for long durations on the science target. The OIWFS in NIFS was commissioned to provide slow flexure correction in conjunction with observations made using ALTAIR. Over the course of a nearly six-hour flexure test covering a wide area on the sky, a target star was found to have moved by less than a tenth of an arcsecond in the NIFS field when using the OIWFS (compared to ~0.25 arcsecond without flexure compensation). Observations made using the NIFS OIWFS have also proven useful for reducing flexure movement to keep a target well-centered behind occulting disks for high-contrast observations. The NIFS OIWFS provides improvement in the AO guiding performance, and in good weather conditions stars with K-band magnitudes less than about 14.5 within ~45 arcseconds of the science target have been used to provide flexure compensation.

NIFS has now been fully integrated into the Gemini observing system. It is included in the Gemini Phase I Tool (PIT) for observation proposals and the Gemini Observing Tool (OT) for observation definition. Figure 4 (next page) presents the NIFS Image Component from the OT and describes the NIFS field and regions for selecting guide stars. The small blue square at the center of the image represents the 3 x 3 arcsecond NIFS science field. The area outlined in red shows the region vignetted by the NIFS science field pick-off probe. AO stars can be selected in this region because ALTAIR is external to NIFS, but OIWFS guide stars can not be selected in this vignetted area. The inner, blue circle defines the area for AO-selected guide stars, and the outer, yellow circle shows the outermost limit possible for selecting

Figure 3. Chris Carter of Gemini (upper) and Jan Van Harmleen of ANU (lower) inspecting NIFS on Gemini North.

OIWFS stars. For optimal performance, the OIWFS (and AO) guide stars should be as close to the science target as possible.

NIFS also has an integration time calculator (ITC) linked to Gemini public web pages. The calculations inherent in the NIFS ITC were verified using commissioning data for flux throughput and the results were found to be very accurate for point-source sensitivity. The NIFS web pages also provide information on the instrument components and sensitivity, proposing to use NIFS, tips and tricks for observation definition, and notes on the NIFS library for the Observing Tool. In April, 2006, the NIFS Gemini IRAF (Image Reduction and Analysis Facility) package was released for use by PIs of the System Verification (SV) projects. The data reduction through the Gemini IRAF package provides the means to flat field NIFS images, subtract off sky emission and dark current, remove bad pixels and rectify the two-dimensional data from the detector image into a spatially calibrated, wavelength calibrated three-dimensional data-cube (x, y, λ). Also inherent in the Gemini NIFS IRAF package are test scripts that describe the data-reduction process for arc and flat field calibrations, telluric calibration stars, and science exposures.

In the near future, NIFS will be used aggressively with the ALTAIR Laser Guide Star (LGS) system. Observations of NIFS+ALTAIR LGS will greatly expand the range of potential science projects to sources that have available LGS tip-tilt guide stars of magnitude R < 18 (in optimal conditions). This increased capability will allow for the study of the structure and kinematics around faint galactic nuclei, galactic star clusters, brown dwarfs, embedded young stars and a range of other astronomical targets of interest. Commissioning of NIFS with the ALTAIR+LGS system is ongoing in the early 2006B observing term. We will commence with observations of approved NIFS+LGS system verification programs and queue projects in the later part of 2006B.

The power of near-infrared adaptive optics-fed integral field spectroscopy is just now being realized at 8-10 meter class observatories with the recent instrument additions of SINFONI at the VLT (Chile) and OSIRIS at the W.M. Keck Observatory (Mauna Kea). It is very exciting to now have NIFS at Gemini North—a sensitive AO-fed near-infrared integral field spectrograph that will add some tough competition to this expanding new realm of astronomical observing tools!

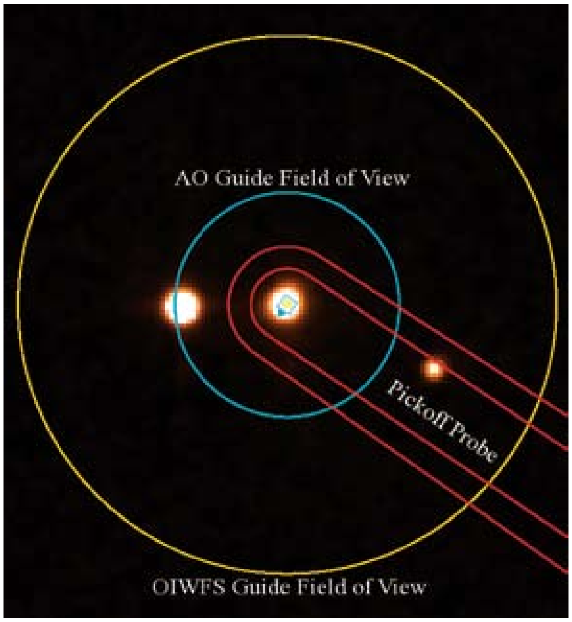
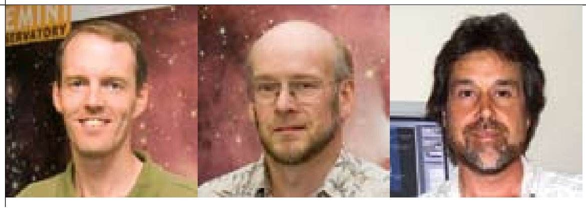


Figure 4. An example of the NIFS field and guide star regions from the Observing Tool (OT) component.

Special thanks to Peter McGregor of the Research School of Astronomy and Astrophysics, Australian National University, for his input on this article.

Tracy Beck is a Gemini science fellow at Gemini North and can be reached at: tbeck@gemini.edu



by Joe Jensen, Tom Hayward
and Doug Toomey

Searching for Planets Using Gemini's Near-Infrared Coronagraphic Imager (NICI)

With the discovery of more than two hundred planets around other stars, we now stand on the brink of a new understanding of the universe and of our place in it. After centuries of debate, speculation, and many false starts and erroneous claims, a population of extrasolar planets has finally been identified in the last decade. In addition to these exciting and fundamental discoveries, we have obtained a few glimpses into the intermediate stages that link the birth of stars to the formation of planetary systems. We are poised now for the transition from discovery of these systems to their characterization.

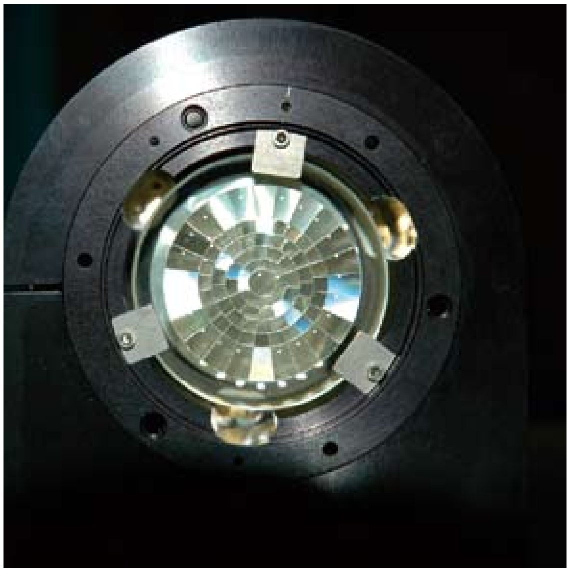


Figure 1. The 85-element wavefront sensor lenslet array in NICI's curvature AO system.

At Gemini we have large-aperture telescopes optimized for high spatial resolution and infrared sensitivity, equipped with advanced adaptive optics (AO) systems and advanced detectors and instrumentation. The Near-infrared Coronagraphic Imager (NICI) is the first Gemini instrument designed specifically to search for and analyze the properties of planets orbiting other stars, and one of the first in the world optimized to image the light from the planets directly.

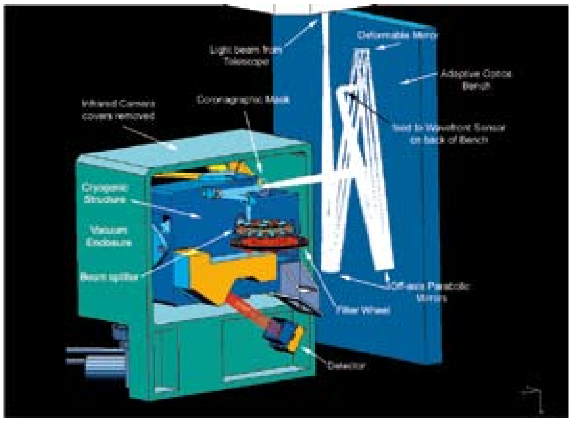
The primary challenge of extrasolar planet imaging is to separate a planet's very faint light from the light of its much brighter parent star. To do this, the light from each object must be confined to as small an area as possible, much smaller than usually permitted by our own planet's turbulent atmosphere. This is a job for adaptive optics. Several teams have used Gemini's AO systems (Hokupa'a initially, and more recently ALTAIR – see articles on pages 43 and 45 of this issue for more details) to search for faint companions around nearby stars. While these studies have yet to pay off with the discovery of a bona fide planet, they have turned up a number of brown dwarfs. In addition, they have helped to develop the observing techniques and data reduction procedures that will enable planet discoveries.

Figure 2.
Schematic diagram of NICI's AO system (right) and science cameras (left). Light enters NICI from the telescope above.

With its own custom AO system, dual imaging cameras, and specialized coronagraph, NICI has been designed to be a significantly more capable planet-finder than existing instruments. The AO system used by NICI is based on an 85-element curvature-sensing wavefront sensor. The signals from the WFS are fed to a deformable mirror, manufactured by CILAS in France, that has an actuator pattern matching the WFS pattern (Figure 1, previous page). The deformable mirror corrects the atmospheric distortions to the infrared light and focuses the starlight on the focal plane coronagraphic mask, which blocks almost all the light from the star.

Once the infrared light has been corrected by the AO system, and most of the starlight blocked by the focal plane mask, the light enters the dual cryogenic science cameras (Figure 2). A pupil mask near the camera entrance has a rotating spider mask to block light diffracted by the secondary supports. Almost all the starlight is blocked by the combination of focal plane and pupil plane masks. The remaining light, including light from planets, then strikes a beam splitter that sends some of its light into each of the two cameras (only the nearest one is visible in Figure 2). Each camera has its own Aladdin II indium antimonide (InSb) detector and set of filters, so two wavelengths can be sampled at the same time. Giant planets that contain methane will appear dark in some narrow infrared filters and brighter in others. The contrast between the two simultaneous images will help astronomers to distinguish methane-rich giant planets from background stars and residual diffracted starlight.

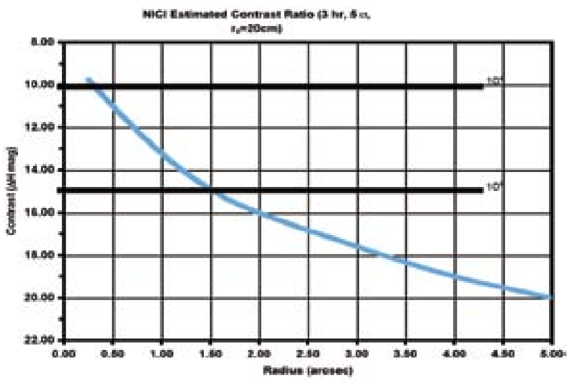
The key to detecting planets is to maximize the contrast between the planet and the parent star. Even young, warm, bright giant planets are many thousands of times fainter than stars, and their projected orbits will be less than an arcsecond or two from the parent star (the farther away the star, the closer the planets will appear to their stars). Therefore, it is of primary importance to maximize the contrast ratio between stars and planets as close to the star as possible. For a particular set of assumptions about typical atmospheric conditions, NICI's AO performance, and the brightness of the stars and planets, we can estimate the contrast ratio



that NICI will achieve. The estimates shown in Figure 3 were used for planning the NICI planet survey (see the accompanying box on next page).

NICI is unique among Gemini instruments in that it was funded by a NASA grant as part of NASA's mission to explore extrasolar planets. This independent funding made it possible to design a specialized AO instrument that might not have otherwise been built because of tight funding within the Gemini partnership. After a competitive bidding process, the contract to construct NICI was awarded to Mauna Kea Infrared (MKIR), a Hilo, Hawai'i company led by third author, Doug Toomey, that specializes in building complex infrared instruments for astronomy. NICI is now nearly complete at MKIR, and by the time this article appears in print, acceptance testing in Hilo will be well under way.

Figure 3.
The contrast ratio between stars and planets has been estimated as a function of distance from the central star. The plot is suggestive of what might be achieved in a 3-hour observation performed during fairly typical observing conditions and a bright AO guide star. Most planets will probably be discovered within about 1 arcsecond of the star. NICI's performance will be measured on the sky during commissioning.



Both cameras have been assembled and tested, the cryogenic mechanisms are working, and the science detectors have been installed and tested. NICI's AO bench is now fully assembled and has been tested with both static and dynamic aberrations. Following acceptance testing in Hilo, NICI will be shipped to Gemini South, where it will be reassembled, tested, and installed on the telescope. NICI should see first light on Cerro Pachón early in 2007.

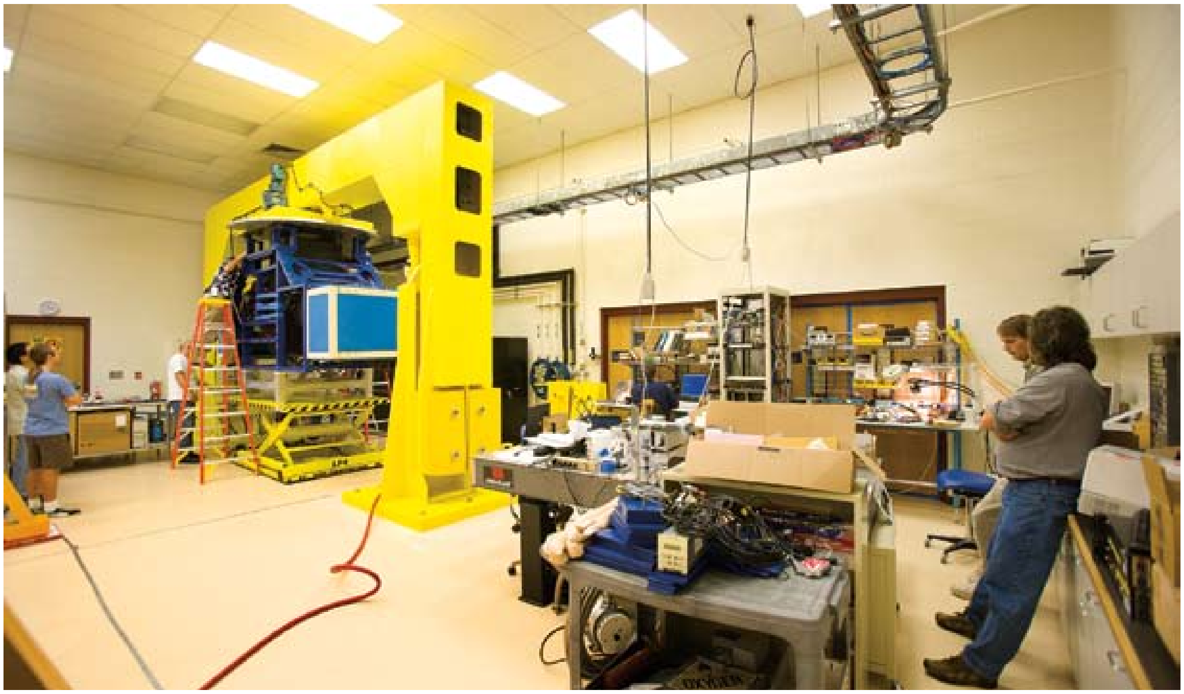


Figure 4. NICI assembled and ready for acceptance testing on the flexure-rig at Gemini's Hilo Base Facility.

NICI is a pioneering instrument that will blaze a trail for future Gemini instruments. The Gemini Planet Imager (GPI), currently being designed by a collaboration led by Bruce Macintosh at Lawrence Livermore National Laboratory, follows directly in the tradition of NICI. GPI builds on what we learn from NICI, both scientifically and technologically. GPI is a coronagraphic instrument with its own onboard AO system, just like NICI, but will have a much higher-order AO system to achieve higher Strehl ratios than possible with NICI. GPI will also have a sophisticated interferometer incorporated into the AO system to further reduce wavefront errors to an absolute minimum. Finally, GPI will have a low-resolution integral field spectrograph to help identify planets and characterize their atmospheres. NICI's legacy will live on at Gemini long after its planet survey is complete.

Joseph Jensen is Head of Instrumentation at the Gemini Observatory and can be reached at: jjensen@gemini.edu

Thomas Hayward is a Gemini South associate scientist and can be reached at: thayward@gemini.edu

Douglas Toomey is Manager and founder of Mauna Kea Infrared (MKIR) and can be reached at: toomey@mkir.com

The NICI Planet Search Campaign

The Near Infrared Coronagraphic Imager (NICI) is the most specialized of Gemini's instruments thus far, and meeting its science goals also requires a specialized approach. Finding planets will require a large survey of nearby stars conducted over several years to find, hopefully, a few needles in a very large haystack. Last year, Gemini announced the opportunity to apply for a large block of NICI time to look for planets around nearby stars. The time allocation process that was followed was more typical of Gemini instrument procurements than a traditional observing proposal process. More than 100 astronomers from across the Gemini partnership submitted letters of interest for the NICI planet search, and three strong international teams submitted applications for up to 500 hours of Gemini time. A committee of experts and the International Time Allocation Committee (ITAC) reviewed the proposals and made recommendations to the Gemini Director, who then chose the team led by Michael Liu (University of Hawai'i) to conduct the NICI planet search survey. The NICI instrument team joined Liu's group, bringing their NICI expertise and a significant number of guaranteed nights to supplement the campaign.

The NICI planet survey will search for massive planets (similar to Jupiter) around nearby young stars. Any young planets will still be glowing with the residual heat of formation, adding to the infrared flux visible to NICI's detectors. With a census of such planets, the NICI campaign team will address three important questions: What is the distribution of masses and separations of planets in *the outer regions of other solar systems? How does the mass of the parent star affect the chances of planets forming? What are the properties and compositions of the young giant planets?*

Most planets that have been discovered around other stars are detected only indirectly via their gravitational influence on their parent stars. We usually can't tell what their masses are or what they might be made of. We can only conclude that most are very massive and orbit quite close to their stars. NICI will look for a very different class of planets, since it will preferentially find the giant planets orbiting out in the regions of their planetary systems comparable to those occupied by the giant planets in our own solar system. NICI will also be able to detect the infrared light from the planets directly, revealing much about their masses, compositions, and temperatures.

Planets are much fainter than their parent stars. Diffraction from the bright star forms long-lived speckles that can be confused with a planet. To help distinguish real planets from the background speckles, the NICI team will use specialized filters and observing strategies. Since the atmospheres of giant planets usually contain methane, the filters in NICI have been specially designed to maximize the contrast between an object with methane in its atmosphere and one that doesn't. The campaign team will also use a specialized strategy of freezing the cassegrain rotator during observations. With the rotator fixed, background stars and planets will rotate in the field of view, while the speckle pattern remains in one position.

Companion planets are also difficult to distinguish from background stars, so the NICI campaign will require follow-up observations taken months later. During the time between observations, the nearby star will have moved relative to the background stars, making it possible to distinguish real planets from background objects. These strategies will maximize the campaign team's chances of finding real planets.

The NICI planet search team is led by Michael Liu (PI) of the University of Hawai`i Institute for Astronomy (UH IfA). Mark Chun (UH IfA) and Laird Close (University of Arizona) are primary co-investigators. The team also includes Adam Burrows (University of Arizona), Doug Toomey (Mauna Kea Infrared), Christ Ftaclas (UH IfA), Neill Reid (Space Telescope Science Institute), Niranjan Thatte, Matthias Tecza, and Fraser Clarke (Oxford University), Harvey Richer (University of British Columbia), Jane Gregorio Hetem, Elisabete De Gouveia Dal Pino, and Sylvia Alencar (Universidad de São Paolo), Pawel Artymowicz (University of Toronto), Doug Lin (University of California-Santa Cruz), Shigeru Ida (Tokyo Institute of Technology), Alan Boss (DTM/Carnegie), Mark Kuchner (NASA Goddard), Chris Tinney (Anglo-Australian Observatory), Sebastian Lepine (American Museum of Natural History), Hugh Jones (Hertfordshire), Tom Hayward, François Rigaut, and Bernadette Rodgers (Gemini Observatory).

by Doug Simons

Gemini South Adaptive Optics Imager (GSAOI)

Among the last of the Phase 2 instruments scheduled to arrive at Gemini is the Gemini South Adaptive Optics Imager. Built by Australia National University (ANU), this instrument shares a number of design features with other Gemini instruments, but also has some completely unique design aspects. GSAOI uses the same vacuum jacket design as NIRI and NIFS and hence, from the outside, looks essentially identical to those other venerable instruments. It also has a similar cold optical bench inside. This approach to "recycling" design concepts across various Gemini instruments was adopted several years ago in an effort to reduce cost, risk, and complexity in Gemini's instrument program. This is one of the "hidden" assets of the large international collection of instrument builders working on Gemini's development program. Over time the Observatory has built up a considerable library of designs that are available for use by new instrument teams, including mechanical drawings, optical designs, and control system software. But, that's where the similarities end. GSAOI is a dedicated near-infrared imager and in fact, hosts the single most technically complex (and expensive) focal plane sensor package of any Gemini instrument. It uses a mosaic of four HAWAII-2RG detectors which together critically sample the entire MCAO corrected field. Given the instrument's plate scale (20 milliarcseconds per pixel), which would be of marginal use under

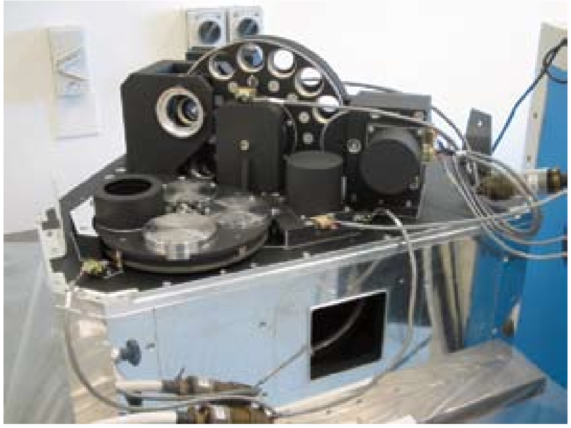


Figure 1. The cold structure of GSAOI is shown. The large vertical wheels house the instrument's filters, while the horizontal wheel is intended to hold focal plane masks. The bench and passive radiation shields on its perimeter are all derived from the design of NIRI.

Figure 2. The fully integrated GSAOI. On the right is the steel plate used to bolt GSAOI to the ISS on the telescope. Immediately behind it is the cryostat.

natural seeing conditions, GSAOI is designed to work exclusively with MCAO's f/33 beam feed. This led to a more compact optical design but, as can be seen in Figure 1, packaging the various mechanisms, lenses, masks, electronics, and detector system remained something of a challenge. Given GSAOI's fine plate scale, the background flux sensed by its pixels is low, and hence a modest read-out rate for its science focal plane is adequate. An SDSU-3 controller is built into GSAOI and provides all array control functions. This controller uses 16 channels (four dedicated to each detector) to achieve readouts that are ultimately limited in speed by the external data handling system. Figure 2 shows the overall instrument package, with a steel space frame used to tie the aluminum cryostat and a pair of thermal electronics enclosures to the cassegrain instrument support structure.

One of the more remarkable features of GSAOI is that it provides multiple tip/tilt guide signals for stars across the MCAO field, but does not incorporate a cryogenic on-instrument wavefront sensor. This represented a considerable savings in cost and complexity. The wavefront sensors used in NIRI, NIFS, and GNIRS (all manufactured at the University of Hawai'i) are fairly complex acquisition and imaging systems unto themselves. GSAOI achieves this functionality without the use of a dedicated wavefront sensor by taking advantage of the unique guide window feature built into the HAWAII-2RG detector system. In practice each of GSAOI's science detectors can isolate a star in its field of view and through a high speed readout in a small (e.g., 8 x 8 pixel) region of interest, generate a tip-tilt measurement up to many hundreds of times per second. One of the real beauties of this design is that there is no differential flexure between the science focal plane and on-instrument wavefront sensor—a problem that is difficult to handle in more conventional instruments and tends to require the use of very heavy/stiff cold structures to achieve the necessary low level of differential flexure. Since the science detector is also used to make tip-tilt measurements, differential flexure is reduced to zero in this elegant and cost effective approach to achieving the necessary functionality in GSAOI.

At the time of this report GSAOI has passed its acceptance tests in Canberra and will be shipped soon to the summit of Cerro Pachón, where it will undergo a series of tests in the instrument lab to verify the health of all its subsystems and exercise various control system interfaces. Unlike all other Gemini facility class instruments that reach this state of maturity though, it will not be immediately mounted on the telescope to enter a commissioning phase. Instead, GSAOI will be stored until 2007, when it will be used as the commissioning camera for MCAO. Ensuring that MCAO has a first-class commissioning (and science) camera is one of the lessons learned from the early days at Gemini North, when the telescope was critically in need of an infrared imager to support telescope commissioning. We wanted to make sure GSAOI arrived in time to support MCAO commissioning, and thanks to the outstanding workmanship and professionalism at ANU, we are confident that this key component of the MCAO commissioning system will be ready, when it is needed.

Douglas Simons is Director of Gemini Observatory and can be reached at: dsimons@gemini.edu

by Marcel Bergmann

FLAMINGOS-2: A New Multi-object Spectrograph on the Block

Figure 1. FLAMINGOS-2 in the lab. Light from the telescope will first enter the MOS dewar, located on top (in this orientation). The camera dewar, which contains most of the optics as well as the detector, is the long cylinder on the bottom. Connecting the two dewars is a spacer ring and a gate valve (hidden from view). Pictured with the instrument are engineers Jeff Julian (right), Greg Benedict (left), and project manager Roger Julian (kneeling).

The twin Gemini Multi-Object Spectrographs (GMOS-North and GMOS-South) are getting a new sibling: FLAMINGOS-2, the FLoridA Multi-object Imaging Near-infrared Grism Observational Spectrometer-2. The instrument is currently under construction in the astronomy department of the University of Florida, and builds on the legacy of the original FLAMINGOS spectrograph that has been in use for many years at the Kitt Peak 4-meter telescope, Gemini South and the Multiple Mirror Telescope. When it is commissioned in early 2007, FLAMINGOS-2 will provide both near-infrared imaging capability and low-resolution multi-object spectroscopy (MOS) in the near-infrared, and can be fed with either the standard (active optics corrected) f/16 beam, or the soon-to-be-delivered multi-conjugate adaptive optics (MCAO) f/33 beam.

FLAMINGOS-2 Design and Components

The development of near-infrared multi-object spectrographs has lagged behind their optical cousins because of the added complications introduced by the need to cool the entrance slits for wavelengths redward of the J-band (toward the thermal infrared). Spectrographs on large telescopes are large instruments. They have big thermal loads, and cannot be warmed and cooled fast enough to enable quick swapping of cold MOS maskplates. FLAMINGOS-2 (and the original FLAMINGOS

Figure 2.
Face on, inside view of the MOS dewar. The lightpath is in the center of the dewar, moving inwards and away from the viewer. Light passes through the MOS wheel, which can be rotated to an opening imaging position, one of several longslit or MOS plate positions, or a pinhole mask (the position shown here). Behind the MOS wheel is a decker wheel, and then a field lens and the gate valve leading to the camera dewar.

instrument) solves this problem by using a two-dewar design (Figure 1, previous page). The larger camera dewar contains the detector, all the camera optics, filters, and grisms. A smaller dewar is used to hold the MOS plates in a wheel. It can be isolated from the camera dewar so that it can be warmed and cooled (and brought from ambient pressure to vacuum and back) while the camera dewar stays cold. The smaller dewar is designed to be warmed up, opened to swap masks, and cooled again, all within twelve hours. This allows it to be used every night for queue or classical observing.

The MOS wheel (Figure 2) can simultaneously hold nine spectrographic masks, six longslits, and two imaging pinhole masks (used for focusing and calibrations), as well as a through-hole for imaging mode. The longslits are permanently mounted in the wheel, but the multi-object spectroscopic masks can be swapped during daytime hours so that there is always a selection of programs ready to be observed. In addition to the MOS wheel, the dewar holds a decker wheel (with imaging, longslit, and MOS options), and the on-instrument wavefront sensor mechanism. The wavefront sensor mechanism which, like the one on GMOS, was built at the Herzberg Institute of Astrophysics in Canada, is operated cold so that the thermal glow from the on-instrument wavefront sensor (OIWFS) arm does not affect FLAMINGOS-2 images or spectra.

The light continues out of the MOS dewar through the gate valve, and then passes through a pair of filter wheels, each with five options (the initial set will include J, H, K' imaging filters and JH and HK broad spectroscopic filters, as well as a pair of narrow-band filters centered near 1.05 microns), a Lyot stop wheel, and the grism wheel. There are three grisms for use in FLAMINGOS-2: an R = 1300 grism for J and H band together, an R = 1300 grism for H and K together, and an R = 3000 grism which can be used for J or H or K, one band at a time. The conversion of FLAMINGOS-2 from f/16 mode to MCAO f/33 mode is done with a simple rotation of the Lyot wheel to the appropriate cold stop. Everything else is done by the MCAO system. Next in the optical path is the camera, a set of six lenses in a single camera barrel. This focuses the light onto the detector, which is a 2048 x 2048 Hawaii-2 HgCdTe (mercury-cadmium-telluride) array, sensitive to wavelengths from 0.9-2.5 microns.

Observing with FLAMINGOS-2

Observing with FLAMINGOS-2 will have many similarities to observing with GMOS. The instrument can be configured on the fly for imaging in one of several broad-band (J, H, K-short) or narrow-band filters. It can do longslit spectroscopy using a 1-, 2-, 3-, 4-, 6-, or 8-pixel wide slit, or multi-object spectroscopy at any time using one of the nine plates installed in the instrument. These plates are custom-designed for each program using some combination of FLAMINGOS-2 imaging and/or reliable target coordinates from some other source. Guiding will be done using the on-instrument wavefront sensor operating at optical wavelengths. The instrument's wavefront sensor has a much greater field of view than the same sensor on GMOS. It can be used with any suitable guide star within a circular radius of 3.5 arcminutes from the field center, and at any choice of position angle (modulo 180 degrees). Unlike the optical GMOS spectrographs, FLAMINGOS-2 can be fed with either the f/16 standard Gemini feed, or the MCAO-corrected f/33 beam, opening up a wealth of new observing opportunities. With the f/16 beam, the plate scale is 0.18 arcseconds per pixel, and the imaging field of view is a circle of 6.2 arcminutes in diameter.

The MOS field of view is a pseudo-rectangular

section of this circle, with a width of two arcminutes in the dispersion direction and a height of six arcminutes perpendicular to the dispersion direction, of which the central four arcminutes provides full spectral coverage. Figure 3 shows a schematic of the imaging and multi-object spectrograph field of view, with slits overlayed on a UKIRT Wide-Field Camera image of the Orion Nebula. When fed by the MCAO beam, the pixel scale is halved to 0.09 arcseconds per pixel, and the multi-object spectroscopy field of view becomes 1 x 3 arcminutes, though MCAO only provides corrections over the central 2 x 2 arcminutes. At this plate scale, the MCAO point-spread function is not fully resolved, so special care must be taken when reducing the spectra of spatially extended sources.

For most imaging purposes, the Gemini South Adaptive Optics Imager (GSAOI), with its much finer pixel scale, will be the imager of choice. FLAMINGOS-2 will then complement GSAOI nicely, being able to take multi-object spectroscopic observations of sources discovered with GSAOI. Additionally, there is a tunable filter assembly, known as the FLAMINGOS-2 Tandem Tunable Filter (or F2T2), under design by Com Dev and led by a group at the University of Toronto for use specifically with FLAMINGOS-2, which will provide a tunable narrow-band imaging capability not available with GSAOI. The arrival of MCAO will enhance the spectroscopic capabilities of FLAMINGOS-2 in several ways. By increasing the spatial resolution it will allow for more closely packed slits, which are good for targets in dense regions such as the galactic center. It will significantly decrease the sky background flux relative to the source flux, per pixel, thus increasing the sensitivity. It will also allow more frequent use of the narrowest slits on point sources (i.e., reducing slit losses), allowing us to obtain the highest spectral resolutions regardless of atmospheric seeing.

Scientific Use of FLAMINGOS-2

FLAMINGOS-2's true calling is as a survey instrument, enabling the rapid expansion of survey samples by an order of magnitude or more. For bright objects in dense environments, such as the center of the Milky Way Galaxy, FLAMINGOS-2 can pack 40+ objects into a single mask, and with nine mask slots in the instrument, spectroscopy of 360+ objects per night is feasible. Multi-object spectroscopy also opens up possibilities for faint target surveys. In the past, it might have been difficult to justify to time allocation committees the observations of individual targets requiring more than 10 to 15 hours of integration. Now, averaging over 20+ targets in a mask takes less than an hour per target.

These kinds of observations will naturally be used to target high-redshift galaxies, such as those in the "optical redshift desert" between $1.4 < z < 2.5$. These galaxies are faint and require long integration times and, because their restframe optical spectra are shifted into the near-infrared wavelengths, they are accessible with FLAMINGOS-2. The advantages that near-infrared multi-object spectroscopy have over optical spectroscopy will also be seen in very dusty regions, such as the star-forming regions in dense galactic molecular clouds, where optical extinction prohibits any GMOS-based investigation.

The addition of MCAO opens up even more fields of study. Crowded-field multi-object spectroscopy of individual stars in nearby galaxies such as the Large Magellanic Cloud should be feasible, as will spectroscopy of young star clusters in the dusty regions in nearby galaxy mergers. For high-redshift galaxies, the increased sensitivity will aid the detection of the faintest and most distant emission line objects.

Figure 3. Schematic diagram of the FLAMINGOS-2 fields of view. The imaging FOV is circular with diameter of 6.2 arcminutes (for the f/16 feed), and is shown here in shaded green. The MOS field of view is the 2 x 6 arcminutes pseudo-rectangular portion of the circle marked here with the dark green border. The detector is a 2048 x 2048 pixel HAWAII-2 array, with 0.18 arcsecond pixels. The spectral dispersion direction is perpendicular to the long axis of the rectangle, and within the MOS field of view an arbitrary number of slitlets can be cut, with length and width specified by the user. When using the MCAO beam, the pixel scale is halved to 0.09 arcsecond per pixel, with the imaging and MOS fields also cut in size accordingly. Background: UKIRT WFCAM commissioning image of the Orion Nebula region, produced by the Joint Astronomy Centre. Data processing by Dr. Chris Davis and Dr. Watson Varricatt.

These are just a few of the many ideas astronomers plan to pursue with FLAMINGOS-2.

Timeline for FLAMINGOS-2

At the time of writing, FLAMINGOS-2 is in the lab in Florida undergoing final mechanism tests and optimization. Acceptance testing is planned for the end of 2006, with delivery of the instrument to Gemini South in early 2007. After reassembly and a period of lab characterization, on-sky commissioning will commence (probably around March 2007). This will last for several months because there is a lag between when images can be first obtained and when the corresponding multi-object spectrograph masks can be designed, fabricated, and installed in the instrument. Following commissioning, there will be a call for system verification and demonstration science proposals, probably around July, 2007. This will pave the way for the first general call for FLAMINGOS-2 proposals in September, 2007, for observations beginning in semester 2008A. Commissioning of FLAMINGOS-2 and F2T2 with MCAO will probably occur after the commissioning of GSAOI, and will include another round of system verification programs prior to inclusion in the general call for proposals.

It is an exciting time to be at Gemini South. With the additions of FLAMINGOS-2, MCAO, and GSAOI, the Gemini Observatory is poised to take the lead in near-infrared spectroscopy and high resolution imaging for the near future.

Marcel Bergmann is a staff astronomer at Gemini South and can be reached at: mbergmann@gemini.edu

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.

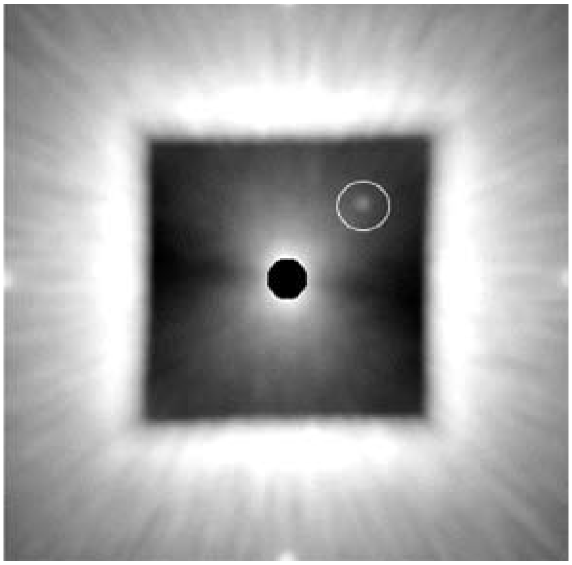


Figure 1. Simulated 20-second broadband near-infrared GPI image of a solar-type star at 10 parsecs (about 32 light-years), showing a 5-Jupiter-mass planet at 6 AU separation. Any bright star seen from the ground is surrounded by a halo of scattered light. Gemini Planet Imager's AO system and coronagraph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

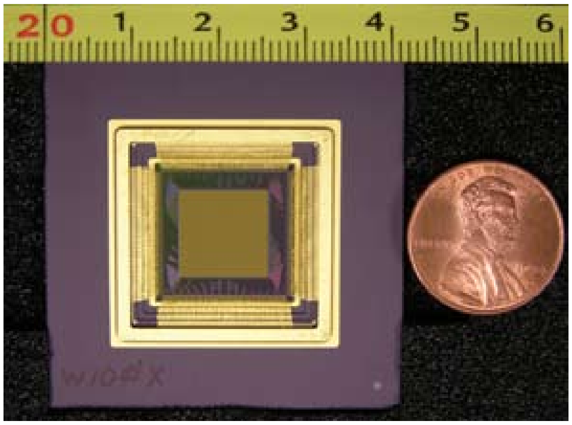


Figure 2. Gold-coated 1,024-actuator Boston Micromachines MEMS deformable mirror.

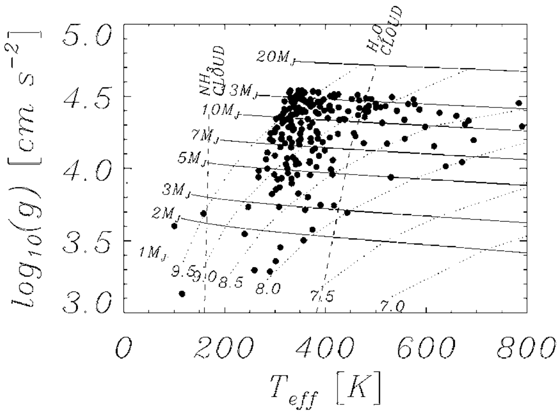


Figure 3. Atmospheric properties of planets discovered by GPI in a simulated observing campaign. Each dot is a planet, plotted on a grid of surface gravity vs. temperature. Solid near-horizontal lines indicate planet mass. Dotted near-vertical lines show constant age, labeled with log10$_{(age)}$. Dashed 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.

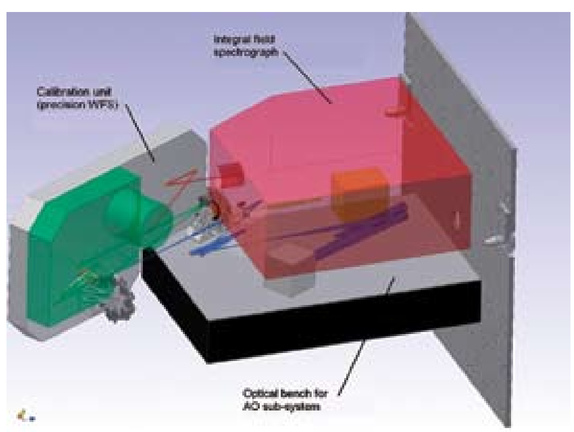


Figure 4. CAD design for GPI, with its covers removed, showing the plate for attaching to the Gemini Instrument Support Structure.

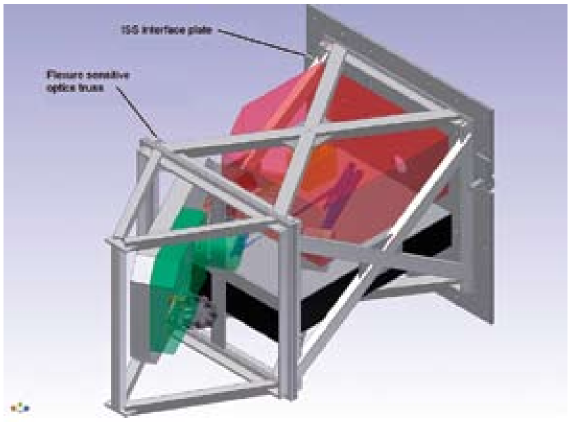


Figure 5. CAD rendering for GPI showing the major subsystems: the AO optical bench, coronagraph masks, precision infrared interferometer, and the science integral field spectrograph.

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

by Richard Myers

Ground Layer AO: A "Third Gemini?"

The existence of a "third Gemini" is a somewhat startling claim that refers to the possible gains in observing efficiency that could be achieved by installing a specialized type of adaptive optics system on the Gemini telescopes. This summary article explains the difference between the ground layer adaptive optics (GLAO) technique and the other types of adaptive optics (AO) systems already familiar to many Gemini observers. In particular, we summarize the results of a feasibility study which Gemini has conducted on the possibilities for implementing GLAO. We also describe the ongoing characterization of the Gemini North site to quantify its suitability for GLAO.

The GLAO feasibility study was part of Gemini's Aspen instrumentation development process and was conducted by the multi-institution team described later in this article. The study received a successful independent review in March, 2005, and following its recommendations, a detailed study of turbulence statistics is being undertaken at the Gemini North site on Mauna Kea.

There are now many different types of AO systems planned or in construction for ground-based telescopes worldwide, but they all share the common goal of overcoming some of the consequences of being ground-based, namely the effects of atmospheric turbulence on starlight. It is this continuous "boiling" of the atmosphere, the so-called "natural seeing," which limits the attainable angular resolution of any ground-based near-infrared/optical telescope. In the case of 8-meter telescopes such as Gemini, the resolution can be degraded by factors of between 10 and 100 with respect to the physical "diffraction" limit. This happens even when telescopes are situated at the very best sites in the world, such as the Gemini telescopes at Mauna Kea in the north and Cerro Pachón in the south.

It follows directly from the principle of GLAO, outlined on page 80, that its effectiveness will depend upon the statistics of the vertical distribution of atmospheric turbulence. How often is there a dominant turbulence layer that carries a sufficient proportion of the turbulence to give useful wide-field correction? How does the occurrence of this condition correlate with general seeing levels? How close is the dominant layer to the altitude of the telescope? Data to answer these questions are available for the Gemini South site. Analyzing the data with a battery of independent GLAO performance models, the feasibility study addressed the key issues for a GLAO implementation on Gemini. What correction performance (vs. field of view, vs. wavelength) could be expected with what frequency and stability? Could the required near-all-sky availability be achieved using natural

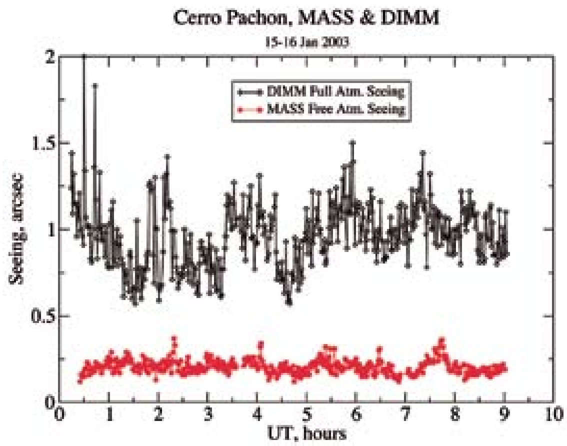

Figure 1. Seeing measurements for the Gemini South site from January 2003. The free-atmosphere seeing records the effect of the atmosphere above the ground layer. The full-atmosphere seeing shows what happens when the ground-layer is included. This is what the observer will experience without AO. Data and figure from Andrei Tokovinin, CTIO.

guide stars alone or would laser guide stars be required? If lasers were needed, how many would be required to perform the tomographic separation of the ground layer contribution? Would an adaptive secondary give good conjugate matching with the dominant turbulent layers and hence provide an elegant and efficient feed to all instruments? The answers provided by the study, and a design concept for implementation of GLAO, are summarized below.

The occurrence of a dominant ground layer is illustrated for a typical good night for GLAO at the Gemini South site in Figure 1. The data were taken with the well-established Multi-aperture Scintillation Sensor/Differential Image-Motion Monitor (MASS/DIMM) technique where the free-atmosphere seeing (everything above the ground layer) and the full-atmosphere seeing are measured simultaneously. Here we see the free atmosphere quiet and stable throughout the whole night, while the ground layer is inducing the bulk of the seeing and variability. These are good conditions for AO and GLAO, in particular. The data also indicate the importance of such monitoring.

The data in Figure 1 certainly looks promising for that particular night in 2003, but what happens when we take into account a whole year's worth of turbulence distribution statistics and model the effect that a GLAO system would have? The first thing we need to consider is how to measure the improvement in image quality. What parameters are appropriate for a GLAO corrected image? For other forms of AO we generally look at parameters like the Strehl ratio, which is a comparison of the achieved image central intensity with that of a perfect image. In the case of GLAO it turns out that the corrected images have very similar shapes to seeing-limited images; they are just sharper. In fact, the GLAO-corrected images look almost identical to images which would have been recorded in better natural seeing. Familiar image quality parameters (and data reduction tools) are therefore appropriate and the study adopted the image full-width at half-maximum intensity (FWHM) as one of its measures of image quality. In Figure 2 we look at the statistical effect of GLAO on the FWHM distribution over a full range of conditions and at a variety of wavelengths.

Looking at Figure 2 in terms of gains in image quality during better conditions, the gains appear modest, particularly at shorter wavelengths (J and R bands). However, when we look at the worst-seeing end of the distributions, we see that bad seeing is virtually eliminated. Without GLAO, the poorest seeing occurs 30% of the time; with GLAO it only occurs 10% of the time. Likewise the best image quality, which was naturally available only 20% of the time, can be available 60 to 80% of the time with GLAO. What would the effect of this gain be on Gemini's observing efficiency? Over the 2004B program we calculate a 1.5 factor gain in efficiency due to systematically reduced integration times. Hence the "third Gemini" notion comes about if we apply GLAO to both telescopes. There is also a sense in which this proposed gain is conservative: the science done in the improved conditions would be "good seeing science," which we know has a higher "impact factor."

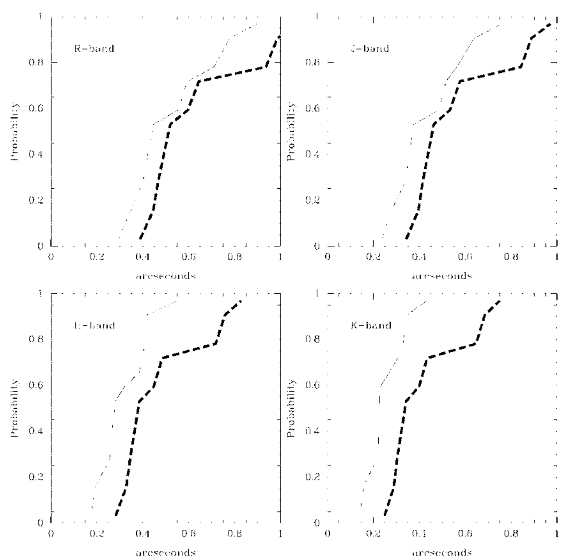

Figure 2. Cumulative histograms of the occurrence of image FWHM at four different wavelengths with GLAO (solid lines) and without GLAO (dashed lines). Figure is from David Andersen, HIA.

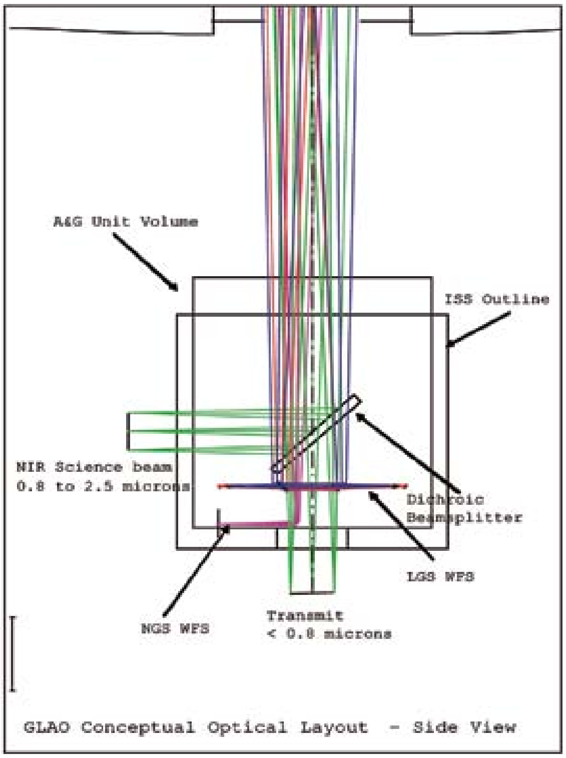

Figure 3. Design concept for a modified Cassegrain Acquisition and Guidance Unit. The existing instrument complement would simply attach to this structure as normal. An important point is that with the beamsplitter retracted, instruments at the bottom port will have access to the full wavelength coverage of Gemini. Figure courtesy David Crampton, Kei Szeto and the HIA team.

So how could this GLAO "seeing improvement" be delivered in such a way as to ensure full availability over the whole sky and without introducing throughput or efficiency penalties of its own? The feasibility study looked at a comprehensive set of implementation options and arrived at a recommendation for an adaptive secondary mirror upgrade to provide the correction and a set of four laser guide stars along with three natural guide stars to measure the atmospheric aberrations. The sensing of the guide star signals would be performed in a modified acquisition and guidance unit. This would be done in a "transparent" or "backwards-compatible" way so that instruments and observers would be essentially unaware of the change—except that good seeing would appear to occur significantly more often!

The need for laser guide stars did not in fact derive from considerations of sky coverage. When we looked at the uniformity of correction over the large GLAO fields we found that the random and irregular natural guide asterisms would not let us meet our specification, at least not easily. An all-natural scheme would have required a completely new optical configuration to pick off the number of guide stars required for uniform correction. The field uniformity that can be achieved with our selected four-laser-guide-star configuration is, in contrast, very good indeed. Furthermore, the laser and beam projection system is a subset of the existing design for Gemini South MCAO. The cassegrain wavefront sensing scheme has some new aspects, of course, but still achieves a substantial re-use of the system that is already in place. The design concept for the modified Cassegrain Acquisition and Guidance Unit is shown schematically in Figure 3.

The performance of our GLAO design concept is illustrated in Figure 4, and shows how a 7 x 7 arcminute scientific field can be oriented with respect to laser guide stars in an outer technical field. The variations in the corrected field's FWHM are illustrated by the contours. Note that the contour interval is very small indeed.

The elegance of the GLAO "universal-upgrade" design is that it will deliver great results for the entire Gemini user community. In fact, the only observers who would not benefit are those using GPI and MCAO; even single-conjugate adaptive optics (e.g., ALTAIR and NICI) will be improved. An important aspect of the design is the reuse of major components of the existing secondary mirror and instrument support systems, and of the LGS design for MCAO. A further welcome consequence is that GLAO will not require much down-time to

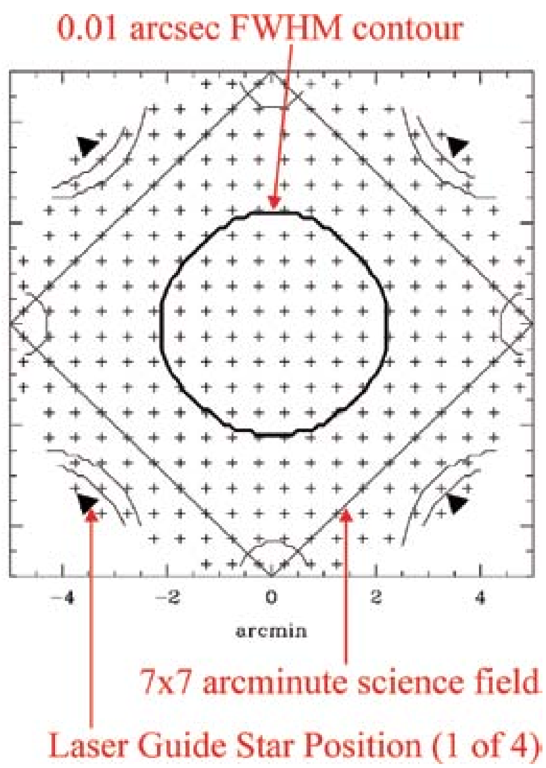

Figure 4. The orientation of the 7x7 arcminute "diamond-shaped" science field with respect to the four laser guide stars arranged on a the corners of square and outside the science field. The contours indicate the non-uniformity of the corrected image FWHM. This is very small: each contour represents only 0.01 arcsecond change in FWHM. Figure is from David Andersen and summarizes part of the work of the GLAO consortium.

implement. It will also be efficient in real-time use.

As mentioned earlier, the major immediate advantage of GLAO is the way it benefits almost all observers nearly all of the time. However, that is not the end of the opportunities with GLAO. Special GLAO-oriented instrumentation could fully exploit its wide-field correction to produce massive survey gains right at the cutting edge of Gemini science. The likely candidates would include a general-purpose near-infrared imager covering the whole GLAO field with pixel sampling optimized for the GLAO images. A rather more elaborate, and very powerful, instrument would be a multi-object integral field spectrometer, capable of performing 3-D spectroscopy in several sub-areas of the GLAO field simultaneously.

GLAO — A Benefit to All

Due to atmospheric spatial resolution limitations Gemini has a substantial AO program that includes:

AO System/Telescope	Type of AO	Status
ALTAIR/Gemini-N	Laser Single-conjugate AO (SCAO)	Available Now
NICI/Gemini-S	SCAO	Available 2007
MCAO/Gemini-S	Laser Multi-conjugate AO (MCAO)	Available 2008
GPI/Gemini-S	Extreme AO (ExAO) Planet Imaging	Available 2011

All of Gemini's AO systems shown in the table above (and reviewed in other articles in this issue) have their own target science and their corresponding specifications for corrected angular resolution and field of view. Of these, MCAO will have the largest uniformly corrected field of view of around one arcminute (~0.3 milli-radians) and it will achieve near diffraction-limited image quality in the near-infrared. GLAO aims for even larger fields of view, up to around eight arcminutes, but accepts a rather lower level of correction, albeit still very uniform across its very large (for AO) field.

Another key difference between other AO systems and GLAO is the natural seeing in which they would be expected to operate. Seeing has a statistical distribution with some nights much better than others. It is much harder to achieve good AO correction when starting with poor image quality, and therefore most AO systems are designed to be operated when the seeing is already quite good (better than average), or even very good (say the best 20%). GLAO, on the other hand, produces some of its best performance improvements in rather poor starting conditions. GLAO is therefore qualitatively different from other AO methods: it is much more a "general seeing improver" than a "specialized seeing remover." This consistent improvement in seeing leads to the "third Gemini" claim. Better seeing has direct and well-quantified effects on required exposure times, observing efficiency and program completion across the majority of Gemini's scientific programs. However this benefit comes with immediate consequences for GLAO implementation: the seeing improvement must be available across the whole sky and must come without substantial light losses or observing overheads to detract from the efficiency gains.

So, how is such GLAO correction achieved? The principle of GLAO is to correct preferentially, ideally exclusively, the lowest altitude turbulence, which for most sites is also the dominant layer. This is the "ground layer" of turbulence and conventionally extends up to one kilometer above the telescope. This idea relates to the "conjugates" referred to in the table (above) of Gemini AO systems. A single-conjugate AO (SCAO) system generally corrects the integrated effects of turbulence along some line of sight. A multi-conjugate AO (MCAO) system uses more than one deformable mirror to correct different vertical ranges of turbulence. One effect of multi-conjugate AO is to correct many lines of sight simultaneously, and hence achieve a wider uniformly-corrected field. GLAO is a "subset" of MCAO, which selectively corrects a single (dominant) layer of turbulence whilst more or less ignoring others. This then is the principal of GLAO: correct only the layer that gives the maximum effect over an extended field of view and accept the limitation on the degree of correction that this restriction entails.

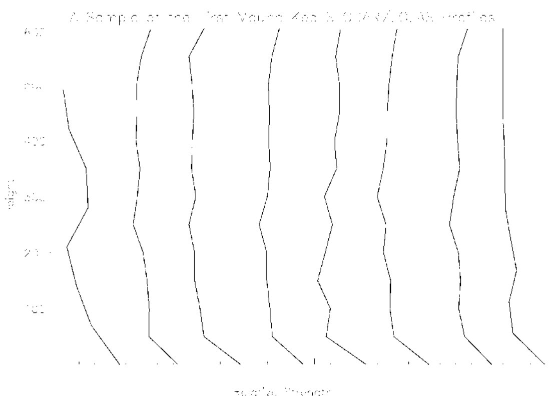

Figure 5. First data from the Mauna Kea GLAO site-study. Each vertical plot is a separate high-resolution relative-turbulence profile measurement over the first 600 meters above the site. The plot is by Mark Chun at the University of Hawai'i. The team at Mauna Kea are Mark Chun and Don Weir (UH), Jose Luis Aviles and Remy Avila (UNAM), Richard Wilson and Tim Butterley (Durham).

The GLAO teams have submitted a paper (to *Publications of the Astronomical Society of the Pacific*) that provides much greater detail on modelling. This includes the comparisons among the five different codes, the site data, and the effects of the placement of the natural guide stars.

The next phase for Gemini GLAO is to investigate the statistics of the vertical distribution of turbulence on Mauna Kea. It might be assumed that we would already have rather complete knowledge of Mauna Kea seeing, but GLAO performance prediction requires rather specialized knowledge of the precise location of the lower turbulent layers with good (about 100 meters or about 328 feet) vertical resolution. These measurements have just commenced and are using two specialized instruments in tandem: the slope detection and ranging SLODAR system from Durham University (also used at the Very Large Telescope (VLT) site) and the new LOLAS (LOw LAyer SCIDAR (SCIDAR = SCIntillation Detection And Ranging)) instrument from Universidad Nacional Autónoma de México (UNAM). The resulting data will be generally available and this campaign will therefore be a valuable service to anyone planning AO for Mauna Kea. There will also be a Gemini GLAO-specific modelling project which will repeat the Gemini South performance predictions for Gemini North.

Figure 5 shows the first-light combined SLODAR and LOLAS profiles from the Mauna Kea GLAO site study. Each vertical plot shows a separate vertical profile of relative turbulence strength vs. altitude over the first 600 meters above Mauna Kea. Note that the vertical resolution is clearly better than the required 100 meters and that there is a significant very low altitude contribution in each profile. These data became available just as we went to press.

The original GLAO team includes David Crampton (feasibility study leader), David Andersen, Jeff Stoesz (now at Observatorio Astrofisico di Arcetri), Laurent Jolissaint, Kei Szeto and Jean-Pierre Veran at Herzberg Institute of Astrophysics (HIA); Michael Lloyd-Hart and Mark Milton at Steward; Tim Butterley, Simon Morris, Richard Myers and Richard Wilson at Durham University. Substantial and continuing help subsequently came from Brent Ellerbroek at TMT and Andrei Tokovinin at Cerro Tololo Inter-American Observatory, (CTIO), Miska LeLouarn at European Southern Observatory provided a cross check against VLT GLAO modelling. The Mauna Kea GLAO site evaluators are Mark Chun at University of Hawai'i, Remy Avila and José Luis Avilés at UNAM (LOLAS) and Richard Wilson and Tim Butterley at Durham (SLODAR).

For more information see:

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The author would like to thank the entire GLAO team for their assistance in producing this article.

Richard Myers is a senior fellow at Durham University and also current Chair of the Gemini Adaptive Optics Science Working Group. He can be reached at:
r.m.myers@durham.ac.uk

by Jay A. Frogel

A History of Funding for AO in the United States

Introduction

My purpose in this article is to examine public and private funding for adaptive optics (AO) research and development (R&D), systems, and instrumentation in the United States. I will concentrate on the period from 1995 through, 2006 with projections through 2009. AO funding during this time period is spread over at least one dozen telescopes and institutions although the bulk of it goes to just a few of these. Private observatories receive close to 60% of all AO funds. The other ~40% goes to public observatories and institutions for work that is of immediate benefit to the entire community. I also determined that by 2009, expenditures on AO by ESO for the VLT alone will be three- to four-times higher than similar expenditures in the U.S. for all telescopes, public and private.

Recognition of the Need for AO Funding in the USA on the National Level

To set the stage for my examination of funding for AO R&D and instrumentation in the United States, it is helpful to review the recommendations of several major national committees over the past two decades. We start with the last two National Academy of Sciences/National Research Council (NAS/NRC) Decadal Surveys. The survey for the 1990s, the *Bahcall Report*, was unequivocal in its call for AO development: "The highest priority [moderate program for ground-based astronomy] is to apply technologies collectively called adaptive optics." The specific recommendation was to spend $35 million over the decade of the 1990s on AO R&D and instrumentation.

The *McKee-Taylor Report* for the current decade did not call for, nor prioritize, an AO program in its main volume. But in the accompanying reports of its panels the importance of AO is clearly stated: "The utility of a 30-meter or larger aperture telescope depends crucially on its near diffraction-limited performance, particularly in the 1- to 25-micron range." The specific recommendation made in the *Panel Report* (but not repeated in the main report) is that there should be an AO effort associated with the development of a Giant Segmented Mirror Telescope (GSMT) funded at $5 million/year over the decade. Adjusted for inflation, this is about the same funding level recommended in the *Bahcall Report*. The *McKee-Taylor Report* correctly pointed out that this AO work will also be a boon to existing large telescopes.

NSF AO Roadmaps

As my daughter's favorite cartoon character, *Dora the Explorer* knows, when starting out on an exploratory trip you need a map, especially if that trip will cost tens of millions of dollars and have many potential dead ends and traps for the unwary. Following Dora's advice, the National Science Foundation (NSF) in 2000 issued a Roadmap for the Development of Astronomical Adaptive Optics, and, in 2004, an addendum to this roadmap. The 2000 roadmap (and presumably the last decadal report) led to the creation of the AO Development Program (AODP) to be administered by the National Optical Astronomical Observatories (NOAO). Its key goal was to ensure that a GSMT would have the AO capability necessary to maximize its scientific effectiveness. The focus of the program for the first five years was to be entirely on technology and proof of concept demonstrations (development), not on instrumentation for research on telescopes (implementation). It was expected (hoped?) that funding from the Telescope System Instrumentation Program (TSIP) would bring usable AO instrumentation to at least the private observatories. Since TSIP's *modus operandi* is to give NSF awards to large private facilities in exchange for publicly available nights on those facilities, the result would be that the entire astronomical community would have some access to state of the art AO tools. Unfortunately, as I will show, neither of these expectations—that AODP would make $5 million/year available for AO R&D and that TSIP would make the fruits of AODP harvestable by the astronomical community—have been fulfilled. Fortunately, a more *ad hoc,* but only partially successful, approach has allowed AO to become a highly desirable and increasingly available tool for astronomers of all persuasions in the U.S.—from solar system adherents to those who would pursue photons that come from the edge of the visible universe.

In the next two sections I will first summarize the channels that NSF uses to fund AO development and implementation in the U.S. and then describe the main private sources of funds. Let me state at the outset that throughout this paper I consider only funds that are used for AO R&D and instrumentation. I do not include any funds used primarily to support science research either astronomical or non-astronomical with AO instrumentation.

Public Funding for AO in the United States

One of my objectives in this paper is to compare the level of "public" and "private" funding for AO in the U.S. I will discuss primarily the period after 1995. Identifying funding sources as private is usually clear-cut. They are most often foundations, individual donors, or institutions that support their own facilities. Use of these facilities is usually restricted to a small cadre of researchers. By public funding, I mean funds that are generally available to all astronomers via a competitive, peer-reviewed proposal process. These funds can then be used at both public and private facilities. In the U.S. there is only one significant ultimate source of public funds for AO development and implementation—the NSF. Figure 1 is a graphical representation of the various channels for public funding.

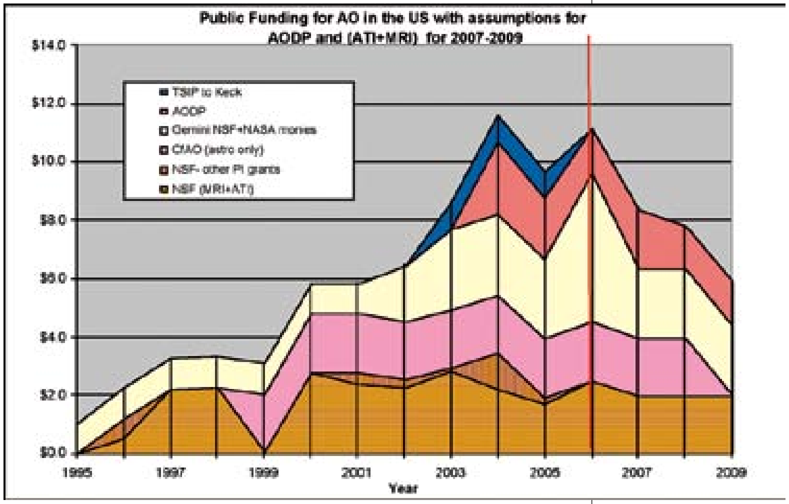

Figure 1. Public funding from various sources in the U.S. for AO activities. Vertical axis is in millions of U.S. dollars.

The Adaptive Optics Development Program (AODP)

AODP was started in response to the 2000 AO Roadmap. The first proposal solicitation by NOAO for this program was made in 2003 and was aimed solely at R&D and proof of concept work. Within this framework, the proposal process was open to all. Six multi-year awards were made for a total of ~$8 million, with funding to start in 2004. My guess is that NSF's expectations were that this was a down payment on the Decadal Survey recommendation of $5 million per year and that this level would be the steady state to be reached after two or three more years of solicitations and injection of new funds. After a second round of solicitations for FY 2004, NSF announced that no new funds would be made available to support these proposals, so no new grants were made. No new funds appeared for FY 2005 or 2006 either. However, there may be ~$1.5 million in new funds available for AODP in FY 2007. In Figure 1, the numbers through 2006 are actual disbursements from the FY 2003 funds. For 2007 to 2009, I have optimistically assumed that $1.5 million represents the level of new funds that will be made available on a yearly basis and that on average the awards will be spread over three years.

The Telescope System Instrumentation Program (TSIP)

As I noted earlier, there was an expectation that TSIP, an NSF program administered by NOAO, would provide some access for the entire U.S. astronomical community to those large telescopes with AO instruments built in part with TSIP funds. However, the only AO instrument built so far under the auspices of this program is OSIRIS, a near-infrared integral field spectrograph for the W.M. Keck Observatory. This instrument received $2.75 million from TSIP of its total cost of ~$5.2 million, of which the balance was covered by University of California operating funds. My guess is that there was a mismatch between the amount of TSIP funds available and the cost of AO instruments on large telescopes. Thus, already halfway through the first decade of the new millennium, the combination of AODP and TSIP is falling short of fulfilling the recommendations of the previous two decadal survey reports with regard to funding AO activities. Since the amount of new funds for TSIP for FY 2006 was only $2.0 million, half of what it had been the previous few years, I assume for purposes of projecting to 2007-2009 that no other AO instruments will come out of TSIP during this period.

The Center for Adaptive Optics (CfAO)

The CfAO at University of California-Santa Cruz is an NSF Science and Technology Center. CfAO has been funded for 10 years through 2008, at $4 million/year. Only half of this is available for astronomical AO applications. The other half goes towards research in vision science and to an extensive education and public outreach program. Most of the funds for astronomical AO are distributed via peer-reviewed proposals, but these are restricted to researchers at the 11 institutions that are members of the CfAO; five of these are units of the University of California system. Of the $2 million/year for astronomical AO at CfAO, about 40% goes towards AO R&D for extremely large telescopes (CfAO's Theme 2), the original purpose of the AODP. The other half goes towards extreme AO for planet finding, or ExAO (CfAO's Theme 3).

Although the funds in CfAO's grants program are restricted to scientists at the 11 member institutions, there are extensive collaborations with other labs and institutes such as Gemini, NSO, HIA, and Keck and with industrial associates. Also, the results of all of the AO work supported by CfAO are made public in a timely fashion so that everyone can benefit. Thus for purposes of Figure 1, I put the $2 million per year funding for CfAO over its lifetime into the "public" pot.

The Gemini Observatory

By international agreement, the NSF funds half of the operations and instrumentation budget of the Gemini Observatory. The other half comes from its international partners. A variable fraction of this budget is spent every year on a wide gamut of AO activities. From 1995 through 2009 (projected), Gemini has and will spend an average of $3.4 million/year from its facility development fund on its AO program. NSF's contribution is half of this, $1.7 million/year. Thus, the NSF funds expended on Gemini are nicely leveraged. I consider these funds as "public" since all U.S. astronomers can apply to use Gemini's AO capabilities during the 50% share of available science time to which the U.S. is entitled. The AO capabilities of the Gemini telescopes are well described elsewhere in this issue of *Gemini Focus*. Here I will just review their cost.

Over the past ten years Gemini's major expenditures on AO activities include the following (remember that NSF's share is only 50% of these numbers):

- MCAO system for Gemini South: $17.1 million;
- The AO Natural Guide Star (NGS) and Laser Guide Star (LGS) systems (ALTAIR) for Gemini North: $7.0 million;
- The near infrared integral field spectrograph (NIFS) on Gemini North at a cost of ~$3.0 million;
- The Gemini South Adaptive Optics Imager (GSAOI) will come on line shortly with a total cost of ~$3.5 million;
- Other related AO expenditures (R&D, etc.): $0.9 million.

In addition to these expenditures NASA, as part of its search for extra-solar planets, gave Gemini $4.5 million to build NICI, which was subcontracted to Mauna Kea Infrared of Hilo, Hawai'i, as prime contractor. There were no NSF or international partner contributions for NICI.

Recently, Gemini has contracted with Lawrence Livermore National Laboratory (LLNL), the Herzberg Institute of Astrophysics (Canada), UCLA, UC Santa Cruz, Jet Propulsion Laboratory, and the American Museum of Natural History (AMNH) to develop and construct the Gemini Planet Imager (GPI), an extreme adaptive optics coronagraph/spectrograph for Gemini South. This major undertaking is expected to take four to five years and cost ~$20 million. In collaboration with Keck, Lockheed Martin Coherent Technologies (LMCT) and the United States Air Force (USAF), Gemini has begun an extensive R&D and fabrication effort on lasers for general astronomical use. Gemini's share of this effort is $3.6 million, while Keck's is $2.8 million. Keck's share is from an NSF grant. This program is in concordance with NSF's AO Roadmap. Gemini's representation in Figure 1 includes all of the items noted in this subsection in addition to the NASA funds. For the former (Gemini) I put in 50% of the expenditures, for the latter (NASA) I included 100%. The remaining 50% of Gemini's budget for AO will appear later in this paper when I examine spending abroad.

	ATI MRI only		Other programs	
Year	# AO awards	M $	# AO awards	M $
1996/5	2	$0.512	2	$.709
1997	3	$2.246	0	0
1998	4	$2.285	0	0
1999	1	$0.071	0	0
2000	4	$2.797	0	0
2001	3	$2.378	2	$0.430
2002	5	$2.295	2	$0.238
2003	4	$2.852	1	$0.100
2004	2	$2.288	1	$1.241
2005	2	$1.692	1	$0.266
2006	5	$2.521	0	0
Total	35	$21.94	9	$2.98

Table 1. NSF expenditures on AO R&D and implementation via its ATI, MRI, and other PI grants programs.

Southern Observatory for Astrophysical Research (SOAR)

As part of the agreement by which NOAO joined the SOAR consortium, NOAO will spend $2 million of its own funds (ultimately from NSF) to build the SOAR Adaptive Optics Module, SAM. Since NOAO's membership in SOAR gives all U.S. astronomers access to this telescope, I consider this money part of the public pot.

The NSF's Grants Program

NSF is the major source of publicly available funding for AO R&D and instrumentation in the U.S. Of the various possible NSF sources for these funds, the largest such source over the period 1995-2006 has been NSF's Principal Investigator grants programs at $24.9 million. Most of these funds are from the ATI and MRI programs. The next two largest sources are Gemini and CfAO that I described earlier. Adding this all up and assuming that the PI grants program will continue to fund AO work to the tune of $2 million a year during the years 2007-2009 (see below), we calculate that the total NSF expenditure on AO activities exclusive of science over the period 1995-2009 is ~$80 million.

Table 1 gives the breakdown for AO related non-science grants since 1995 to September 25, 2006.

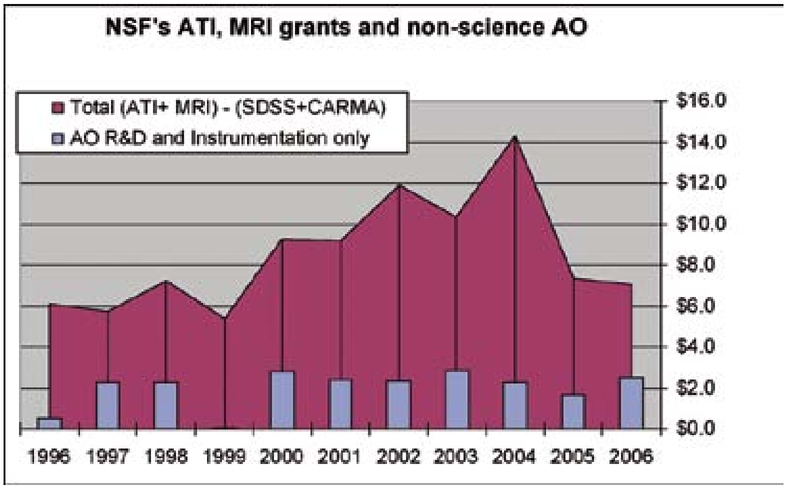

Figure 2. NSF's ATI and MRI programs together with amounts spent from these programs on awards to do AO. Vertical axis is in millions of U.S. dollars.

Note: I have combined data for 1995/96 into the 1996 label and also excluded the very large awards made to Sloan Digital Sky Survey (SDSS) and the Combined Array for Research in Millimeter-Wave Astronomy (CARMA). Of the $24.9 million, 86% is from the ATI and MRI programs. One of these grants is through NSF's ATM division to support instrumentation to make solar observations with AO. Solar astronomy both here and abroad is making increasingly heavy use of AO. The remaining 14% of AO PI awards directed towards astronomical applications (as determined from the abstracts of these awards in the NSF database) comes from a number of other divisions such as Computational Math. For example, the Computational Math grants generally are for image reconstruction techniques applicable to telescopic images. Figure 2 illustrates the total funds awarded per year by the ATI and MRI programs as well as the amounts awarded for AO R&D and instrumentation work in these programs.

In Figure 2 we see that the total funds awarded in the ATI+MRI programs generally increased from 1995/96 to 2004, but that in each of the past two years these funds were cut nearly in half. On average, the AO awards in these programs accounted for 14% of all successful proposals (35 total) in these programs but 25% of the funds awarded, or $2.29 million/year, for a total of $21.9 million over the time period. The nine non-science AO grants from the other NSF programs account for $3.0 million over the same time period.

The AO awards included in Table 1 are quite concentrated in terms of institutions and individuals. Table 2 shows that 70% of the awarded funds (but only 21 out of 44 awards) went to just five private institutions. Researchers at 17 other institutions received the remainder of the funds. Note that state universities are considered "private" since access to their facilities is not public in the broad sense. Table 3 shows that 69% of the awarded funds went to only nine astronomers out of 34 awardees. These nine individuals were awarded 16 of the 44 grants. Not surprisingly, this concentration of awards is strongly directed toward institutions with significant access to telescopes and to individuals at these institutions. To elucidate a couple of the entries: Oppenheimer at AMNH brings his instruments to the telescope at the Air Force's Starfire Optical Range facility in New Mexico while Rimmele built his instrument for use at NSO. Between 1990 and 1994, there were a few AO related NSF PI grants. Table 4 lists the four biggest recipients of these awards.

Table 2. Top five institutions receiving AO grants since 1995.

Institution:	# Awards	Amount	% of Total
U of H	6	$5,921,295	24%
U of A	7	$5,118,028	21%
AMNH:	4	$2,364,045	9%
NJIT	3	$2,186,630	9%
CARA	1	$1,958,000	8%
sum			**70%**

Table 3. Top nine PIs receiving AO funding since 1995.

PI	# Awards	Amount	% of Total
Ftaclas	3, UH, MTU	$3,009,987	12%
Oppenheimer	4, AMNH	$2,364,045	9%
Lin	1, UH	$1,978,755	9%
Wizinowich	1, CARA	$1,958,000	9%
Rimmele	1, NJIT	$1,821,322	7%
Lloyd-Hart	3, UofA	$1,791,435	7%
Close	1, UofA	$1,280,516	5%
Simons	1, Gem	$1,241,000	5%
Thompson	1, U Ill	$1,228,138	5%
sum			**69%**

Table 4. Four largest recipients of NSF AO related grants between 1990 and 1994.

PI	# Awards	Inst.	Total
Roddier	2	UH	$1.77M
Kibblewhite	3	U Chi	$4.17M
Thompson, L.	2	U Ill	$3.81M
McCarthy	1	UA	$1.05M

The National Solar Observatory (NSO) is a public facility, but much of its equipment is built by researchers at other institutions with NSF grants. In the 1995 to 2006 period, the NSF ATI and MRI grants specifically for AO systems for solar studies totaled $4.11 million, or 17% of the total NSF grants outlined in Table 1. These include all of the New Jersey Institute of Technology (NJIT) grants (Table 2). All but one of the solar grants was for work at the NSO.

Finally, after many hours of eye-strained searching the NSF database, I needed some literary relief. So I checked back over my list for the best award title. And the easy winner is: William Junor, from the University of New Mexico. In 1998 he was awarded $13K for a grant entitled: "*Catching the Perfect Wave: The Application of AO to Optical Interferometry for the Next Generation of Optical Telescopes*."

Other NSF Funds for AO

There is an interesting funding line in the House and Senate Conference Report on the FY 1992 Appropriations Bill for the Departments of Veterans Affairs and Housing and Urban Development (VA and HUD), which contains funding for NSF. In this Conference Report there is an amendment to the original NSF funding level which includes the following statement: "The conferees are in agreement with the following changes to the budget request: +$12,500,000 for astronomy facilities for an advanced adaptive optics program and operations and maintenance." As far as I have been able to determine there was never a reprogramming request that would have changed this amount, so this amount was in the final appropriations bill that then became law. Funding at this level would have been a good down payment on the Bahcall report's request for a national adaptive optics program. However, I have been unable to ascertain what happened to these funds.

Private Funding for AO in the United States and Major Recipients of AO Funding from all Sources

In trying to determine the largest private sources of funding for AO related work in the U.S., I first identified the institutions with active AO programs and then asked the cognizant individuals where their money came from. The remainder of this section summarizes my findings. There may be two ways in which this survey could be incomplete. First, there are some private observatories for which I did not examine AO funding, while for others for which I identified public sources of money, I was unable to determine if there were any private funding sources as well. Second, for the observatories that are listed, I may have missed some NSF grants that were used to support some of their AO activities.

Figure 3 illustrates the yearly funding to the private observatories from non-public (i.e. non-NSF or CfAO) funds. In this figure I have assumed that the base level of support for Keck will stay at ~$2 million/year through 2009. I cannot assess the likelihood that other private sources of funding will become available to pick up the fall off in funds shown in Figure 3 after 2008. Given this, and the fact that I have not investigated the funding stream for all private observatories, the upper envelope in this figure is probably a lower limit to the yearly private funding at private observatories.

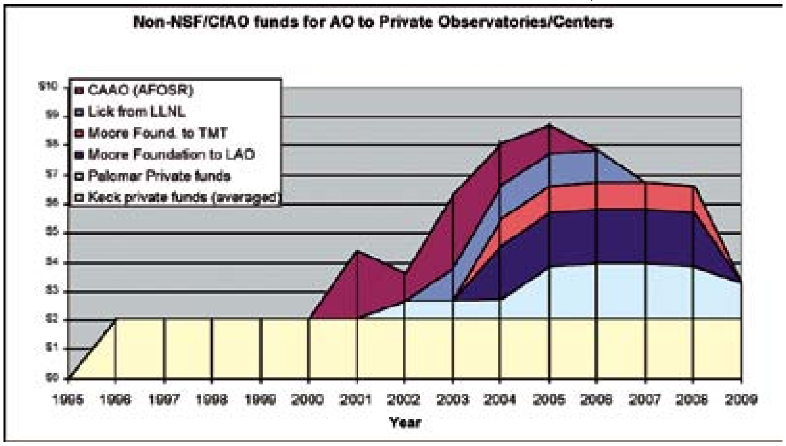

Figure 3. Major sources of private funding for AO related activities. Vertical axis is in millions of U.S. dollars.

Major Private Recipients of AO Funding from all Sources both Public and Private:

- W.M. Keck Observatory: Keck has or will receive ~$34 million from 1996 to 2009 for AO R&D and implementation from NASA, the W.M. Keck Foundation, the University of California (UC) system, Lawrence Livermore National Laboratory (LLNL), CfAO, NSF, and AODP. This amount does not include funding for AO-related activities from these same sources to other units of the UC system (e.g. UCLA, UCSC, LLNL) that might ultimately be used for Keck work. Nor does it include costs of planned future instruments for which funds have not yet been identified. This works out to $2.6 million a year, an amount comparable to the averaged total annual outlay for non-science AO from the entire NSF PI grants program or to the average annual expenditures on AO by the Gemini Observatory that can be attributed to NSF funds.

Of the ~$34 million that Keck has received, 80% is from private sources, mainly UC operating monies (38%), the W.M. Keck Foundation (24%) and NASA (15%). I consider the NASA money as "private" since it is non-competed; NASA partially supports Keck operations. Of the $34 million, ~40% has gone towards the LGS and NGS AO systems themselves. Just over 30% has gone towards two Keck II science instruments: NIRC2 and OSIRIS. The remaining 30% is committed to AO projects that are under development including: LGS R&D work in collaboration with Gemini, upgrades to the existing AO systems, a LGS system for Keck II, and R&D for the next generation of AO systems. Note that the science instruments themselves account for less than a third of the total AO budget. A recent NSF award to Wizinowich (CARA, 2006) for $1.96 million is for AO development work on the Keck Interferometer.

- Palomar Observatory: it will receive a total of ~$10.4 million in non-NSF funds from 2002-2009. These funds are from Caltech operating funds, gifts, and partners in the operation of the Hale Telescope. In 2006 Dekany (Caltech) received a $205,000 grant from NSF (ATI program) to develop a visible light AO system. He also received a $400,000 NSF/ATI grant in 2001 to develop tomographic wavefront sensing for the Palomar AO system.

- Lick Observatory: it has received ~$4.5 million from LLNL to outfit the Shane Telescope with AO including a laser guide star facility. There is one NSF/ATI grant to Gavel (UCSC, 2006) for $100,000 for work related to AO at visible wavelengths. See also UCSC just below.

- UCSC: the Laboratory for AO (LAO) on the UCSC campus has received $9.1 million in seed funds from the Gordon and Betty Moore Foundation, mostly for AO R&D work including MEMS and LGS. See also the previous entry for Lick above.

- The Thirty Meter Telescope (TMT) Project: The TMT has received ~$4.7 million for AO studies in 2004 - 2008 from the Gordon and Betty Moore Foundation.

- Center for Astronomical Adaptive Optics (CAAO): The CAAO is part of the University of Arizona. Since 2001, its major source of funding ($8.2 million) has been the Air Force Office of Science Research (AFOSR). Since 2002, it has received an additional $3.9 million from the NSF. These funds have been AO-specific PI grants, whereas the AFOSR funds have been used for more broadly applicable R&D developments such as deformable secondary mirror technology and demonstration of a multiple-laser AO system. Since support from the AFOSR ends in 2006, the future of the CAAO is uncertain. See also the next entry for University of Arizona below.

- University of Arizona Steward Observatory and the MMT: as is evident from Tables 2 and 3, the University of Arizona has been one of the major recipients of NSF funds for AO work since 1995. From 2002 onward, I credited NSF grants for AO work to CAAO (see above). Between 1995 and 2002, there were four NSF grants for AO work for a total of $2.5 million. Between 1990 and 1995, there was one sizable grant for AO work (Table 4). I do not know if any additional private funds have gone toward AO activities, for example from the operating budgets or partner institutions of either of these observatories.

- Magellan Telescopes: in 2003, NSF awarded a $1.28 million grant to Laird Close, (PI) of the University of Arizona to develop an AO system for one of the 6.5-meter Magellan Telescopes on Cerro Las Campanas.

- Institute for Astronomy (IfA), University of Hawai'i (UH): as is evident from Tables 2 and 3, UH has been one of the major recipients of NSF funds for AO work since 1995. Reading through the abstracts of the awards, some of the funds went towards systems for the telescopes operated by UH, and some of the funds were used for systems on other telescopes on Mauna Kea and for the solar telescopes on Haleakala. Also, between 1990 and 1995, Roddier at UH received two NSF/ATI awards for AO totaling $1.84 million. I do not know if any private funds have gone toward AO activities, for example from the operating budgets of the IfA.

- Mount Wilson Observatory: MWO has received several substantial NSF grants for AO-related work. Laird Thompson (PI, University of Illinois) received $3.33 million in 1990 for the MWO/Illinois AO system and another $1.23 million in 2001 for a laser guide star system. R. Jastrow (PI) received $360,000 for the AO program in 1995.

- Astrophysics Research Consortium (ARC): two large NSF awards to E. Kibblewhite (PI, University of Chicago) have gone to develop AO systems for the ARC telescope. The first, in 1990, was for $3.57 million and the second, in 1998, was for $1.16 million. A third award for student training and laboratory work for $600,000 in 1993 appears, from the abstract, to have in part supported the same activity.

To summarize this section, the major funding sources I have identified for private research centers that support AO R&D and development and that are unavailable to the general community are: The University of California and Caltech operating funds, the W.M. Keck and Gordon and Betty Moore Foundations, AFOSR and LLNL.

A Comparison of Public and Private Financing of AO R&D and Development in the U.S.

In Figure 4, I have combined all of the private sources from Figure 3 into one category and superimposed them on the public sources of Figure 1. Figure 5 answers the question of what fraction of all AO R&D and development money is from private sources. The private sources included are as discussed in the previous section. The public sources include the NSF PI, AODP, and TSIP grants programs, the CfAO, and the fraction of NSF money spent on Gemini operations that goes towards AO. Note that NSF money to private

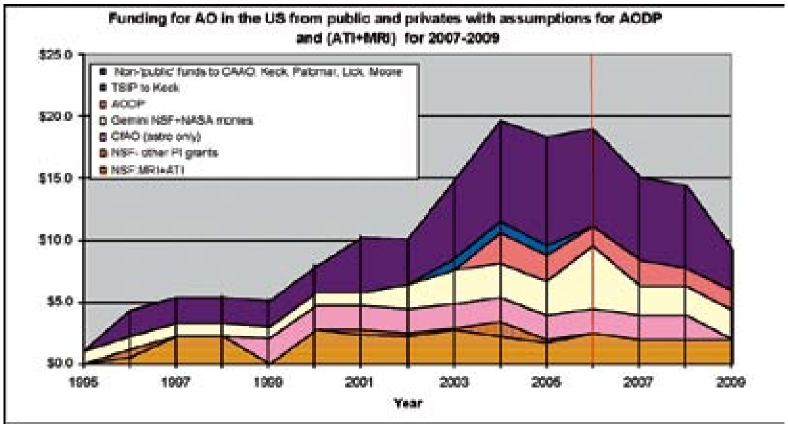

Figure 4. Major sources of private funds in the U.S. compared with public funding sources. Vertical axis is in millions of U.S. dollars.

observatories is counted only in the total AO funds, not in the private basket, i.e., only in the denominator of the ratio for Figure 5. As Figure 5 shows, private funding sources have held pretty steady at about 40% of total AO spending in the U.S. The projected dip for 2009 is due to the termination of the two Gordon and Betty Moore Foundation grants to TMT and LAO in 2008.
If we ask a different question, namely what is the total AO funding—public and private—that goes to the main private centers, we would need to include about $10 million from the NSF PI grants

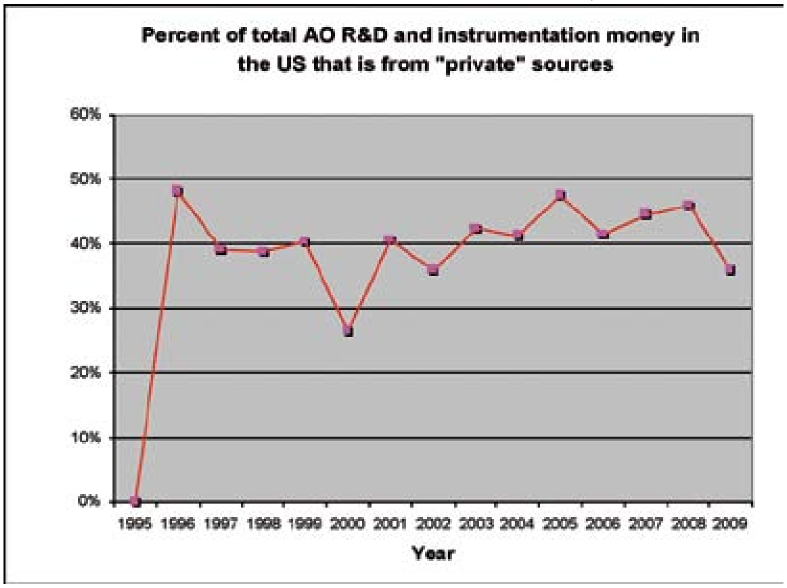

Figure 5. Percentage of all AO monies that are from private sources.

program (ATI and MRI), the TSIP money that went to OSIRIS, and some fraction of the AODP and CfAO funds. So, as an estimate, let's say that about $20 million of the "public" money has gone to private institutions in the 1995-2006 time period. This amount is 30% of the total public funds, or 40% of the private funds that the private institutions had for AO during this same time period. If it were spread out over the time period of 1995 to 2009,

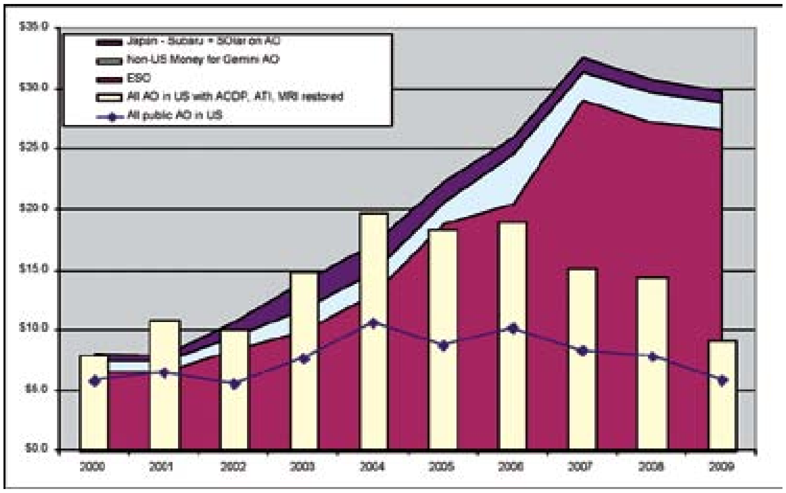

Figure 6.
A comparison of spending by ESO, Japan, and non-U.S. members of the Gemini partnership on Gemini AO activities. Vertical axis is in millions of U.S. dollars.

the average value from the graph in Figure 5 would now be nearly 60% of the total, rather than 40%.

Public (i.e., NSF) Funds for AO R&D Compared with the Recommendations of Decadal Surveys and Roadmaps

As we saw in the first section of this paper, the Bahcall and the McKee-Taylor reports recommended an expenditure of $3.5 million/year on AO in the 1990s and $5.0 million/year for this decade, respectively. The latter amount was to be spent primarily on R&D in preparation for a GSMT. Presumably these funds were to be from NSF and other public sources. What is the reality?

- NSF PI grants: for all grants that went into Table 1 the split is $19.5 million for instrumentation to go on telescopes ($1.6 million/year) and $5.4 million for R&D, or an average of $0.45 million/year.

- AODP grants: if we make the assumptions stated earlier concerning new funds for 2007-2009, then we have a total of $10.93 million or an average of $1.8 million/year for R&D.

- CfAO: based on years six and seven of the CfAO budget, 41% of the $2 million/year for the two astronomy themes is for R&D or ~$0.8 million/year.

- NSF/Gemini: AO expenditures here are almost entirely for instrumentation.

- TSIP: by definition these funds are for instrumentation only.

- Other NSF: I have been unable to ascertain the fate of a Congressionally appropriated amount of $12.5 million for NSF in FY 1992.

So the AO R&D public average for 2004-2006 is $3.05 million/year; for 2000-2003 (before AODP), it was $1.25 million/year. In 2009, it will drop again since funding for CfAO will have ended. These amounts fall short of the recommendations in the last two decadal surveys. Private spending would bring these amounts up a bit, but funding still is falling quite short of the decadal recommendations.

AO Spending in the U.S. as Compared with ESO and Other Countries

Even aside from ESO, many European countries and Japan have expended considerable effort to add AO capabilities to their telescopes for both daytime and nighttime observing. I will give some examples and then discuss ESO in some more detail. Figure 6 illustrates some of the numbers used in this section France and Canada provide primary support for AO on the Canada-France-Hawaii Telescope (CFHT) - PUEO, the CFHT Adaptive Optics Bonnette, for example. Italy and Germany will be supporting AO efforts on the Large Binocular Telescope (LBT), on Mount Graham, Arizona. Spain and Germany are developing a LGS AO system for the 3.5-meter telescope on Calar Alto in Spain. The UK, Netherlands, and Spain have built an AO system for the William Herschel Telescope on La Palma, and are actively developing a suite of AO instruments and a laser guide star facility. They are currently spending about $1 million/year on AO instrumentation. Between 1997 and 2006, they will have spent ~$9 million on AO instrumentation and support infrastructure. For instrumentation, the main source of funds has been the UK's Particle Physics and Astronomy Research Council (PPARC), but also the European Union. European solar telescopes on La Palma and Tenerife with existing, or AO systems under development, (including MCAO), are the 1-meter New Swedish Solar Telescope (NSST), and the German Vacuum Tower Telescope (VTT) and Gregor Telescope.

Japan is currently spending between $1 million and $2 million yearly for AO. The National

Astronomical Observatory of Japan (NAOJ) is the main source of funding. Between 1995 and 2006 they will have spent a total of $17 million for AO, about 10% of which goes to solar work. The rest is for the Subaru Observatory including the NGS and LGS systems and instrumentation. No major new instruments or AO systems are planned for 2007-2009, so a level budget of ~$400,000-$500,000/year is projected for Subaru, plus ~$50,000/year for solar work. Spending by Japan is shown in Figure 6.
The international partners in Gemini contribute an amount equal to that put in by the U.S. via NSF for AO work on the two Gemini telescopes. This is shown in Figure 6.

The annual funds ESO is spending, or has commitments for in AO R&D and instrumentation on the VLT, are now comparable to and (based on the projections in this article) will soon exceed the total amount spent in the U.S. from all sources on all observatories. Unit Telescope 4 (Yepun) is dedicated entirely to AO observing. It has an NGS system (NAOS) with an LGS system expected by the end of the year. MACAO (Multi-Application Curvature AO for VLTI) is available at the Coudé focus of all four Unit Telescopes (UTs) with a NGS system. Also currently available is SINFONI, a Spectrograph for Integral Field Observations in the near-infrared. The attached AO module uses either NGS or LGS. MAD is the Multi-conjugate AO Demonstrator at the Nasmyth focus.

There are a number of AO instruments in the works for the VLT. An adaptive secondary with 1,170 actuators is planned for the year 2012. HAWK-I is a near-infrared wide-field imager due to be completed in 2007 but has been designed with the adaptive secondary in mind. Each of the 4 UTs will have a LGS by 2010. Ground Layer Adaptive Optics (GLAO) is being worked on as well. An ExAO planet finder system is expected to be completed by 2010. A concept study is being carried out for an instrument called FALCON, a MOAO IFU system. MUSE (Multi-Unit Spectroscopic Explorer) is planned for 2012. Ultimately, this will have 24 IFUs for AO work in the visible.

I have been able to obtain real costs for about 80% of past, current, and committed expenditures on the VLT. For the remaining instruments I have made cost estimates based on scaling up from similar but smaller and less ambitious instruments elsewhere. The sum of the ESO expenditures by year is illustrated in Figure 6. For comparison, I also show the total (public plus private) expenditures on AO in the U.S. from Figure 4 (bars) and the public expenditures in the U.S. alone (solid line). In comparing these different spending profiles it is important to keep in mind that ESO expenditures are for one observatory, albeit with four 8-meter telescopes. In contrast, the total expenditures on AO in the U.S. that I have examined in this report, and even just the public expenditures, are distributed over many telescopes at many sites: Gemini x 2, Keck x 2, Palomar, Lick, MMT, Magellan x 2, ARC, MWO, NSO, Starfire, etc.

So what can we conclude from Figure 6?

- ESO is outspending the total Gemini AO budget by a significant factor even when the Gemini numbers are scaled upwards by a factor of two to go from two to four telescopes (I am not folding in the fact that operating on two sites is inherently more expensive than on one).

- In 2000, ESO and U.S. public expenditures for AO were comparable at ~$8 million. By 2006, public U.S. expenditures had flattened out at $10 million/year while ESO's had more than doubled to $20 million/year.

- My extrapolation of U.S. public AO expenditures through 2009, based on current spending levels and a small restoration of the AODP budget, shows a slow decline to $6 million. ESO's, on the other hand, shows a rise to $26 million, nearly four times greater than the U.S.'s public level.

- Even the private funding level in the U.S. drops off after 2006 for reasons stated earlier. One certainly hopes that other sources of private monies are found to support the AO effort at the private observatories, but absent any new monies, current projections have the private plus public total declining to $9 million/year by 2009, compared with ESO's $26 million, nearly three times as much for one observatory and only four telescopes.

Summary and Findings

AO systems are not just the wave of the future; the leading edge of the AO wave has already broken on land where the world's biggest telescopes stand and its reach extends back to the edge of the visible universe. Examples of the power of AO to contribute to fundamental science are amply demonstrated in the other articles in this issue of *GeminiFocus* and by the strongly increasing number of refereed articles in the major journals. There are now nearly 100 such papers per year presenting results based on observations made with AO systems on both nighttime and solar telescopes. This is twice as many as there were six years ago at the turn of the millennium.

John Bahcall was especially prescient in the NAS/NRC Survey report for astronomy and astrophysics for the 1990s that bears his name. Written more than a decade and a half ago, the report gave adaptive optics the highest priority of all moderate sized ground-based programs. This, in spite of the fact that during the entire decade of the 1980s there were only 20 refereed papers on AO, almost all of which were about technique; hardly any scientific results are in evidence amongst these 20. The science results now being obtained with AO systems on the world's large telescopes could not have been obtained in any other way. The largely unanswered call for support in the Bahcall Report was echoed a decade later in the *McKee-Taylor Report*. It emphasized the essential role AO would play in the operation of any extremely large telescope being contemplated and requested that $5 million/year be spent on AO R&D with the results of this work used to put AO systems on existing telescopes.

In this report, I have attempted to present an overall picture of AO funding in this country for the past ten years in order to take a measure of how well we are meeting the goals and priorities of the two decadal survey reports. I have also presented a comparison of spending patterns for AO in the U.S. with those in other countries, especially ESO. My findings are drawn from the numbers in the text and the figures. They are:

1. AODP, the program created in response to an NSF roadmap for AO, got off to a good start in FY 2003, but it is not succeeding. After its initial year, no new funds were made available for FY 2004, 05, or 06. Even if revived to the level I assumed for FY 2007, it will still fall short by more than a factor of three.

2. NSF funding of the CfAO, which ends in FY 2008, has been able to partially fill the gap left by the suspension of the AODP, but ends just as the AODP will be struggling back at a substantially reduced funding level. The other NSF PI grants programs contribute only a small amount to the R&D effort.

3. Public funds for non-R&D AO have been moderately successful at helping to put AO systems and instrumentation on some of the largest public and private telescopes in the U.S. For the past two to three years these funds have been as high as ~$6 million to $7 million/year, but are projected to decline for 2007/09. NSF's PI grants programs, especially the MRI and ATI, have been one of the largest contributors to this pot of money. However, funding for these programs was cut nearly in half for 2005 and 2006, although the amount going towards AO in these two programs has declined by a relatively smaller amount compared to funding in past years. TSIP has so far contributed partial funding for only one AO specific instrument on a private facility.

4. The biggest impact of the public funds for AO systems and instruments can be seen on the Gemini telescopes since NSF Gemini funds are matched by an equal amount from the other partner countries. Both Gemini North and South are being outfitted with a good suite of AO systems and instruments.

5. For the past decade, the rate of increase of private funding for AO-related work of all kinds has closely followed the rate of increase of public funding. Over this time period, private funds have accounted for just over 40% of all AO funding, public and private, with little scatter on a yearly basis. The bulk of these private funds have gone directly or indirectly to the W.M. Keck

Observatory. As for public funds, the level of private funding is projected to drop off after 2006 unless new sources can be tapped.

6. In addition to private funds which, by and large, go only to private facilities, about 40% of the non-Gemini public funds (or ~30% of the total public funds) between 1995 and 2006 went to support work at private facilities. Thus, private facilities, (including Keck, Palomar, the University of California campuses, UH, UA, and AMNH), have received about 60% of the total funding for all AO development and implementation between 1995 and 2006. If one goes back to 1990, then ARC and MWO need to be added to the list of major recipients of public funds.

7. Between 2000 and 2005, total AO funding in the U.S. per year was a bit higher than ESO's expenditures for AO work. However, from the best projections I have been able to obtain, by 2009 ESO expenditures for AO will be nearly three times the yearly total of U.S. expenditures on AO. Bear in mind that ESO's money goes to support one observatory with four telescopes. U.S. funds go towards the support of more than one dozen solar and night time telescopes at ten separate sites.

8. All of ESO's funding for AO is public in the sense that it supports all astronomers in ESO's member countries. From 2000 to 2004, public spending for AO in the U.S. was below ESO's on an annual basis (but growing). From 2004, onwards, U.S. public AO spending flattens out and then declines on a yearly basis. In 2006, U.S. spending is about half that of ESO's. By 2009, my projections show that the public part of AO spending in the U.S. will be one-quarter that of ESO's.

9. The total of actual plus projected expenditures for AO work at Gemini between 2000 and 2009, multiplied by two to scale to ESO's four VLT telescopes, it is only 60% of ESO's AO expenditures over the same period.

Conclusions

Current projections indicate that AO implementation on public and private telescopes in the U.S. will soon seriously lag that on the ESO VLT as measured by funds available. There needs to be a significant infusion of public funds for AO development (through AODP) and for AO implementation (through TSIP) so that, when combined with private funds, the U.S. astronomical community as a whole can take full advantage of AO systems on both public and private telescopes. Total funds for AO work at Gemini are also projected to be significantly below that for ESO/VLT, when scaled by number of telescopes. To equip the major telescopes in the U.S. with forefront AO facilities is a costly undertaking. TSIP has the potential to play a central role in the successful pursuit of this undertaking and thus optimizing the scientific benefit to be derived from the facilities. However, this can only happen if there is a substantial infusion of new public funds directed towards the AO goals of the last two decadal surveys and the NSF's roadmap. Without new U.S. funding, ESO astronomers will soon gain a strong competitive edge. This will allow them to take maximum advantage of state-of-the-art AO facilities to carry out forefront astronomical research now, and to plan for the extremely large telescopes of the future.

Acknowledgements:

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Jay A. Frogel is Vice President for Science at the Association of Universities for Research in Astronomy (AURA) and can be reached at: jfrogel@aura-astronomy.org

by Jean-René Roy
and Scott Fisher

Recent Gemini South Science Highlights

With this issue's focus on adaptive optics, all of the science highlights presented in this special *GeminiFocus* issue prior to this article have been from Gemini North since Gemini South's AO system is pending integration over the next 12-18 months. Of course astronomers have been using Gemini South for a wide variety of observations, with subjects of interest ranging from star formation in nearby galaxies to the haunting deaths of stars similar to the Sun. Here are a few highlights from the past six months.

Chemical Enrichment History of the Milky Way Bulge

In 1944, the German-born American astronomer Walter Baade showed that galaxies contain three or four different types of stellar populations: those in the halo, the thick disk, the thin disk and the bulge. The Milky Way shows this diversity, and each stellar population has different signatures in the kinematics, metal abundances and ages of its stars.

We have a good understanding of most components of our galaxy, except for the central bulge. This region is heavily obscured by dust, and even its most luminous stars are distant (about 26,000 light-years (8 kiloparsecs)), which makes them appear faint. High-resolution spectroscopy using a large-aperture telescope like Gemini in the infrared overcomes these observing obstacles of obscuration and distance.

Katia Cunha and Verne Smith from the National Optical Astronomy Observatories, Cerro Tololo Inter-American Observatory have used PHOENIX on the Gemini South Telescope to study seven red-giant bulge stars at a spectral resolution of about 50,000. They have studied the behavior of several elements (iron, carbon, nitrogen, oxygen, sodium and titanium) to help disentangle processes involving star formation and metal enrichment throughout the history of the bulge.

Comparing the behavior of oxygen versus iron abundances, Cunha and Smith have inferred that the bulge underwent more rapid metal enrichment than the halo, but that star formation continued over a longer period. Sodium in bulge stars shows a dramatic increase with increasing metallicity ([Fe/H]), possibly betraying a metallicity-dependent yield from Type II supernovae (elements blasted into space by exploding stars that were more massive than about seven solar masses). The bulge appears to have undergone a more rapid metallicity enrichment from supernovae Type II than the halo.

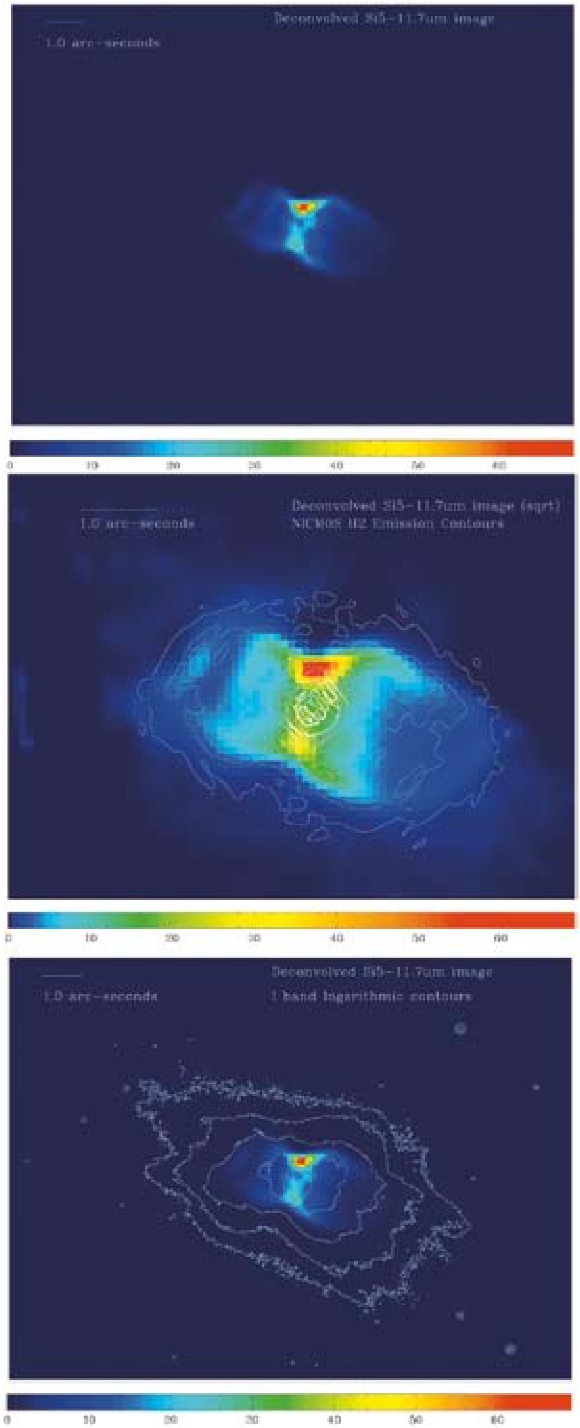


Figure 1.
A comparison of the morphology of IRAS 16594-4656 observed at optical (HST), near-infrared (HST) and mid-infrared (T-ReCS). The upper panel shows the deconvolved Si-5 T-ReCS image. The middle panel shows the Si-5 filter image again with different display scale to emphasize the lower level. The overlaid contours are from a HST NICMOS image in H_2. The bottom panel shows the same image with the log spaced contours from an I-band image from HST.

Fast outflows in young proto-planetary nebulae

Kevin Volk (Gemini Observatory) and his collaborators have obtained high spatial resolution images of the proto-planetary nebula IRAS 16594-4656 using the Thermal Region Camera Spectrograph (T-ReCS) at Gemini South. The images show a nebula that is at a critical phase of morphological transformation for planetary nebulae. A bright equatorial torus and a pair of bipolar lobes can be easily seen in the images (Figure 1). There is a good match to the Hubble Space Telescope optical image as well. The shape of the bipolar lobes indicates that the fast wind from the star is confined by the remnant circumstellar envelope of the progenitor asymptotic giant branch star. The morphology of the lobes clearly shows that they are confined by the circumstellar medium. In fact, the collimated outflow has not "broken out" yet, giving the nebula the appearance of being "capped" on its ends. The image is asymmetrical: the western lobe (right) may represent a slightly more advanced stage of breakout. It is predicted that both lobes will open into a butterfly morphology in a few hundred years.

Planetary mass brown dwarfs in Orion

Phil Lucas (University of Hertfordshire) and his colleagues have conducted a spectroscopic survey of 11 planetary mass objects in the Trapezium Cluster (in the Orion Nebula) with GNIRS at Gemini South and NIRI at Gemini North. They have derived the properties of the objects, including their masses, as inferred from gravity-sensitive indicators in the infrared spectrum. The triangular profile of the H-band pseudo-continuum, which peaks in the infrared at ~1.675 microns, is an indicator of low gravity. Because they are only about a million years old, the brown dwarfs of Orion have low surface gravity compared to field dwarfs of similar spectral type. This behavior is a good indicator of cluster membership. Masses were derived from model isochrones using the measured luminosity and assumed age. The new observations add significantly to the evidence that free-floating planetary mass objects exist in very young clusters. Planetary-mass objects that range between 3 to 14 Jupiter masses may contribute to as much as 14% of the population.

Hidden Mass Concentration in Starburst Galaxy M83

Using the near infrared integral field spectrograph CIRPASS at Gemini South, Rubén Díaz and an international team of astronomers, have discovered a previously unknown hidden mass concentration in the nearby spiral galaxy M83 that looks like a second nucleus. It is located at the youngest end of a giant star-forming arc near the galaxy's center (Figure 2). This concentration probably represents the wreckage of the nucleus of a smaller galaxy being swallowed by M83.

This double nucleus arrangement is also associated with complex kinematics (motions of objects and material) near the center of M83 (Figure 3). The masses of the objects were derived from the kinematics of the ionized gas. The nucleus of the intruder body has an estimated mass of about 16 million times the mass of the Sun, compared to two million solar masses for the optical "main" nucleus. The two nuclei are about 326 light-years (100 parsecs) apart and are probably harboring black holes. Numerical modeling conducted by the team suggest that the two nuclei would coalesce to form a single massive core in about 60 million years.

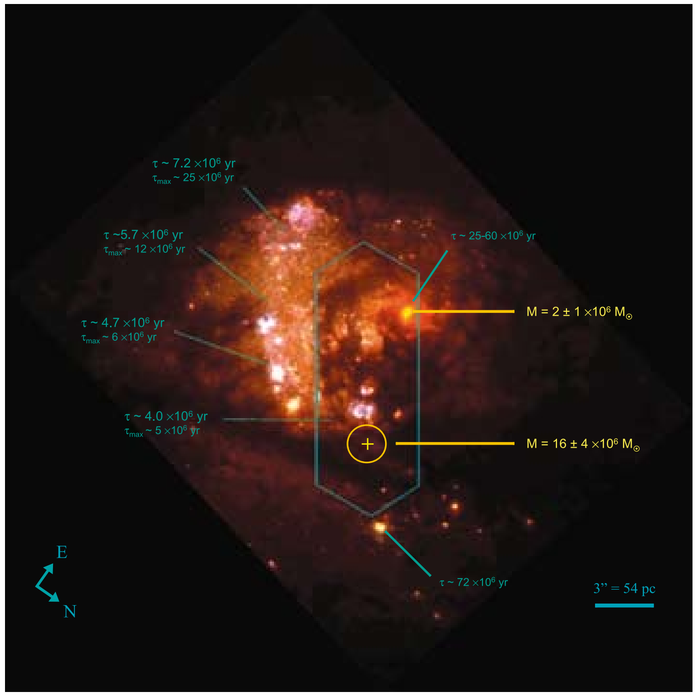


Figure 2. The CIRPASS integral field is depicted and superposed on a Hubble Space Telescope pseudo-color optical image of the center of M83. The rotation center of the galaxy (intruder nucleus) is at the youngest end of the partial ellipse that describes the positions of the main star forming regions of the giant arc.

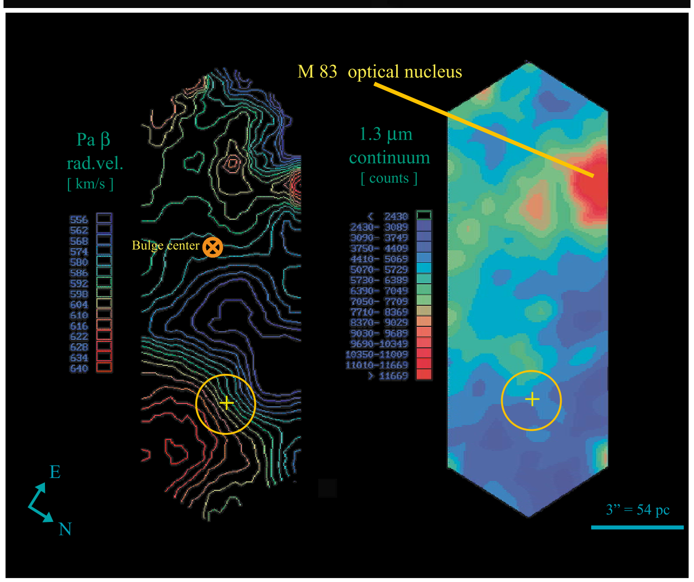


Figure 3. Left: the radial velocity of the ionized gas, corresponding to the main integral field observed. Note the position of the optical nucleus at the upper right of the CIRPASS field, the bulge center, and the intruder nucleus inside the yellow circle. Right: an image generated from the continuum in the spectral region of 1.28 microns. The achieved resolution is 0.6 arcseconds.

Located about 12 million light-years (3.7 megaparsecs) away, Messier 83 is a grand design galaxy displaying intense star-forming activity, likely the result of a recent merger of an accreted satellite galaxy.

Stellar Birth Control in the Young Universe

A study done with the Gemini Near Infrared Spectrograph (GNIRS) at Gemini South identifies a surprising class of distant ($2.0 < z < 2.7$) massive galaxies with strongly suppressed star formation. An international team led by Mariska Kriek of Leiden Observatory (Netherlands) and Yale University has found that 45% of a small sample of 20 massive high redshift galaxies have very low or lack star formation activity. The existence of "dead" massive galaxies at high redshift, at a time when the universe was between a quarter to a third of its current age, is unexpected. This recently published work puts a new twist on the growing evidence that most massive galaxies formed very early in the history of the universe.

The chosen galaxies are relatively massive, with a range of stellar mass between 0.9 and 460 billion solar masses. Surprisingly, nine of the galaxies have no detected emission lines based on their equivalent width of the Balmer hydrogen-alpha (Hα) line (Figure 4). Both the Hα measurements and the stellar continuum modeling imply that the star formation in these galaxies has been strongly suppressed.

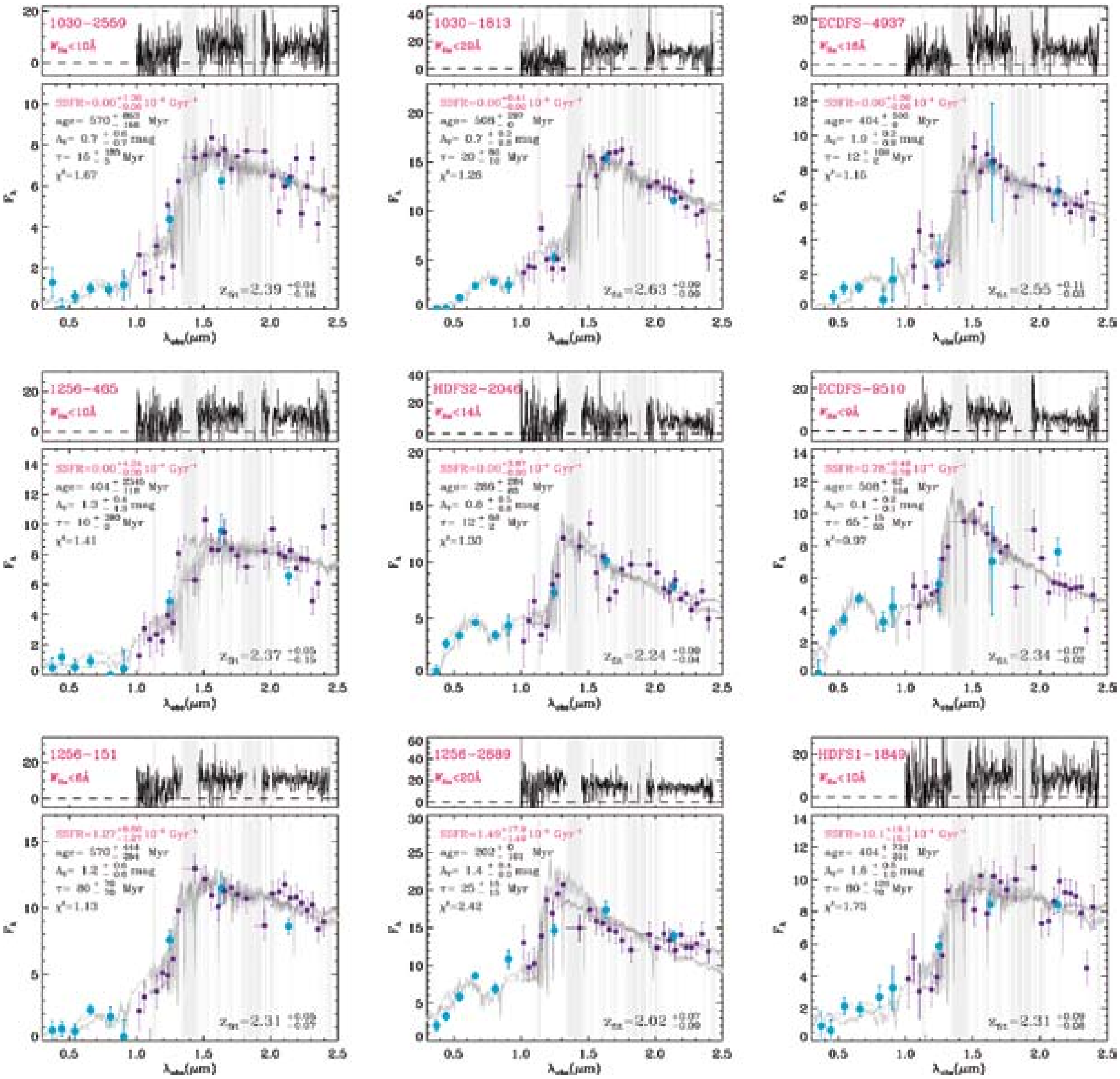


Figure 4. GNIRS infrared spectra (purple) and optical to near-infrared photometry (blue) of the nine "dead" galaxies. These galaxies show no (Hα) emission, which indicates that their star formation rates are extremely low. The upper panels show the original GNIRS spectra.

Feedback mechanisms like supernova or active galactic nucleus-driven mass loss could produce dead massive galaxies at high redshifts. Injection of huge amounts of mechanical energy and momentum over a relatively short period may also remove a huge fraction of the galaxy's gas in a short time and heat the remaining interstellar medium, making it stable against gravitational collapse. Activity from an active galaxy nucleus may have cleared the gas from the central dense regions.

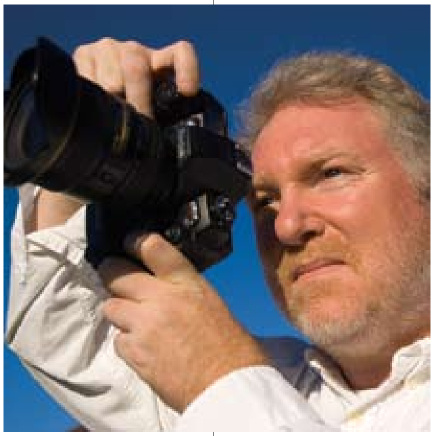
Jean-René Roy is Deputy Director and Head of Science at Gemini Observatory and can be reached at: jrroy@gemini.edu

Scott Fisher is a Gemini science fellow and can be reached at: sfisher@gemini.edu

by Carolyn Collins Petersen

Michael West: Gemini South's "Science Enabler"

Life at an observatory is a constant balancing act between getting ready for nightly observations and actually carrying out those observing runs. Oversight of all the work and personnel requires someone who understands the machines, the science, and the people who all come together to make it work. At Gemini South, the wizard who oversees the daily (and nightly operations) of the telescope and its executed science programs is Michael West, Head of Science Operations.



It's Michael's responsibility to ensure the efficient and scientifically productive operation of the telescope. He lives between the worlds of science and engineering, but as he states, the job requires more of him than that. "I like to think of myself as an advocate for the science staff, working hard to protect their research time, their safety, and being responsive to issues of importance to them," he said recently. "I'm also a point of contact with the Gemini user community, and so need to react quickly to user concerns. Above all, I see myself as a 'science enabler' whose job it is to help ensure that astronomers around the world receive the best data they can from Gemini South."

It's a big job. Michael sometimes compares the sheer amount of work he does with drinking from a fire hose. "Every day brings new challenges to deal with," he said, noting that, like other scientists who also do administrative work, finding time for his own research on galaxy formation and evolution, star clusters, clusters of galaxies, and the large-scale structure of the universe can be a struggle. On the bright side, however, he says, "I think I've finally learned most of the myriad of Gemini acronyms!"

Gemini's Deputy Director and Head of Science, Jean-René Roy considers the Head of Science Operations at either Gemini North or South among the most important and challenging positions at any modern, publicly funded observatory. "Michael is in a very strategic position at Gemini South since it is his responsibility to make sure that the products delivered at the end of each night correspond to the astronomer's requirements and, that the quality of the data obtained each night ensures a long legacy value in the Gemini Science Archive," said Jean-René. "I'm also quite sure Michael didn't realize the full complexity of the job he was taking when he signed on. However, after almost a year at Gemini South, Michael has not only survived, but he has demonstrated leadership, innovative ideas and strategic vision. He has come out with flying colors. Gemini South staff and colleagues of other observatories have commented most positively on Michael's management style and his wonderful team spirit."

As busy as he is with operations, Michael makes time out for another interest: public outreach. He takes it very seriously, presenting papers at professional meetings about ways to bring the wonders of astronomy to the public. He feels that it's a special duty that must be done. "As astronomers, we're very fortunate to be able to do what we do for a living," he said. "I feel that we have an obligation to give something back to the public that funds our astronomical explorations with these telescopes through their tax dollars. Plus it's a lot of fun!"

Michael's outreach efforts take shape in various forms. In Chile, he gives talks about astronomy at various social and media events. Before joining Gemini, he spent three years overseeing astronomy content development for the new 'Imiloa Astronomy Education Center in Hilo, Hawai'i, as a professor at the University of Hawai'i at Hilo. He has also been involved with the International Astronomical Union's Working Group on Communicating Astronomy with the Public. A feature article he wrote titled "Mauna Kea's Spectacular Skies" appeared recently on *Astronomy Magazine's* website. And then, of course, there's his beautiful book, *A Gentle Rain of Starlight*, which tells the story of astronomy on Mauna Kea in words and pictures. "The book was truly a labor of love," he said. "It grew out of my passion for astronomy and my desire to share the wonders of Mauna Kea with others."

He had the idea for the book during his work with the 'Imiloa Center. "My motivation for working at the 'Imiloa Center was a sincere desire to help build a bridge between the astronomical and Hawaiian communities and to communicate the joy and fascination of astronomy to as wide an audience as possible," he said. "In a sense, this book was a continuation of that effort. Mauna Kea is an amazingly special place—I'm still awed every time I'm up there—and I wanted share that with other people."

His idea was to capture not only in words but also in images the reverence that astronomers and native Hawaiians alike feel for the mountain. It resulted in a book with more than a hundred images (many of them his own), plus a story about Mauna Kea that captured the meaning that the mountain has for Hawaii's people.

Michael West's research career began as a theorist when he was a student at Yale University. "My doctoral dissertation at Yale was a computational study of the growth of galaxy clusters in universes dominated by different types of dark matter," he said. "I continued to do theoretical research for several years, including as a postdoc at the Canadian Institute for Theoretical Astrophysics. But I gradually moved more into observational astronomy. Much of my research efforts over the past ten years have focused on using the globular cluster populations of nearby galaxies to reconstruct the histories of their parent galaxies. But I'm also doing some work at high redshifts. For example, I'm part of a team that recently discovered the most distant x-ray selected galaxy cluster."

According to Michael, astronomers today are living in exceptionally exciting times, with a growing understanding of how and when the first stars and galaxies came into existence. "But there are still surprises, such as the existence of massive old galaxies in the young universe," he said. "They suggest our picture isn't yet complete. Fortunately, the abundance of exquisite data coming from Gemini and other state-of-the-art telescopes means that real progress is being made every day."

Former classmate and longtime friend Michael Gregg (now at University of California-Davis) says that Michael is someone who manages to see well-known things in new ways. "He can conjure up unexpected results from old or apparently ordinary places," he said. "Partly this is because Michael thinks hard and creatively, and is not shy about challenging the status quo. Even so, he is a gentle and diplomatic person, and can be hilarious!"

Gregg and West began working together in 1993 when they started imaging the Coma Cluster at Kitt Peak using the Burrell Schmidt telescope. But, as Michael Gregg points out, that wasn't the first time he'd had a taste of Michael's personality. They have been good friends since graduate school in the early '80s at Yale. "I remember that he liked strong coffee, had a pile of wadded up papers all around (but not in) his trash can because he was a terrible shot," Gregg said. "He also tortured us all with his alternative/punk music. "Land of the Glass Pinecones" stands out in my memory."
These days Michael West is still into music, preferring alternative music whenever he can find it. He says he always has music playing when he's at work or at home. Outside of work, he spends most of his time with his wife Cheryl and their five-year-old son Caden. They like to bicycle along the beach in La Serena and find the area very pleasant. Bernadette Rodgers, assistant astronomer at Gemini South, points out that Michael and his family have really taken to life in La Serena. "I think they've tried every restaurant in La Serena," she said. "Plus, Michael makes a real effort to speak Spanish with people at work whenever he can."

To that end, Michael has been taking classes to improve his Spanish-language skills. According to Lucia Medina, who is Michael's assistant at Gemini South, Michael takes his language tasks very seriously. "We accomplish many of our daily tasks in Spanish, and although he could handle himself in our language pretty well before, he takes pleasure in learning more Spanish," she said. "I am happy to work with him on it, even though he is very self-sufficient and rarely needs my assistance."

His other interests include travel, reading and writing, and what Michael describes as voracious reading. He tends to gravitate more towards literature than non-fiction. "I particularly enjoy short fiction," he said. "Lately I've been especially intrigued by 'flash fiction' in which authors write short but intense stories that aim to have an impact on a reader in just a few hundred words."

One of Michael's aspirations is to do more writing in the future, and has ideas for other books to work on. He takes his inspiration from the late Carl Sagan. "His book *Cosmic Connection* just "blew me away," said Michael. "It inspired me to become an astronomer."

The same qualities that inspired Michael are now what he uses to inspire others in his job. His friend Michael Gregg said it best: "Michael is a great pleasure to work with. His insights and diplomacy are qualities that make him an outstanding teacher and will no doubt help him succeed at Gemini."

Gemini's Recruiting Ambassador

For most new hires at Gemini Observatory, the prospect of relocating to Hilo or La Serena can be a daunting one. The distances to be moved and the very different cultures at each location can be a huge challenge for both new employees and seasoned veterans alike. Fortunately, the observatory is blessed with an exceptional recruitment and relocation specialist in Jeracah Holland. She is island-born and bred, which makes her a natural ambassador, bringing "aloha" to both Gemini locations.

The main part of Jeracah's job is to recruit Gemini employees, and then follow through as they begin their work at the observatory. She arranges and participates in interviews and, once someone is hired into a job, she takes charge of their moving and settling-in arrangements. "I am usually the first Gemini employee to contact them," she said. "I like being that first main contact and then helping to bring new staff onboard."

Jeracah's job is demanding and stimulating, and puts her in the middle of every hiring decision made at Gemini. "One of the biggest challenges in recruitment is scheduling the interviews," she said. "Our interview panels consist of anywhere between three and eight people, located in Chile and Hawai'i. It is quite a task to get them all to sit down at the same time for the interview."

Her work brings Jeracah into contact with some amazingly talented and diverse people from around the world. Through e-mail and phone calls, she gets to know candidates, learning their personalities and preferences. She has met some that she would really love to work with who, for one reason or another don't end up coming to Gemini. "It's tough when you have a slew of great candidates for a position and can only pick one," she said. "On the other hand, it's rewarding to see new employees succeed on the job and find happiness both with the job and in Hawai'i or Chile, and to know that I was part of the process. It's also gratifying when the recruiting managers thank me for the work I have done in a particular recruitment. Their appreciation motivates me and keeps me going when it's past dinner time and I'm still at work."

At work Jeracah is all business, according to officemate Gretchen Magnuson. "Jeracah thrives on the tough parts of her job," she said, "She can appear formal, which some may interpret as stand-offish, which is not true. Jeracah wants to appear professional at work. She strives for perfection in everything she does and does not hesitate to take on additional responsibilities."

More work did come Jeracah's way when two key positions in Human Resources recently fell vacant.

Typical of her professionalism and resolve to do the job right, Jeracah took on the duties of those jobs until others could be hired to fill them. "Overnight I became the most experienced person in the Human Resources department at Gemini," Jeracah said. "People came to me with their HR questions, and employee relations issues."

Away from the office, Jeracah spends her time with boyfriend TJ (a firefighter) and a cat named Buttercup. She practices yoga and is a wonderful vegetarian cook (who nonetheless, according to Gretchen Magnuson, fantasizes about pastrami sandwiches). "Jeracah is an excellent baker and makes these tasty mint brownies. She enjoys a good margarita now and then, and has the largest wine glasses I've ever seen," said Gretchen.

An environmentalist, Jeracah introduced Gretchen to the Union of Concerned Scientists and their informative newsletters on the best cars to buy, best foods to eat, and organic products to buy. "Jeracah is a conscientious consumer of organic foods and environmentally friendly products," said Gretchen, "Even Buttercup eats organic foods!"

Jeracah says that her concern for the environment and love of organic ways of life led her mother to dub her part of "Generation Yes!"—people between ages 25 and 32 who want to make a difference in the environment and the world.

Her fun side manifests itself in dancing, listening to live music, and taking in Big Island scenery in her own way. "I really enjoy driving in my car with the windows down and the sunroof open blasting Bruce Springsteen on my shabby sound system, going on roadtrips to Kona, discovering new places on the island, and riding my bike," she said.

Jeracah was born on Kauai and raised on the Big Island before moving with her family to Georgia after her sophomore year of high school. She graduated from the University of Georgia in 2001 with a B.S. in psychology. "Athens was such a fun college town," she said. "I miss it sometimes."

After college, she decided to skip the stress of trying to find a job and instead chose the stress of graduate school, attending Appalachian State University in Boone, North Carolina for her Master's degree in Industrial-Organizational Psychology and Human Resource Management. After graduation, she thought she might stay in the southeast and move to Atlanta and look for a job, but a trip back to Hawai'i changed her mind. "In 2003, I came to Hawai'i for about a week to go to a friend's wedding," Jeracah said. "One night of my trip, I was looking at the stars with a bunch of my hanai (adopted Hawaiian) family, and I told one of my aunties that I wanted to live in a place where you could see the stars at night."

The stars over Hawai'i were a deciding factor in her decision to return to the islands. A few months later she was back on the Big Island looking for a job. An ad in the paper led her to Gemini and her current position. It's a job she loves, and where she learns more about the magnificence of astronomy as she recruits people to work at the observatory.

"I am proud to work for a non-profit organization that is expanding the knowledge of our universe for all humankind," she said. "I recently went on a staff tour of the telescope on Mauna Kea and it was amazing. I am awed by how powerful an instrument it is, even if I don't exactly understand how the astronomers analyze and make sense of the data. I am proud of what Gemini does and honored that I get to be a part of it."

Carolyn Collins Petersen is a science/astronomy writer based in Massachusetts, and associate editor of GeminiFocus. *She can be reached at cpetersen@charter.net*

An Adaptive Optics Glossary of Terms

Altitude Conjugated. *When an AO system uses optics to form an image of a given turbulent layer (corresponding to a specific altitude) on an optical element.*

Anisoplanatism and Isoplanatic Patch. *Atmospheric turbulence is distributed in a volume (through approximately the first 20 kilometers above the telescope), so the phase perturbation measured along a line of sight is only valid for that line of sight. Going off axis, the degradation (anisoplanatism) is gradual, and there is a certain area in the sky where the error will be small. This angular area is called the "isoplanatic patch" (typically ~ 30 arcseconds in radius at 2.2 microns, scaling at the wavelength to the 1.2 power).*

Cone Effect. *Since a laser guide star is created at a finite altitude its light returning to the telescope forms a cone. In comparison, the light from an astronomical object (at essentially an infinite range) forms a cylinder. This difference has several detrimental effects on the ability to correct the wavefront distortions.*

Classical AO. *Uses a natural guide star as a reference source. It also uses a single deformable mirror and a single wavefront sensor. This is in contrast to laser guide star AO, multi-conjugate AO, or ground layer AO systems.*

Deformable Mirror (DM). *A device used in AO systems that can be deformed to match the (essentially) arbitrary shapes of the incoming wavefront. A deformable mirror operates within a limited range of spatial frequencies. Typically, these mirrors have dozens to hundreds of control elements (usually actuators, or miniature pistons attached to the back of the mirror that push or pull it).*

Extreme AO (ExAO). *A type of AO system in which the order of correction (number of elements in the deformable mirror/wavefront sensor) is very high. The goal is to achieve a very high correction quality, or a very high Strehl ratio.*

Ground Layer Adaptive Optics (GLAO). *An AO variant in which the deformable mirror is conjugated to the ground, and only the ground layer turbulence is measured and compensated for. This leads to only a partial correction, but on a field of view that can reach several arcminutes across.*

Laser Guide Star (LGS). *An artificial star created by exciting the sodium atoms located in the Earth's atmospheric sodium layer, at an altitude of 90 to 100 kilometers. A narrow, powerful laser, emitting yellow/orange light at 589nm is used to excite the sodium atoms.*

Multi-Conjugate Adaptive Optics, (MCAO). *Multiple wavefront sensors are used to measure the turbulence in different directions in order to reconstruct it in the entire 3-D volume over the telescope's field. Measuring not only how much turbulence there is, but also the altitude at which it lies, allows a set of deformable mirrors, conjugated to various altitudes, to enlarge the size of the AO compensated field.*

Natural Guide Star (NGS). *A star or any natural object that is bright and compact enough to be used by a wavefront sensor.*

Sodium Laser. *A laser used to deliver a yellow/orange beam at 589nm (sodium D2 line) light that excites sodium atoms in an atmospheric layer at an altitude between 90 and 100 kilometers.*

Strehl Ratio. *A measure of the quality of an image when close to the diffraction limit of an optical system. The Strehl ratio is the ratio of the maximum intensity of the actual image to the maximum of a perfectly diffraction limited image (provided both images are normalized in total intensity).*

Tip-tilt Correction. *Compensation of image motion only.*

Tomography. *The act of reconstructing 3-D information from a set of 2-D maps (or measurements). In the case of AO this is from turbulence measurements in multiple directions.*

Wavefront. *A light wave, characterized in a given X, Y plane by an intensity and a phase.*

Wavefront Sensor. *Device to measure the phase of a wavefront (that is, the deformations, i.e. bumps and holes). There are two primary types, a Shack-Hartmann and curvature which are described in more detail at: http://www.gemini.edu/ao_glossary*

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Gemini South image of the N44 Super Bubble Complex with Gemini mirror

Gemini Observatory
Northern Operations Center
670 N. A'ohoku Place Hilo, Hawai'i 96720 USA
Phone: (808) 974-2500 Fax: (808) 935-9235

Gemini Observatory
Southern Operations Center
c/o AURA, Casilla 603 La Serena, Chile
Phone 011-5651-205-600 Fax: 011-5651-205-650

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