

# The Scientific Case for Next Generation Adaptive Optics

## – a report prepared by the NGAO Scientific Advisory Team

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### Executive Summary

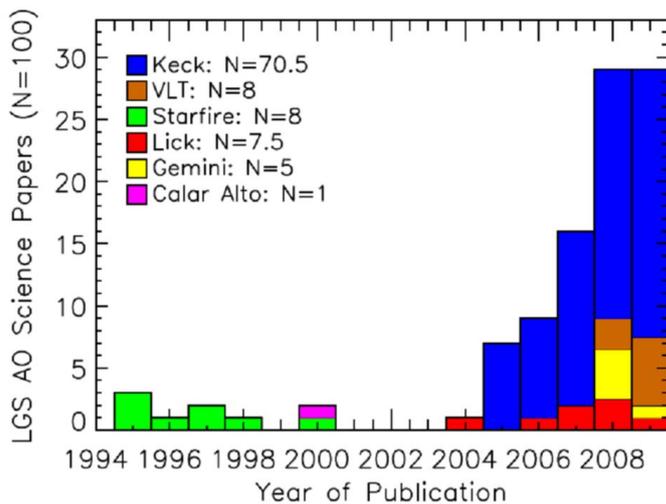
The demand for the deployment of adaptive optics (AO) by the community of users of the W.M. Keck telescopes has grown dramatically as the Observatory has continuously improved the laser guide star (LGS) AO facility, and as a large fraction of the community has increasingly recognized the value of AO for achieving its scientific objectives. This demand, the worldwide leadership of the Observatory in the development of AO, and the tremendous scientific potential of taking AO technology to the next phase, all warrant taking the next important step by constructing the advanced LGS AO facility, Next Generation Adaptive Optics (NGAO). This document briefly reviews the scientific motivations for NGAO, summarizing the key science cases that led to its present design. It then examines NGAO in the context of other AO projects being developed for large telescopes and identifies the scientifically important characteristics that set NGAO apart from the other facilities. The most powerful features of NGAO are then illustrated by examining specific science cases, including some of the key science cases, which are examined with an updated perspective. We also present some new cases that illustrate the exciting scientific impact of NGAO. Finally, we look to the future to evaluate the role of NGAO as a contemporary of JWST and ALMA, and consider how that role might change with the construction of the Thirty Meter Telescope and other next generation telescopes.

## I. INTRODUCTION

### A. Background and current state of the project

The use of adaptive optics (AO) on large telescopes has had a profound scientific impact since its relatively recent inception, with impressive advances in many areas from the solar system to the large-scale universe. The W.M. Keck Observatory (WMKO), with its twin 10-m telescopes has been at the forefront of this enterprise, providing the first natural guide star (NGS), and then the first laser guide star (LGS) AO systems on large telescopes. The WMKO has also led the international AO community in technical developments, producing a nearly continuous stream of improvements in wavefront sensing, software, system stability and Strehl ratio.

With all that has been accomplished using AO, it has become clear that the future of ground-based astronomy – particularly those endeavors at the scientific frontiers – will rest heavily on AO capabilities. Furthermore, because NGS observations are limited to such a small fraction of the sky, LGS AO will undoubtedly remain the most strongly demanded technique for an increasing fraction of astronomical research projects. The pathbreaking role of LGS AO at Keck is illustrated by the numbers: over 70 refereed papers based on LGS AO carried out at WMKO were published from 2005 to 2009 (and 79 as of this writing), compared with under 30 LGS AO papers from all other observatories – see Figure 1.



**Figure 1:** Annual output of peer-reviewed LGS AO publications from all observatories possessing the capability.

With the goal of fostering a greatly enhanced potential for discovery by enabling substantially improved wavefront corrections, and with a long-term view toward paving the way for the technical developments that will be needed by the TMT, it is natural and timely for the WMKO to carry forward its considerable momentum in LGS AO by engaging in the Next Generation Adaptive Optics project. As representatives of the user community, we see this as the optimal response to the need for innovation to drive scientific progress.

The design of NGAO was driven by key science cases that will remain very compelling and exciting throughout the coming decade:

1. High-redshift galaxies: the characterization of the internal structure and dynamics of high redshift galaxies, with a focus on redshifts between 1 and 3, where the diffraction-limited resolution of the Keck Telescopes will have the greatest impact.
2. Black hole masses in nearby AGNs: the increased Strehl of NGAO permits access to the black hole's dynamical sphere of influence, and thus enables the detection of the Keplerian rise in the velocity dispersion around nearby Galaxies. The resulting black hole masses can be used to refine the  $M_{\text{BH}}$ -sigma relation, and therefore to improve our understanding of the co-evolution of Galactic nuclei and bulges.
3. General relativity at the Galactic center: the anticipated 100  $\mu\text{s}$  astrometric precision made possible with NGAO imaging and the 10 km/s radial velocity precision of the integral field unit (IFU) will make it possible to follow the 3D motions of the closest stars to the Galactic Black Hole with sufficient accuracy to measure the general relativistic prograde precession of their orbits, and possibly to detect other post-Newtonian effects.
4. Planetary and brown dwarf companions to low-mass stars and brown dwarfs: faint low-mass stars and brown dwarfs provide the most favorable contrast to nearby self-luminous giant planets. Using a simple coronagraph, it should be possible with NGAO to achieve  $\Delta H = 10$  at a separation of 0.2", sufficient, for example, to detect planets as cool as  $T_{\text{eff}}=280$  K within 1 AU of old (1 Gyr) field (10 pc) brown dwarfs. More distant (145 pc), but younger (5 Myr) very low mass ( $\sim 10$  Jupiter) primaries will allow NGAO to detect planets less than 0.5 Jupiters in mass and as close as 7 AU.
5. Asteroid and KBO companions: with NGAO, it will be possible to explore the multiplicity of minor planets in considerable detail, providing accurate

measurements of the sizes, shapes, and orbits of companions with contrasts exceeding  $\Delta H = 5.5$  at separations of  $0.5''$ . Near-IR IFU spectroscopy will inform the compositions, which, combined with the dynamics, facilitate a reconstruction of the history of these systems.

Many additional science drivers have been considered as well, including gravitationally lensed galaxies, QSO host galaxies, resolved stellar populations in crowded fields, debris disks and YSOs, and many solar system topics. A wide range of astrometric investigations that would be enabled by increased precision has also been considered. The ensemble of science drivers was analyzed with widespread participation from the Keck community in the assembly of the NGAO Science Case Requirements Document, initially prepared for the April 2008 System Design Review (SDR), and updated for the current PDR. Numerous simulations of the science cases were produced in the process that led to the basic design. The SDR was followed in March 2009 by a Build-to-Cost Review, which set the current 60M then-year dollar cost cap on the project while giving an enthusiastic green light to proceed into the Preliminary Design Phase. While the cost cap led to the exclusion of some of the original ambitions for the project, notably a deployable Multi-Integral Field Spectrometer, the design that emerged from that exercise captures an extremely wide variety of science goals, and therefore satisfies the primary research needs of the community aiming to work at the diffraction limit of the Keck Telescopes.

*The NGAO Scientific Advisory Team, or NSAT, was formed in the Summer of 2009, soon after the build-to-cost review, and was charged with further developing the NGAO science cases, providing scientific advice on the details of the requirements, supporting funding efforts by contributing to related proposals, and with informing the community about the NGAO project and eliciting broad community input and support for the project.*

## **B. NGAO's Role Within the Astronomical Landscape**

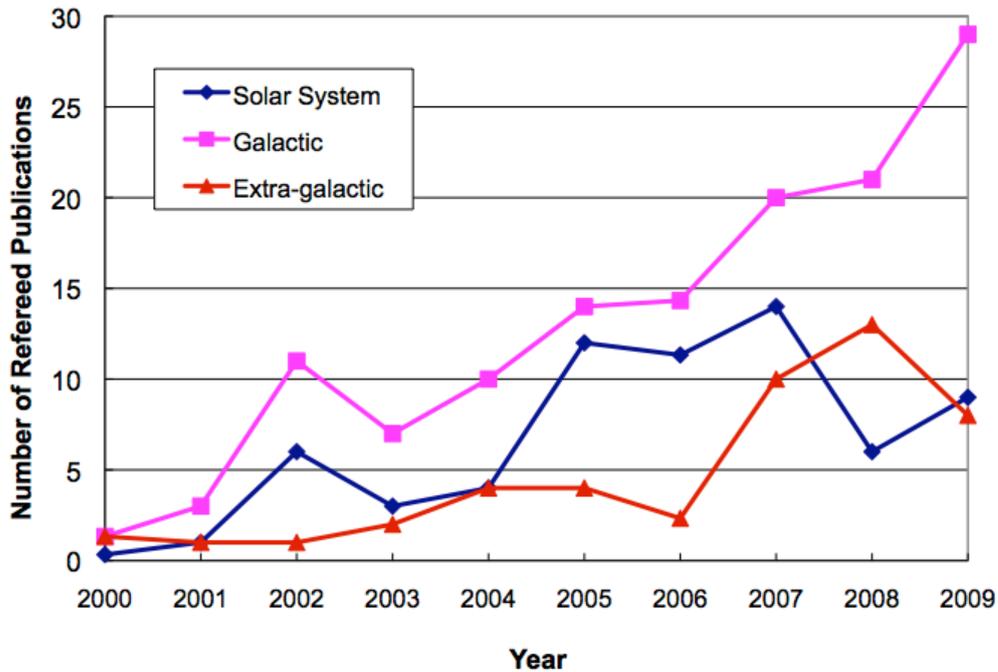
The NGAO facility is designed to have the following observational capabilities, based on the science requirements:

- <> near-diffraction limited performance in the near-IR (K Strehl  $\sim 80\%$ ). On the Keck telescopes, this gives it the highest spatial resolution available at any of its operating wavelengths, and the very high Strehl is the key enabler of the science envisioned with NGAO.
- <> AO corrections at wavelengths as short as  $7000 \text{ \AA}$  (up to  $14\%$  Strehl, depending on the science case)
- <> substantially increased sky coverage, compared to existing AO systems
- <> imaging with a reconstructable and relatively consistent PSF over a  $\geq 20''$  diameter field
- <> integral field spectroscopy at  $R \sim 4000$  from  $0.7$  to  $2.4 \mu\text{m}$ , with three pixel scales from  $10$  to  $50$  or  $70 \text{ mas}$ , and a field of view of  $4'' \times 4''$  at  $50 \text{ mas}$  sampling. The presence of an AO-fed *medium-resolution* NIR IFS is unique among next-generation AO systems under development.

Table 1 lists the next generation AO systems currently under development for  $8 - 10 \text{ m}$  class telescopes. Some of these, notably GPI and Sphere, are also designed for

very high Strehl, but typically over a relatively small field of view and with low sky coverage, as appropriate for finding planetary or brown dwarf companions to stars. Several others are designed for wide-field capabilities, suitable for surveys of faint objects or for imaging extended structures. NGAO's high Strehl over a moderately large field of view is a singularly versatile design that maximizes the breadth of its applicability to cutting-edge science.

<b>Table 1: Next-Generation AO Systems Under Development for 8 - 10 meter Telescopes</b>					
<b>Type</b>	<b>Telescope</b>	<b>GS</b>	<b>Next-Generation AO Systems for 8 to 10 m telescopes</b>	<b>Capabilities</b>	<b>When operational</b>
High-contrast	Subaru	N/LGS	High-contrast addition to Coronagraphic Imager (CIAO)	Contrast ~ a few x $10^6$ at distances between parent star	2011
High-contrast	VLT	NGS	Sphere (VLT-Planet Finder)	Contrast ~ (1 - 5) x $10^6$ at distances between 0.1" and 0.6" from parent star	2011
High-contrast	Gemini-S	NGS	Gemini Planet Imager (GPI)	Contrast ~ a few x $10^8$ at distances between 0.2" and 0.8" from parent star	2011
Wide-field	Gemini-S	5 LGS	MCAO	2' FOV	2010
Wide-field	VLT	4 LGS	HAWK-I (near IR imager) + GRAAL GLAO	7.5' FOV, AO seeing reducer (reduce EE by 30% at K band relative to no-AO), Pixels 0.1"	2014
"Wide-field"	VLT	4 LGS	MUSE (24 vis. IFUs) + GALACSI GLAO	1' FOV; Pixels 0.2", gain in EE of factor of 2 at 750 nm relative to no-AO	2014
Wide-field	LBT	Multi-LGS	ARGOS GLAO	4' FOV, NIR MOS or Imager on both 8.4 m arms	2012
Narrow-field	LBT	NGS	SCAO, twin adaptive secondaries	30" FOV NIR 0.015"/pix imager on both 8.4m arms	2010
Narrow-field	Magellan 6.5 m	NGS	SCAO Visible and mid-IR AO w/ adaptive secondary	VisAO imager will work down to 0.63 micron with 10% Strehl, 8.5" FOV, 0.0085 arc sec pixels	2012
Narrow-field	VLT	4 LGS	MUSE (24 vis. IFUs) + GALACSI GLAO	7.5" FOV, 5-10% Strehl @ 650 nm, Pixels 0.025"	2014
Interferometer	LBT	NGS	AO for LBTI (FOV 30 arc sec) or LINC-NIRVANA	Phase 1: Single conj., 2 tel's Phase 2: MCAO 1 telescope Phase 3: MCAO both telescopes	Phase 1 in ~2011



**Figure 2:** Numbers of peer-reviewed LGS/AO-based publications from each of the three broad communities. The rapidly rising trend in the extragalactic community continues into 2010, with as many papers published already as there were in all of 2009.

### C. Objective of this Document

Beyond the key science cases that have led to the requirements for NGAO, there is a vast array of scientific explorations for which NGAO can provide a substantial leap in progress. Already, LGS AO has been widely adopted by the Galactic, extragalactic, and Solar System communities (see Figure 2), and its applications are growing. There is every reason to expect this trend to continue, and thus we expect the NGAO facility to be in extremely high demand.

In the following two sections, we highlight a selected set of science cases that we regard as exciting areas for which NGAO will be well placed for breakthroughs. Some of these cases were originally used to motivate the NGAO design, and for those we embellish and update the vision of the science that can be done. In addition, we describe some new science cases for NGAO that go beyond what has previously been discussed.

At the conclusion of this document, we consider the long-term role and impact of NGAO and how it will influence or interact with the major observatories that will emerge in the coming decade, including JWST, ALMA, TMT and GMT.

## II. KEY SCIENCE VENTURES WITH NGAO

### A. The Galactic Center: Black Holes, Extreme Stellar Dynamics and Tests of General Relativity

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Diffraction-limited near-IR imaging of the central few arcseconds of the Galaxy with 8-10 m class telescopes over the past 15 years has led to a widespread acceptance that a 4-million solar mass black hole is located there, and that it dominates the stellar dynamics out to beyond a parsec, about 30 arcseconds (Ghez et al. 2008; Gillessen et al. 2009). Also, in spite of the extreme stellar confusion in this high-density region (Figure 1), the relatively dim accretion flow onto the black hole has itself been detected and its dramatic variability monitored (Hornstein et al. 2007; Do et al. 2009; Meyer et al. 2008, 2009; Eckart et al. 2008).

Precision studies of the stellar orbits around the Galactic black hole (GBH) have been, and will continue to be, the key to this investigation, in terms of both the proper motions and the radial velocities of the stars. So far, the orbits appear to be consistent with being Keplerian, including the best-characterized stellar orbit, that of S0-2, which is just now completing its 15-year period since systematic Galactic center observations began at the Keck Observatory. The well-defined orbits that are emerging from this research have provided not only the *mass* of the black hole, but also a good measure of its *distance* (Ghez et al. 2008), and the accuracy of the latter fundamental parameter will improve rapidly with time as the orbital measurements continue.

The next exciting frontier for discovery is the search for non-Keplerian effects. The GBH gives us access to a regime of strong gravity in which general relativity (GR) has not yet been tested. The highly eccentric orbit of S0-2 brings it to within 100 AU of the GBH, corresponding to  $\sim 1000$  times the black hole's event horizon, and the retrograde precession predicted for this orbit by GR is 0.2 degrees per orbit (Rubilar & Eckart 2001). This is a challenge for current instrumentation except on a time scale of at least a decade (Weinberg et al. 2005). Other relativistic effects that may be accessible are those that affect radial velocities: the transverse Doppler shift, and the general relativistic gravitational redshift (Zucker et al. 2006). Detection of these would require about a decade of study for a precision of  $\sim 20 \text{ km s}^{-1}$  in the radial velocity measurements.

Potentially competing with the retrograde GR precession of the orbits is the prograde precession that would be caused by an extended mass distribution around the GBH.



**Figure 1:** Three-color (HK'L') Keck LGS/AO image of the central few parsecs of the GC, showing the location of SgrA\*, the radio/IR source coincident with the dynamically inferred Galactic black hole. Very blue stars are foreground stars, while the luminous bluish stars are the massive stars constituting the high-mass end of the central stellar cluster. Warm dust is evident in L' (red).

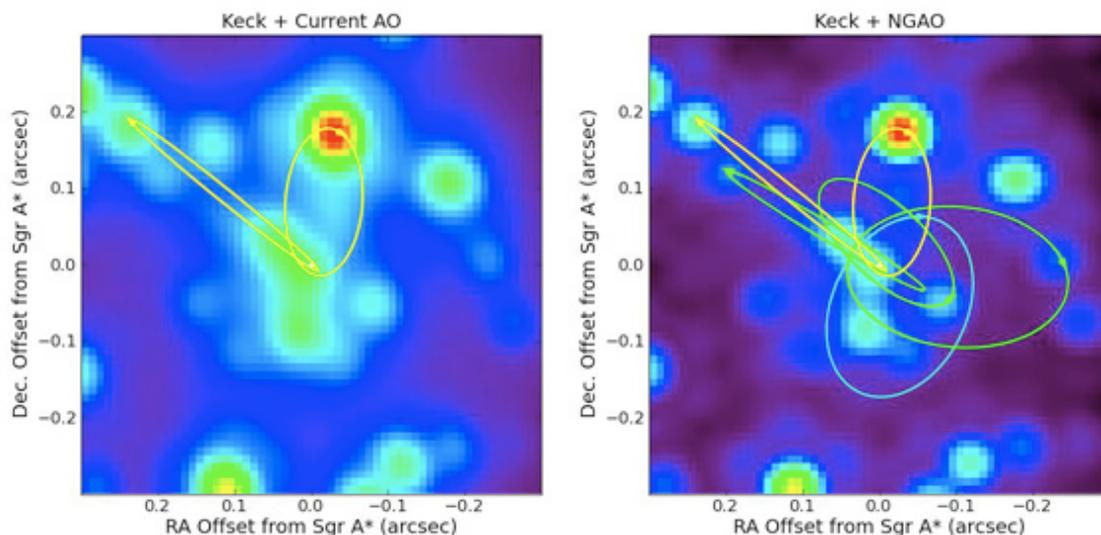
The observed stellar sources around the GBH may represent only a fraction of the total matter content. Within 0.01 pc, the matter density may instead be dominated either by compact stellar remnants such as neutron stars or 5-10  $M_{\odot}$  black holes (Morris 1993; Miralda-Escudé & Gould 2000), or by cold dark matter (Gnedin & Primack; Bertone & Merritt 2005 & references therein). Whether the resulting orbital precession is prograde or retrograde, or whether these effects conspire to cancel each other out for any given star depends on the semi-major axis and the eccentricity of its orbit, and of course on the extended mass distribution. GR will win for the closest orbits, while prograde precession due to an extended mass distribution will dominate further out. Measurement of *any* of these effects would constitute an important astrophysical breakthrough, not only for extending the tests of GR into a new regime, but also because the Galactic center is our template for understanding much of the detailed structure of all galactic nuclei.

At present, the primary limitation on our ability to measure non-Keplerian effects on stellar orbits with AO on the current generation of telescopes is the combination of the high stellar density in the GC, *i.e.*, confusion, and the pervasiveness of seeing halos, with their complex, extended structure. Both of these factors impact astrometric precision, and both can be markedly improved with an increased Strehl ratio. This point was made forcefully in a recent paper by Fritz et al. (2010), entitled "What is Limiting Near-IR Astrometry in the Galactic Center?". They conclude,

“Clearly, the astrometry in the GC would benefit from an AO system that yields the highest Strehl ratio possible over a relatively small field.” *This requirement is extremely well matched to the design characteristics of NGAO.*

There are manifold ways in which the high Strehl ratio (SR) of NGAO, when coupled with a sensitive imager and IFU, would provide both the precise astrometry and the high S/N radial velocity determinations needed to extract the non-Keplerian orbital parameters:

1. *More orbiting stars.* The high SR not only improves the S/N of each source, but it also reduces the intensity and complexity of the local background resulting from the extended seeing halos, so that fainter stars can be detected and followed, giving rise to more orbits, possibly even shorter period ones than S0-2 (see figure 2). More orbits means not only having the opportunity to get a better handle on the non-Keplerian orbital effects, but in addition, the eccentricity distribution of these closely orbiting stars also tells us something about the dynamical origin of these stars (*e.g.*, Perets & Gualandris 2010).



2. *Better astrometric orbits.* The unavoidably overlapping stellar images in a field as crowded as the GC introduce biases to the fitted star locations, but when most of the flux is in the core of the PSF, and especially when the PSF is known and well-behaved, the centroid determinations are much more reliable for both stars, and the errors in the orbital parameters can thereby be reduced substantially. Furthermore, the recognition and accounting for the bias introduced by fainter stars, which has not yet been included in the analysis, allows for a greater number and depth of such corrections.

**Figure 2:** Comparison of images (background color) and orbital determinations (lines) of stars in the central 0.6'' of the Galactic nucleus for the case of current Keck + LGS AO measurements (left) and simulations of NGAO imaging (right). The centroiding accuracy and the number of stars detectable is much greater with NGAO (courtesy of A. Ghez).

3. *Improved radial velocities.* The young stars that orbit close to the GBH have relatively weak absorption lines, but the stellar radial velocities provided by those lines as the stars accelerate around in their orbits have been invaluable for the orbit

determinations. NGAO IFU observations of these stars with an SR as high as 0.8 at K band would give much higher S/N in the line profiles than are now possible, and consequently better instantaneous velocity determinations, with a precision on the order of, or even better than, the  $\sim 20 \text{ km s}^{-1}$  needed to enter the domain of post-Newtonian effects. Radial velocity measurements of multiple orbiting stars would also allow one to constrain the line-of-sight velocity of the GBH which, with present sensitivities, is consistent with zero (Yelda et al. 2010, in preparation).

4. *Better periapse measurements.* The closest approach to the GBH is the most important point in the orbit for measuring or constraining post-Newtonian effects. This is particularly true for the few stars that are known to come quite close to the GBH. However, because the GBH is itself a luminous and time-variable point source, there is an inevitable astrometric bias at periapse that has been difficult to correct. In fact, such points have simply not been used in the most reliable analyses. However, with high SR observations, and a reasonably well-known PSF, the observations much closer to periapse can be used for the orbital fits.

A closely related area of Galactic center research that would be strongly advanced by the capabilities of NGAO is the investigation of the massive central cluster of young stars surrounding the black hole (Lu et al. 2009; Bartko et al. 2009). Precision proper motion measurements of accelerations of stars further out from the GBH than the central arcsecond will be valuable for elucidating the stellar and gas dynamics that apparently led to the formation of a stellar disk about 5 – 7 million years ago. But the inverse square law of gravity implies that the acceleration measurements in these more distant stars require very astrometrically precise measurements of the kind that NGAO can provide.

Finally, the stellar dynamics immediately around the GBH have become even more interesting recently as it has been recognized that the theoretically expected stellar cusp around the black hole is missing, and in fact, there may be a hole in the stellar distribution (Do et al. 2009b; Buchholz et al. 2009). To now progress with the investigation of this puzzling phenomenon requires the ability to measure the dynamics – both proper motions and radial motions – of fainter stars than is now possible. NGAO will be exceptionally valuable for taking the next step in this enterprise. Determining the fate of these “missing” stars is of considerable importance, as it is tied to the growth of the black hole, whether that growth takes place by the scattering of stars into the loss cone, or by the inspiral of intermediate-mass black holes.

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## B. Dark Matter and Dark Energy

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In the standard cosmological model, the Universe is dominated by two mysterious constituents: dark matter and dark energy. The two components do not interact with light and therefore have been detected only through their gravitational effects on astronomical scale. Two of the most compelling open questions in the dark sector are the so-called “missing satellite problem” and the nature of dark energy. The improvements in resolution and sensitivity afforded by NGAO over current system will enable revolutionary progress on both fronts as described below.

“*The missing satellite problem*”. Cosmological Numerical simulations predict that dark matter halos of galaxies like the Milky Way (MW) should be surrounded by thousands of satellites. Yet, the number of observed satellites of the MW is much smaller, even taking into account recent discoveries (e.g. Strigari et al., 2007; see Figure 1).

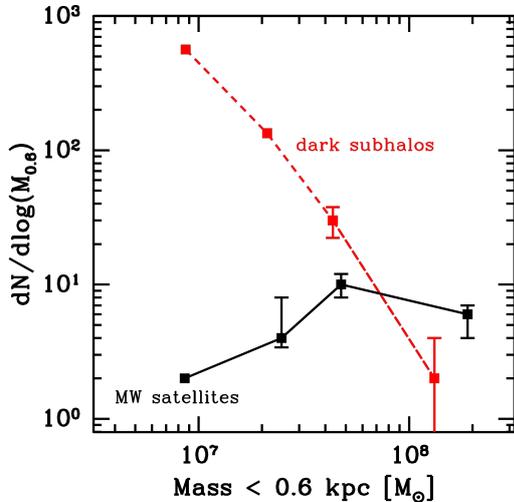
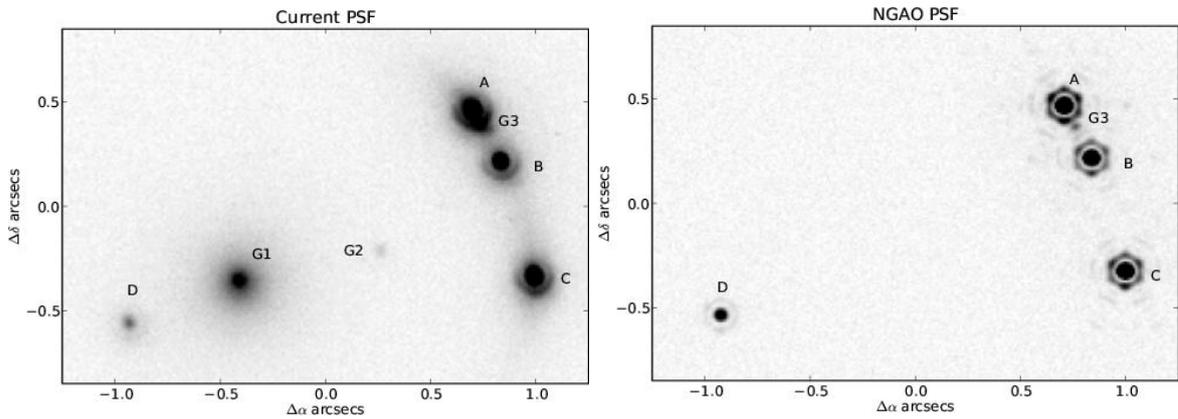


Figure 1: Comparison of the observed mass function of MW satellites with the predicted numerical dark subhalo simulations (from Strigari et al. 2007). **Notice the different slopes and the “deficit” of observed satellites below  $10^8 M_{\text{sun}}$ . Are they dark or do they not exist?**

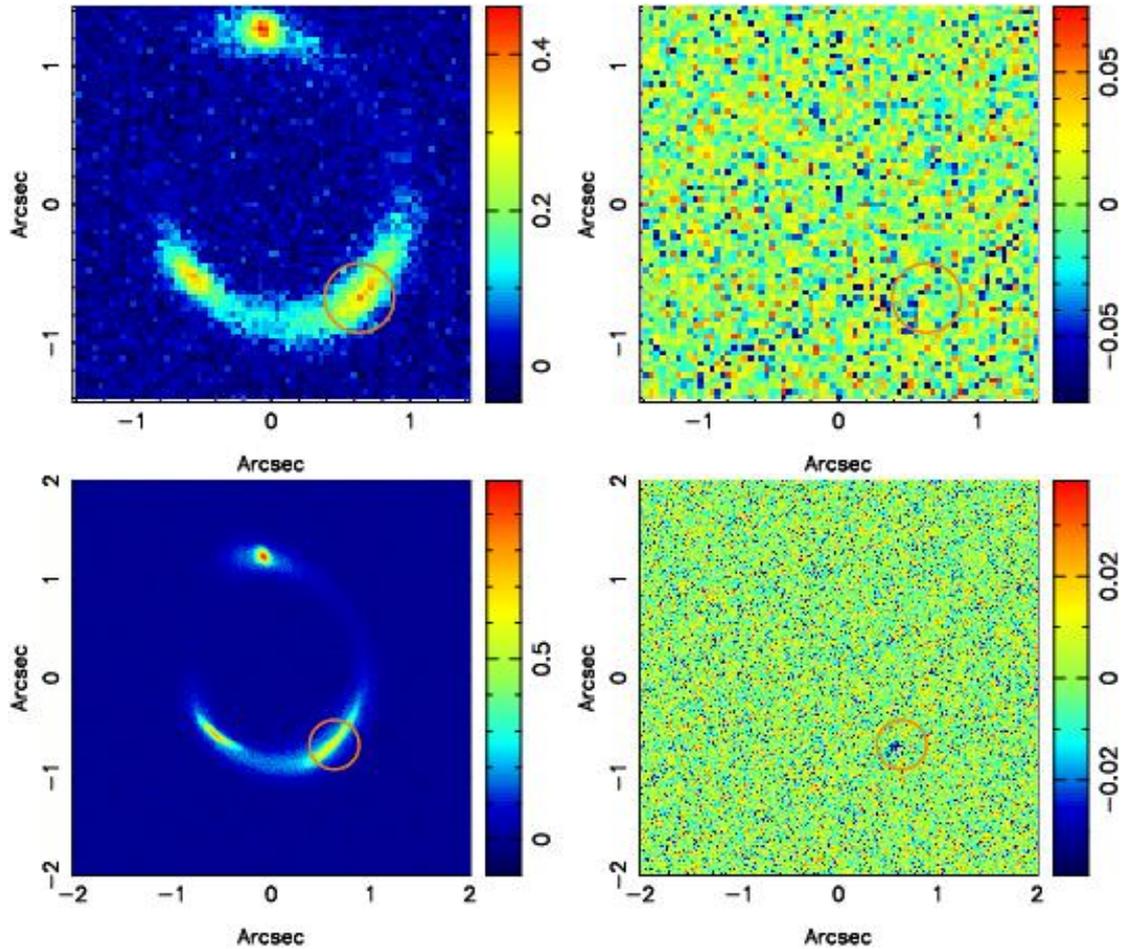
This discrepancy implies either that satellites do not form stars and are therefore dark and invisible, or that the cold dark matter scenario is fundamentally wrong. Gravitational lensing holds the key to answering this question. Dark satellites of a galaxy, if present, can be detected via the perturbation of the positions and fluxes of multiple images of background lensed galaxies (e.g. Koopmans, 2005; McKean et al., 2007 in the left panel of Figure 2). The current detection limit at HST resolution is a few  $10^8$  solar masses (Vegetti et al. 2009), i.e. at the high mass end of the MW satellite mass function where the agreement between theory and observations is best. However, the detection limit depends critically on resolution (quadratically for compact mass distributions). At the resolution of the NGAO system we expect to push down into the  $10^7$  solar mass range (in the K-band), where the predicted mass function of sub-halos is most in contrast with observations of the MW satellites (Figure 3). If high Strehl can be achieved a shorter wavelength the gain would be enormous, since the mass sensitivity scales as the inverse of the resolution (or resolution square, if the substructure is very compact). High-Strehl images at  $1 \mu\text{m}$

would therefore render NGAO superior even to JWST for this application.

NGAO will also enable complementary progress on the detection of the luminous counterparts to dark satellites. Comparing the satellite mass function with their luminosity function will help answer some of the questions related to the mechanisms that regulate star formation in low mass galaxies. NGAO will present two major advantages over current AO technology. On the one hand the improvement in Strehl ratio will improve the detection limit of the compact satellites by a typical factor of 3 in flux at fixed exposure time, plus the additional gains due to reduced thermal background with respect to the current AO system. On the other hand, the reduced amount of light in the seeing limited wings of the PSF will enable detection of luminous satellites much closer to the multiply-imaged quasars, where the sensitivity to the perturbations induced by their mass is maximal (in the right panel of Figure 2).



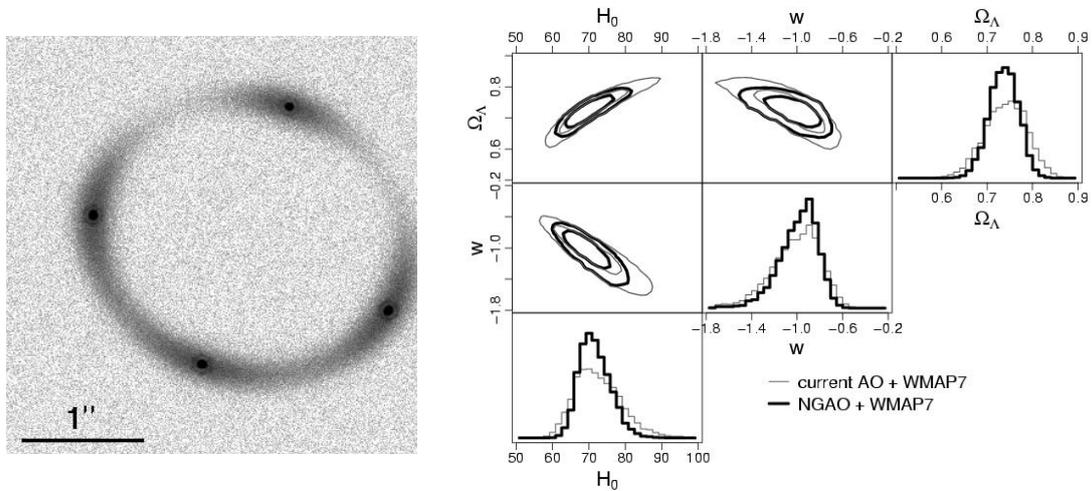
**Figure 2: Illustration of luminous satellite detection via strong gravitational lensing. Left Panel.** *The flux of image B is expected to be equal to the sum of the fluxes of images A and C, in the absence of mass substructure. Instead it is the faintest image. This flux ratio anomaly predicted the presence of a satellite. A previously unknown satellite galaxy (G2) of the main deflector (G1) is detected in this deep and high resolution Keck LGS AO K-band image (McKean et al. 2007). A small mass located at the position of the satellite could explain the observed anomaly. However, it is more likely that the anomaly is due to a smaller satellite much closer to the position of images ABC, such as that of the barely visible G3, that has been artificially added to the real data. Unfortunately the wings of the PSF limit the sensitivity in this region. Right Panel:* with the improved PSF of NGAO, satellite G3 becomes easily detectable, in the same amount of exposure time as in the NIRC2 image on the left.



**Figure 3: Illustration of dark satellite detection via strong gravitational lensing. Top row. Left panel:** *NIRC2 image of the strong gravitational SDSSJ0737 (Marshall et al. 2007). A dark satellite of mass  $3 \times 10^7$  solar masses has been added at the location indicated by the orange circle. Right panel:* *The perturbation to the lensed images due to the dark satellite is too small to be detected, as indicated by the residuals consistent with noise. Bottom row. Left panel:* *simulated NGAO image of the same system (8hrs integration time). Right panel:* *The perturbation to the image configuration due to the dark satellite is clearly detected, as indicated by the significant residuals.*

*The nature of dark energy.* What is causing the acceleration of the Universe? Determining the equation of state of dark energy parameter  $w$  is considered by many as a fundamental first step in answering this question. For example, excluding  $w = -1$  would rule out the oldest dark energy model, the so-called cosmological constant. At present, limits on  $w$  come from a variety of experiments, typically combining constraints from the cosmic microwave background to determinations of the Hubble constant,  $H_0$ , to break the fundamental degeneracy between  $H_0$  and  $w$  in Cosmic Microwave Background (CMB) data. It has recently been shown that gravitational time delays can deliver high precision measurements of  $H_0$  and  $w$  when combined with sufficiently high quality information on the mass distribution of the deflector galaxy and in the line of sight (Suyu et al. 2010). Hence

gravitational time delays offer an alternative route to dark energy. This is particularly attractive for a number of reasons when compared with the traditional distance ladder methods: the measurement is global, i.e. insensitive to the peculiarities of the local volume, and is based on simple physics (gravity) and therefore insensitive to issues such as metallicity of variable stars and dust extinction. All that is needed to make progress is a large number of systems with accurate time-delays and good complementary data. Time delays are already available for some systems and are expected to become available in large numbers with the next generation of time domain surveys like LSST. NGAO images will enable major progress. High Strehl images in the K-band will reveal the host galaxy of the multiply imaged variable quasars. The multiply imaged extended structure of the host galaxy constrains the local gravitational potential, breaking the degeneracy between  $H_0$  and gravitational potential radial behavior. The progress afforded by NGAO is illustrated in Figure 4. NGAO halves the error on the local gravitational potential and reduces the error budget from a single lens from 9% to 6% on  $H_0$  and from 21% to 16% on  $w$ . Thus a sample of nine lenses imaged with NGAO could provide the best measurement to date of  $H_0$  (2%) and  $w$  (4%), thus enabling the most stringent test of the nature of dark energy to date (see for comparison Riess et al. 2009).

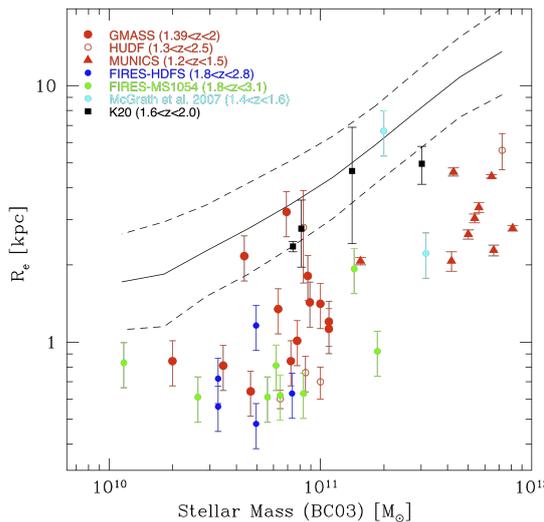


**Figure 4: Illustration of cosmography with gravitational time delays.** Left panel: simulation of a quadruply-imaged quasar and its host galaxy imaged with NGAO. Right panel: cosmological constraints obtained by combining the constraints from this system with those from WMAP7 ( $\Omega_\Lambda$  is the energy density of dark energy in critical units). The constraints obtained by imaging the same system with the current AO system are shown as thin lines for comparison.

### C. Morphology of Compact High-redshift Early Type Galaxies

Authors: E. McGrath, C. Max (UC Santa Cruz)

There has been much debate recently about how the most massive galaxies form and evolve over cosmic time. In particular, “red and dead” galaxies at high-redshift do not appear to follow local scaling relationships such as the mass-radius relation (see Figure 1). These galaxies appear to have assembled the majority of their mass, have finished forming stars, and are already on the red sequence, however they are significantly more compact than their local counterparts, with surface densities up to 10 times higher than local early-type galaxies (van Dokkum et al. 2008). This implies that some form of size evolution is required, possibly through dry-mergers.



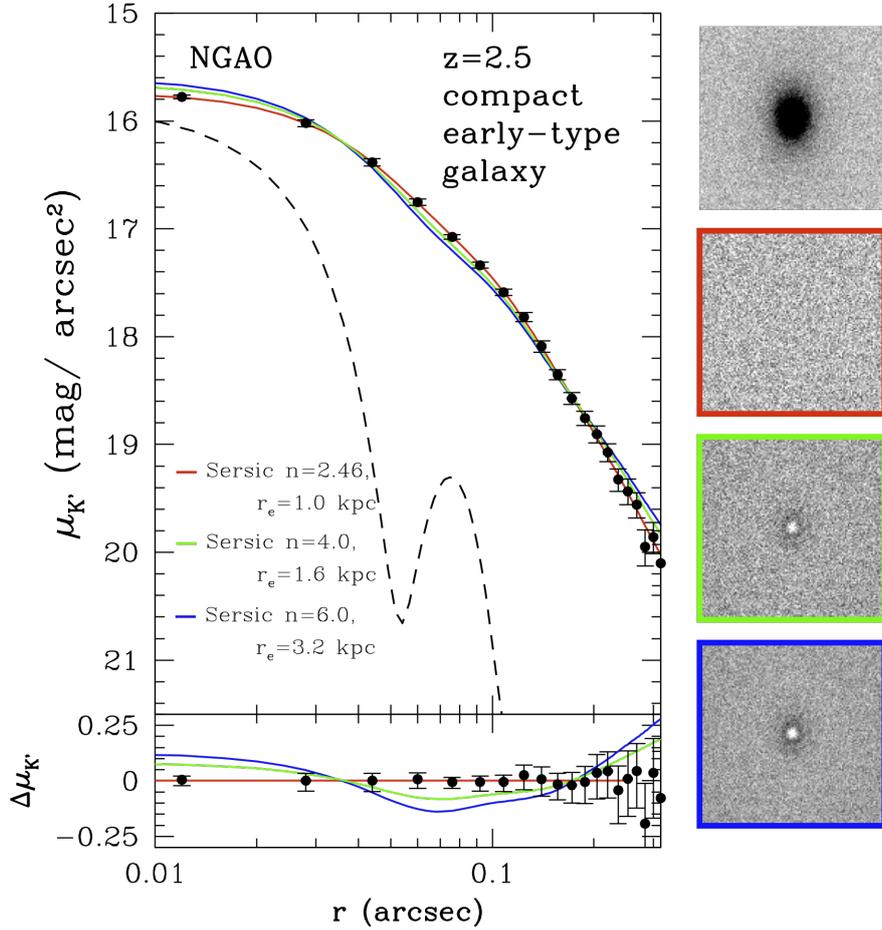
**Figure 5** Stellar mass-radius relation for early-type galaxies. The local relation from SDSS (Shen et al. 2003) is shown as the solid black line along with its corresponding 1 sigma scatter (dashed lines). Data points show values from various high-z studies. Note that most of the galaxies at high-redshift fall significantly below the local relation, implying that some size evolution is required in order to make them consistent with the relation by the present day. (From Cimatti et al. 2008)

Recently, however, it has been suggested that these results may be the consequence of poor signal-to-noise data (e.g., Mancini et al. 2010), and that these galaxies may in fact have extended faint halos that have remained undetected, even in deep HST imaging. Understanding the true galaxy sizes is extremely important for placing constraints on formation mechanisms.

There are two main limiting factors for accurately determining a galaxy’s morphology. In the central regions, PSF-broadening limits the ease in discriminating between more sharply peaked profiles of elliptical galaxies and the more gradual decline of disk-like profiles. At large radii, the limiting factor is achievable SNR, which depends on things such as the intrinsic galaxy brightness, sky background, and detector characteristics. NGAO will provide a significant advantage in the central regions of galaxies since the PSF core will be significantly smaller and better sampled than both HST and JWST, respectively.

We considered the case of a massive early-type galaxy at  $z=2.5$  similar to the “quiescent” galaxies in the van Dokkum et al. (2008) and Stockton et al. (2008) samples. We modeled the flux received from a  $2L^*$  galaxy assuming an age of 2 Gyr for the stellar population and an intrinsic galaxy profile of Sersic index,  $n=2.5$ , with an effective radius of 1.0 kpc. We then convolved this galaxy model with a model of the NGAO PSF (Neyman, KAON 466), and added sky background as well as detector and thermal noise from the NGAO system (Adkins & McGrath 2010). We used this simulated image as input to Galfit (Peng et al. 2002). At first, we treated the galaxy

centroid, magnitude, Sersic index, effective radius, position angle, and axis ratio as free parameters. Then we held the Sersic index fixed at  $n=4$  and  $n=6$  (similar to values for local ellipticals) to see if we could recover a profile with a larger effective radius. In Figure 2, we show the results of this simulation. Qualitatively, we can pick out the best-fit model by comparing the residuals on the right hand side of Figure 2. A more quantitative analysis can be made by comparing the simulated NGAO-observed surface brightness profile and associated  $3\sigma$  error bars with each of the Galfit model profiles (left hand side of Figure 2). In three hours, we find that we are able to recover the intrinsic profile and rule out more peaked or more extended profiles to high confidence.



**Figure 2:** Early-type galaxy at  $z=2.5$ . Top panel: Simulated galaxy surface brightness profile along with  $3\sigma$  error bars (black data points). The red line shows the best fit to the data, where we essentially recover the input profile of  $n=2.5$  with  $r_e=1\text{kpc}$ . The blue and green lines show profiles for higher Sersic indices, which have extended low-luminosity wings, leading to larger effective radii. These profiles clearly provide a worse fit to the data and would rule out a galaxy size  $> \sim \text{few kpc}$ . The dashed line represents the shape of the NGAO PSF with an arbitrary intensity scaling. Note that the HST PSF would be much broader ( $\sim 0.2''$  at this wavelength), and that the JWST profile would not be sampled as well ( $0.03''/\text{pix}$  for NIRCcam vs.  $0.008''/\text{pix}$  for DAVINCI), washing out the inner structure where the discrimination between models can be made. Bottom panel: Difference plot which compares the simulated galaxy surface brightness profile (black points), the  $n=4$  (green), and  $n=6$  (blue) models to the best-fit  $n=2.5$  model (red). Right, grayscale images: Top image shows the simulated galaxy as observed by NGAO in  $K'$ . Residuals obtained by subtracting the model fits from the simulated galaxy are shown, color-coded in the same manner as before.

Results from NGAO for these compact galaxies will be complementary to JWST in that NGAO provides the resolution and sensitivity necessary to distinguish galaxy morphology in the central regions, while JWST will provide higher sensitivity at large radii. Together, these datasets will help determine whether early-type galaxies at high- $z$  are indeed more compact than their local counterparts, which will help us learn how the most massive galaxies have evolved over time.

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## D. Imaging and Characterization of Extrasolar Planets around Nearby Stars

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Editors: Claire Max and Elizabeth McGrath

Updated by Laird Close

### Scientific background and context

The unique combination of high-contrast near-IR imaging (K-band Strehl ratios of 80-90%) and large sky coverage delivered by NGAO will enable direct imaging searches for Jovian-mass planets around nearby young low-mass stars and brown dwarfs. Both the Gemini Observatory and ESO are developing highly specialized planet-finding AO systems (GPI, and SPHERE) with extremely high contrast for direct imaging of young planets. These "extreme AO" systems are very powerful, but their design inevitably restricts them to searches around bright, solar-type stars ( $I < 9$  mag).

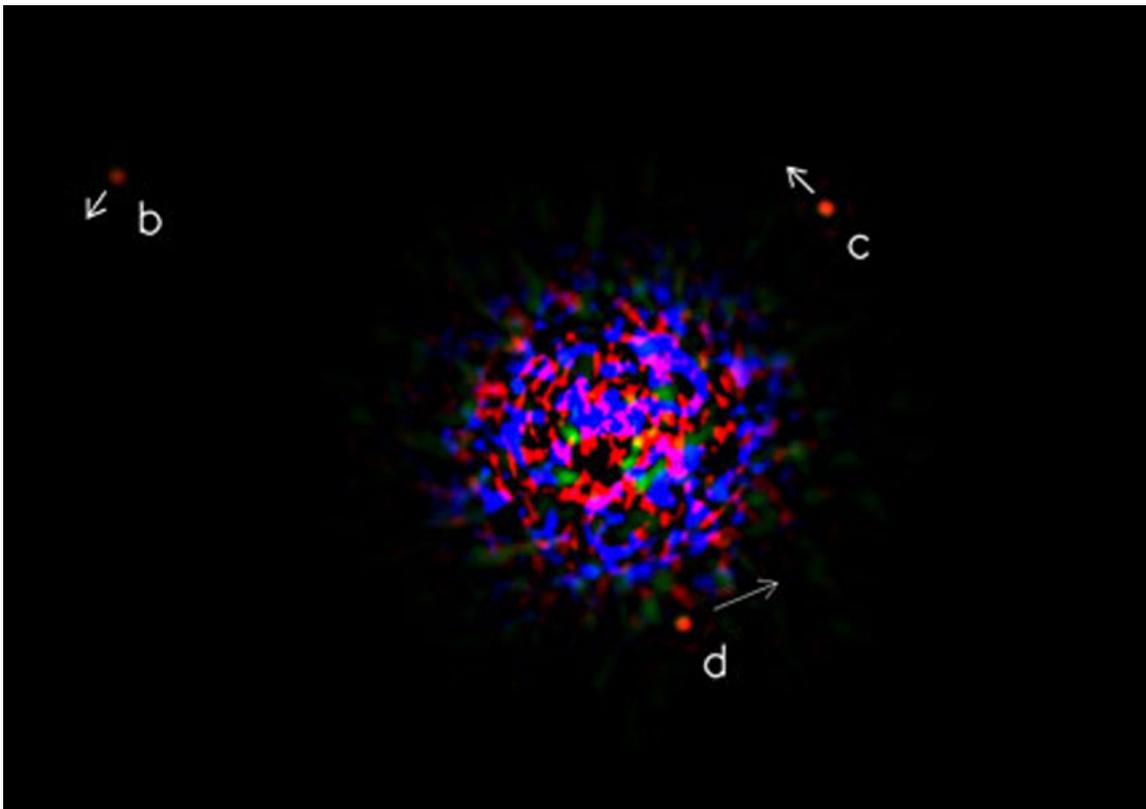


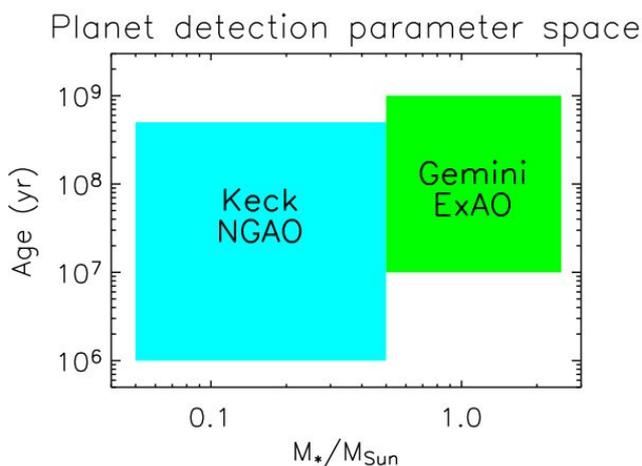
Figure 1: The triple planetary system around HR 8799 from KECK NGS (Marois et al. 2008). NGAO will be able to detect such planets around much fainter (hence lower mass) primaries with the aid of LGS.

NGAO will strongly distinguish work at WMKO from all other direct imaging searches planned for large ground-based telescopes. By number, low-mass stars ( $M \leq 0.5 M_{\odot}$ ) and brown dwarfs dominate any volume-limited sample, and thus these objects may represent the most common hosts of planetary systems. Such cool, optically faint targets will be unobservable with specialized extreme AO systems because their parent stars are not bright enough ( $I > 11$  mag) to provide a high-

order wavefront reference. But thousands of cool stars in the solar neighborhood can be targeted by NGAO because of its laser guide stars. Direct imaging of extrasolar planets is substantially easier around these lower mass primaries, since the required contrast ratios are smaller for a given companion mass. In addition, the very youngest stars in star-forming regions such as Taurus or Ophiucus are generally too faint for extreme AO systems but easily accessible to NGAO. However, for both these science cases, the key angular scales are relatively small (0.1-0.2 arcseconds), requiring both the large aperture of the Keck telescopes and careful coronagraph design.

### Scientific goals

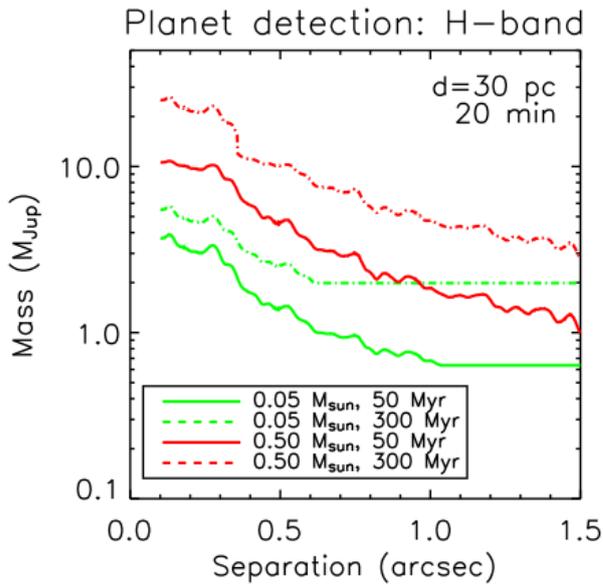
Direct imaging of extrasolar planets by NGAO would allow us to measure their colors, temperatures, and luminosities, thereby testing theoretical models of planetary evolution and atmospheres. NGAO spectroscopic follow-up will be an important means to characterize the atmospheres of extrasolar planets, which are otherwise essentially inaccessible to spectroscopy. Figure 2 summarizes the relative parameter space explored by NGAO and extreme AO. The complementarity of the two systems is very important: establishing the mass and separation distribution of planets around a wide range of stellar host masses and ages is a key avenue to understanding the planet formation process. The optical faintness of low-mass stars, brown dwarfs and the very youngest stars make them inaccessible to extreme AO systems but excellent targets for NGAO.



**Figure 2. Schematic illustration of the parameter space of Keck NGAO and of the Gemini Planet Imager for direct imaging of extrasolar planets. In theory even lower mass objects could be probed by NGAO if other tip-tilt star could be utilized.**

### Planets around low-mass stars and Brown Dwarfs

Direct imaging of substellar companions (brown dwarfs and extrasolar planets) is substantially easier around lower mass primaries, since the required contrast ratios are smaller for a given companion mass. Indeed, the first bona fide L dwarf and T dwarfs were discovered as companions to low-mass stars (Becklin & Zuckerman 1988, Nakajima et al. 1995), and the first planetary-mass companion imaged orbits the brown dwarf 2MASS1207 (Chauvin et al 2004). Thus, searching for low-mass stars and brown dwarfs is an appealing avenue for planet detection and characterization. Given that low-mass stars are so much more abundant than higher mass stars, they might constitute the most common hosts of planetary systems. Figure 3 shows an estimate of the planet detection sensitivity for NGAO.



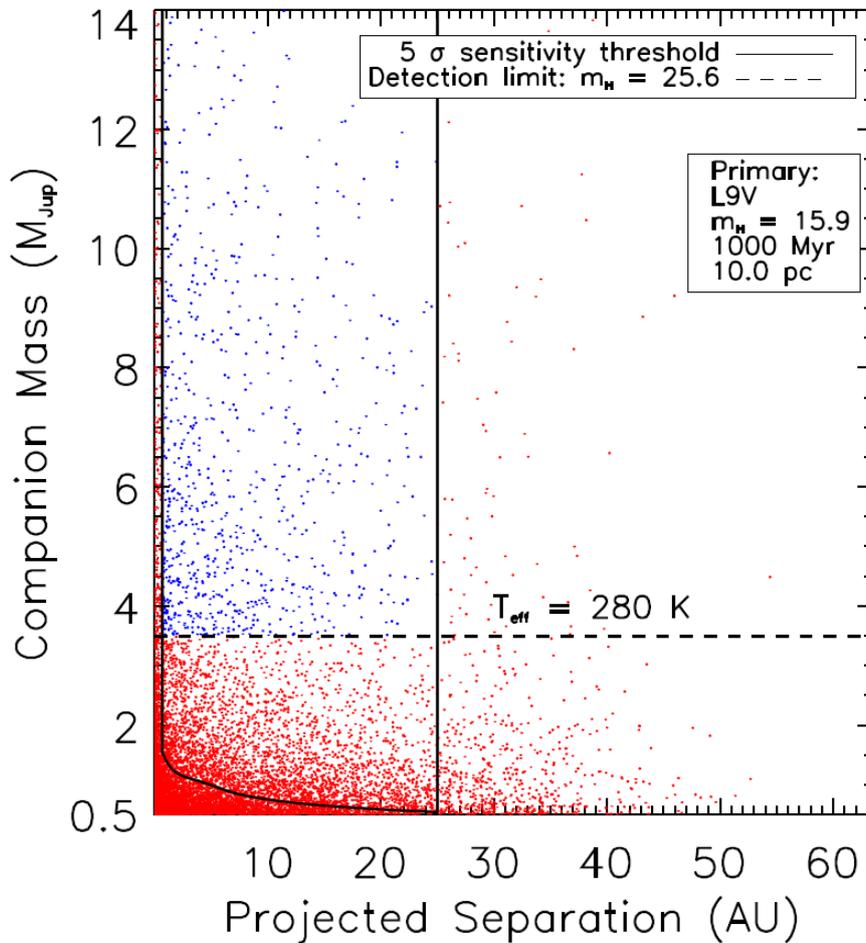
**Figure 3.** Estimated NGAO sensitivity for direct imaging of extrasolar planets. Red lines: planets around low-mass stars; green lines: planets around brown dwarfs. NGAO will be able to search for Jovian-mass companions around large numbers of low-mass stars and brown dwarfs in the solar neighborhood.

Since these targets are intrinsically faint, the contrast between the primary and the planetary companion is reduced. For example, a 40 Jupiter-mass brown dwarf with an age of 1 Gyr has an absolute H magnitude of 15.8 (using the DUSTY atmospheric models). A 2 Jupiter-mass planetary companion has an absolute H magnitude of 24.99 (using the appropriate COND models), for a contrast of  $2.5 \times 10^4$ . The known distribution of brown dwarf binaries peaks at 4 AU (Close et al. 2003). Assuming a typical target distance of 20 pc, this leads to a contrast requirement of  $\Delta J = 10$  at 0.2 arcseconds. If most targets come from the 2MASS catalog, they will have IR magnitudes  $< 15$  and hence be suitable for on-axis IR tip/tilt sensing.

Spectroscopic follow-up of the coldest companions will be an important path in characterizing the atmospheres of objects in the planetary domain. Strong molecular absorption features from water and methane provide diagnostics of temperature and surface gravity at modest ( $R \sim 100$ ) spectral resolution. Below  $\sim 500$  K, water clouds are expected to form and may mark the onset of a new spectral class, a.k.a. "Y dwarfs". Such objects represent the missing link between the known T dwarfs and Jupiter, but are probably too faint and rare to be detected as free-floating objects in shallow all-sky surveys such as 2MASS and SDSS. Furthermore, the coolest/lowest mass objects may not exist as free-floating objects if there is a low-mass cutoff to the initial mass function of the star formation process, e.g., from opacity-limited fragmentation of molecular clouds ( $M_{\min} \sim 5-10 M_{\text{Jup}}$ ; Silk 1977). Even cooler/lower mass objects might only form via fragmentation, akin to the formation of binary stars, and may only be found as companions.

An interesting question is just how cool a companion could NGAO detect? We have simulated (with the extrasolar planet simulation code of Nielsen & Close 2010) how faint (and cool) a companion the NGAO system could detect around a low mass 40 Jupiter brown dwarf in the field. At 10pc a 1 Gyr old brown dwarf (of which many will be detected by the WISE survey) would have  $H=15.9$  mag. The NGAO IFS should easily be able to detect in 1 hour an object as faint as  $H=25.6$  mag. Based on this limit we find, with the COND models an "extreme" Y dwarf of only  $T=280$  K could be

detected as close as 1 AU from the brown dwarf primary. In fact as Figure 4 below clearly shows that longer integrations could detect even fainter companions since the contrast curve of Flicker et al. is not the limiting factor in this particular science case, indeed it is the background itself limiting us to  $H \sim 25.6$  mag in 1 hour.



**Figure 4:** Based on the predicted contrast of the NGAO (Flicker et al. 2007, KAON 49x, Fig 6;  $10^{-4}$  contrast at  $0.2''$ ,  $10^{-5}$  at  $1''$  at H band) we can simulate just how cool a companion could be detected around a field 40 Jupiter-mass brown dwarf at 10 pc of age 1 Gyr. In 1 hour of integration we find (based on the COND models) that an extreme “Y-dwarf” of  $T_{\text{eff}}=280\text{K}$  could be detected inside 1AU and of mass just under 4 Jupiters. Indeed this limit is set by the faintness ( $H=25.6$  mag) of these companions. Since the brown dwarf is itself so faint ( $H=15.9$  mag) it’s halo noise (dark solid line) is not the limiting factor. Note that all the blue dots in the above simulation could be detected by NGAO in 1 hour, but the red dots cannot.

#### Very young planets in the nearest star-forming regions (detecting planets around planets)

Imaging searches and characterization at the very youngest (T Tauri) stages of stellar evolution provide a unique probe of the origin of extrasolar planets, by constraining their formation timescales and orbital separations. Young stars and brown dwarfs can be enshrouded by substantial dust extinction, both from the natal molecular cloud and their own circumstellar material. Thus most young (T Tauri) stars are too optically faint for current NGS AO systems or future ExAO systems. Keck NGAO imaging will probe physical separations of  $\geq 5\text{-}10$  AU around these stars.

It is still an open question whether giant planets form extremely rapidly ( $\leq 10^4$  yr) due to disk instabilities (*e.g.*, Boss 1998) or if they first assemble as  $\sim 10 M_{\text{earth}}$  rocky cores and then accrete  $\sim 300 M_{\text{earth}}$  of gaseous material over a total timescale of  $\sim 1$ - $10$  Myr (*e.g.*, Lissauer 1998). Potentially both mechanisms may be relevant, depending on the range of orbital separations and circumstellar disk masses. In addition, imaging searches of young T Tauri stars both with disks (classical TTS) and without disks (weak TTS) can help to constrain the formation timescale. In particular, weak T Tauri stars with planetary companions would suggest that planet formation occurs even when disk evolution/dissipation happens rapidly.

The brightness of these very young planets is highly uncertain. Marley et al (2007) show variations in the accretion history of a planet can produce changes in luminosity. Most published models have initial conditions that correspond to formation through adiabatic contraction, resulting in a “hot start” and bright planets at young ages. Planets that form through runaway accretion in a protoplanetary disk, by contrast, dissipate much of their gravitational potential energy in an accretion shock, and will be orders of magnitude dimmer. However, NGAO will be sensitive primarily to planets in wide (15-30 AU) orbits, where contraction or gravitational instability are more likely formation mechanisms. At the age and distance of Taurus, a  $1 M_J$  hot-start planet has an effective temperature of 300K and a J magnitude of 22 ( $2 M_J$  corresponds to  $J=19.5$ ). A typical parent star would have a J magnitude of 11. A separation of 15 AU in nearby star-forming regions corresponds to 0.1 arcseconds. The contrast requirement is therefore  $\Delta J = 8.5$  mags at 0.1 arcsecond,  $\Delta J = 11$  mags at 0.2 arcseconds, with a goal of  $\Delta J = 11$  at 0.1 arcseconds. Achieving this performance at 0.1 arcseconds may require a coronagraph optimized for very small inner working angles, and perhaps multi-wavelength imaging for speckle removal.

A related science case is observations of slightly older (5-30 Myr) stars in young associations such as the TW Hydrae association or older star-forming regions. These stars will be typically 40-80 pc in distance, but it is highly desirable to probe scales similar to the orbit of Jupiter (5 AU), leading to an aggressive inner working angle of 0.07 arcseconds. High-mass young association stars will also be observable with Gemini or VLT Extreme AO, but Keck NGAO can potentially access the lower-mass members of these associations.

We can simulate what the sensitivity of the NGAO system would be around an object at the edge of the planet/brown dwarf boundary. In Upper Sco this boundary is  $H=21.6$  ( $\sim 10$  Jupiters at 5 Myr at 145 pc). Such massive planets are ideal for NGAO. We find in our simulations that there is no significant speckle noise from that halo of the  $H=21.6$  primary (given the excellent LGS correction). Hence the limiting factor is the limiting H magnitude for the system. In this manner NGAO should be able to easily detect companion planets of masses  $< 0.5$  Jupiters as close as  $\sim 7$  AU. It is hard to be definitive about the lowest masses that will be actually detected by NGAO since there is great uncertainties in the theoretical evolutionary models for planets as young as  $< 5$  Myr and masses  $< 0.5$  Jupiters. Indeed NGAO will likely play a key role in benchmarking these theoretical models in this, as yet, unexplored piece of extrasolar atmospheric physics parameter space.

### Proposed observations

For each of these science cases, observations would consist of a moderate sized (100-300 target) survey of suitable targets. To achieve this in an acceptable amount of telescope time, it would be necessary to reach the required contrast levels in 20-30 minutes per target. Follow-up observations would be used to distinguish true companions from background objects and to spectrally characterize candidate companions

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## **III. OTHER IMPORTANT NGAO SCIENCE CASES**

### **A. Pushing Keck NGAO towards the visible wavelength range: Our Solar System**

Author: I. de Pater (UCB), edited by M. Morris (UCLA)

As many objects in our Solar System are visible in reflected sunlight, one might expect that such bodies may be easiest to spot at visible wavelengths, near the peak of the Sun's radiation. Indeed, asteroids, KBOs and moons are usually discovered in the visible wavelength range. Hence pushing Keck AO towards the visible wavelength range may open up a new window for discoveries. The following focuses on selected investigations that are relevant to gas giants and their companions.

One intriguing topic is that of interactions between rings and moons, which manifest themselves in a variety of ways: some moons are known to "shepherd" rings (Cordelia and Ophelia shepherd the  $\epsilon$  ring); others define their sharp edges (Porco & Goldreich 1987); yet others can raise sinusoidal patterns on ring edges (French and Nicholson 1995, Showalter and Lissauer 2004), and lastly dusty rings are usually produced by small moonlets orbiting the planet within or on the outskirts of the ring. This can be seen, for example, in Jupiter's rings (de Pater et al., 2008 and references therein, in particular Burns et al. 1999), Saturn's E ring (Enceladus) as well as other rings+moonlets discovered by Cassini, and the Uranus *mu* ring (with Mab; Showalter and Lissauer, 2006). The precise orbits of moons can be influenced by gravitational torques as well, which could be the cause of variations in the orbits of Galatea (Neptune) and Mab (Uranus). In addition, small moons in the Uranus system, the closely-packed "Portia group," show significant orbital changes over timescales of a few years.

The orbit of Mab is least understood of all; moreover, Mab orbits Uranus within the *mu* ring, which itself is rather peculiar. This ring is blue, like Saturn's E ring,

implying a preponderance of small (~1-micron sized) particles. The E ring is produced by geysers on Enceladus. However, Mab seems to be too small (10-20 km?) to be volcanically active. So both the blue color of the mu ring, and the chaotic orbit of Mab need to be explained.

To date, Mab has been spotted only in a reanalysis of old Voyager data (Figure 1) and in HST observations. In total, 85 detections have been made on HST images obtained between 2003 and 2006 (ACS data). Mab has been too faint in the IR (or the IR background is too high) to show up in Keck data. From the available data it is clear that this moon usually does not appear at the location where it should be if it were on a regular (Keplerian-like) orbit; something disturbs its orbit.

Unfortunately, there is not much data to precisely characterize the orbit: does Mab “jump” at particular times/locations? Is it a smooth chaotic orbit? Such questions need to be answered before one can develop a good theory.



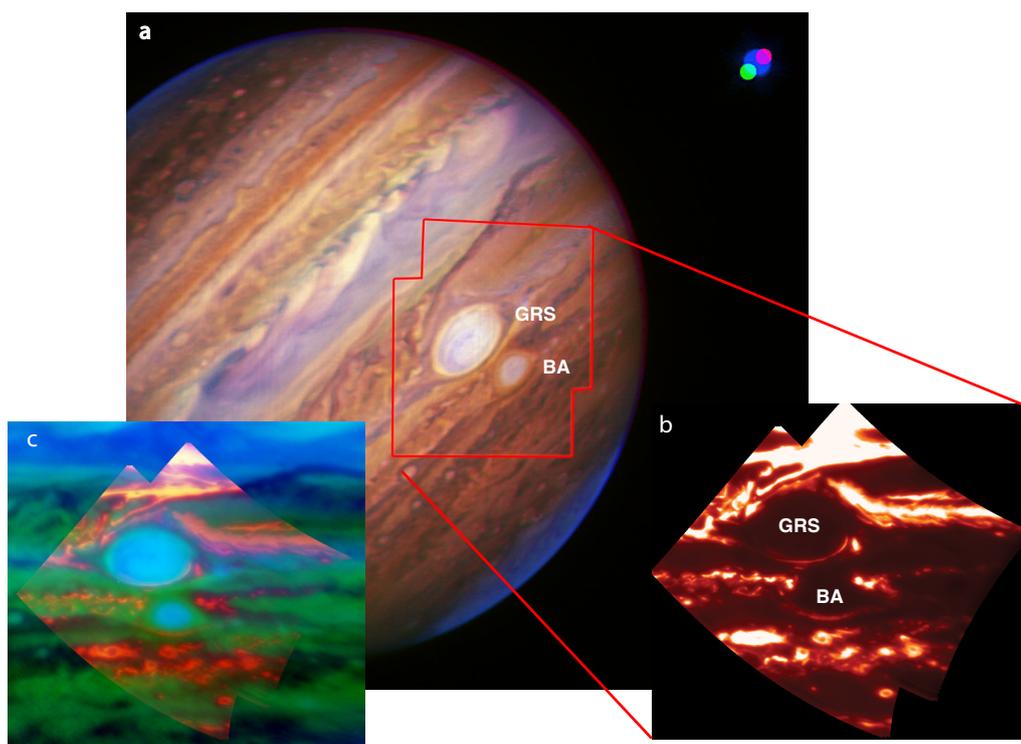
**Figure 1:** The recovery of Mab from three Voyager images. The figure was constructed by overlaying strips from 3 images separated by 4.8 min each. Arrows and circles indicate the location of Mab in each image. For reference, dashed lines mark orbital radii  $\pm 2000$  km from Mab's nominal orbit. Mab is displaced slightly inward, which suggests that it has been imaged near pericenter (from Showalter and Lissauer 2006).

Hence, precise astrometry is needed. To date, Mab has only been seen on HST (ACS; perhaps WFC3) images. We need both a higher sampling rate over perhaps 2-4 weeks time scales, and a long-term series over many years, at sparser intervals. Keck NGAO operating at visible wavelengths would be the only ground-based telescope with which we expect to detect Mab and to determine its position at high spatial resolution (few tens of km or better). With such a system one could take a snapshot image every night (in perhaps 10 minutes) over a few weeks to build up an astrometric database superior to any other. At the same time, such snapshots provide information on the chaotic orbits of the other moons, and on the odd asymmetries in the mu ring, as revealed by HST and which is not understood either (are these phenomena related? We don't know).

Much of this science can be done with LGS AO, but the effectiveness of the observatory would be enhanced by retaining an NGS AO capability. WMKO's current NGS AO has been optimized to perform diffraction-limited imaging on the extended ice giants Uranus and Neptune; it is the only facility that can provide near-IR imaging on these planets with 40 – 50 mas spatial resolution, which is critical for most solar system science projects. Fortunately, NGS capability is planned to be built into the NGAO facility. (It will use a visible-light wavefront sensor and do single-conjugate AO, as is done today. But because there are more degrees of freedom for the NGAO system, it would give better correction but would need a brighter guide star than LGS AO.)

## Jupiter:

We have made much progress towards understanding Jupiter's atmosphere and storm systems through a combination of HST and Keck AO observations (see, for example, de Pater et al. 2010a, b). Ideally, we would like to obtain high contrast, high S/N data at different wavelengths (0.5-5  $\mu\text{m}$ ; perhaps with IFUs) to determine wind velocities both globally and locally (in vortices, as GRS, Oval BA). Such fields at different wavelengths provide information at different depths (e.g., Figure 2). As shown in a recent set of papers, we made considerable progress towards understanding Jupiter's atmosphere, but we still have a long way to go. In particular, changes in the atmosphere, such as merging vortices, changing colors, upheavals, new storms, etc, should be observed and monitored long enough that



**Figure 2: Jupiter's Great Red Spot and new Red Oval with the Keck AO system.**

a) False-color composite Keck AO image of Jupiter in July 2006. The satellite Io is visible in the upper right corner in the green, red and blue colors of the 1.29, 1.58 and 1.65  $\mu\text{m}$  filters, respectively. The motion of the satellite with respect to Jupiter during the observing sequence is evident. (Io appears larger in the blue because the colors have been stretched to 'brighten' Jupiter.) Note that the high altitude haze above the polar hood makes the planet blue here. b) A close-up of the two red spots through the 5- $\mu\text{m}$  filter. The individual images were deprojected before being mosaicked together. c) The 5- $\mu\text{m}$  image (in orange) superposed on a composite Keck image at 1.58  $\mu\text{m}$  (green) and 1.65  $\mu\text{m}$  (blue). Whether the 5- $\mu\text{m}$  bright arc on the south side of the GRS is on the boundary of the clouds or in the dark strand below it, is hard to tell. Navigation is difficult, and the PSFs at 1.58/1.65  $\mu\text{m}$  are broader than at 5  $\mu\text{m}$ .

the phenomena can be interpreted (long enough: sometimes a few times a night; a few times a week or a month, or once every year, depending on the phenomenon -- but to determine winds one always needs data sets separated by 1-2 hrs).

Jupiter will push the NGAO system most. Placing lasers around Jupiter (Jupiter is 32" at its smallest size, up to 50" when it is largest) is ideal to get good correction on the whole disk; preferably 1 or more Galilean satellites can be used as tip/tilt stars. Jupiter's bright background can present difficulties for the AO system if the tip/tilt stars or the laser guide star are too close. The limit now is at least 10-15" off Jupiter's limb. But it should be possible to suppress Jupiter's background using a sufficiently narrow-band sodium filter in the optical train that leads to the LGS wavefront sensor.

Finally, it is very important for any solar system research, in particular spectroscopy, to be able to track differentially, since a planet, its moons, and the background tip/tilt stars may all move in different directions.

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### **B. Preplanetary Nebulae; Peering Deep into the Bipolar Driver**

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As classical a subject as planetary nebulae might be, one of the most critical mechanisms that determines the morphology of these evolved structures is not understood. When AGB stars undergo mass loss in their superwind phase, they display spherical symmetry, but at some point near the end of that phase, an axisymmetric phenomenon – a collimated high-speed wind, or jet – very often asserts itself, and carves out low-density bipolar cavities in the AGB wind (Morris 1990; Sahai & Trauger 1998), and this is accompanied by a concentration of the mass loss into an equatorial disk. The result is that most planetary nebulae bear the imprint of this occurrence: a bipolar or at least an elongated morphology. However, the nature of the launching mechanism for the collimated outflow remains undecided; is it a magnetic phenomenon or is a binary companion always responsible (Bujarrabal et al. 2000)?

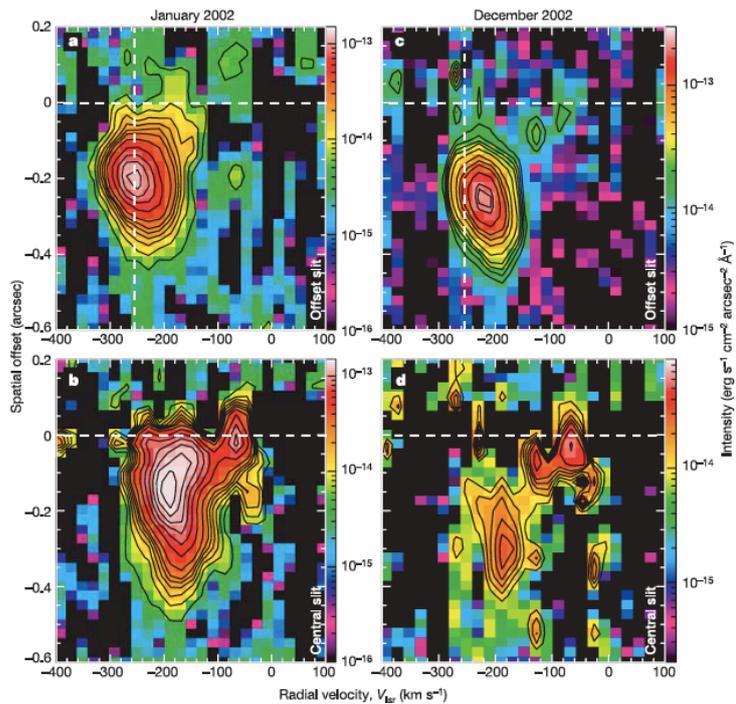
HST observations with the STIS spectrometer have revealed a remarkable occurrence in a single, well-observed system, the carbon star V Hydrae. Sahai et al.

(2003) found that the collimated ejection in this bipolar system – a precursor to even a preplanetary nebula – emerged as a high-speed (240 km/s) blob (fig 1).

This observation raises the possibility that the collimated outflows of preplanetaries consist of a discontinuous series of discrete ejections. Subsequent unpublished observations of V Hya also show that the outbound blob does not remain detectable for long after its initial appearance. It is clear from this finding that further characterization of the earliest stages of the mass ejections in nascent preplanetaries will require spectroscopy with the *highest attainable spatial resolution and Strehl ratio*, especially given the high contrast between the stellar brightness and that from the blob. Furthermore, because these systems are intrinsically subject to high extinction by dust, it will be necessary in many of them

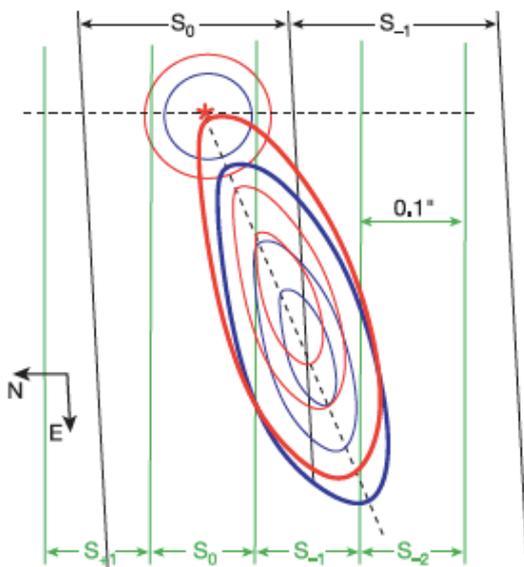
**Figure 1 (right):**

[SII]  $\lambda 4069.7$  line emission from a blob emerging from V Hya. The stellar continuum, lying along the horizontal dashed line at zero spatial offset, has been subtracted. The top and bottom show two adjacent slit positions, and left and right columns show two epochs.



**Figure 2 (below):**

Model intensity contours for the sky projection of the high-velocity emission feature, based on the data in fig 1. Red and green contours show the two successive epochs. Vertical lines show the slit projections



to observe near-IR emission lines such as [FeII]  $\lambda 1.257 \mu\text{m}$ , Brackett- $\gamma$ , and the ro-vib lines of  $\text{H}_2$  near  $2 \mu\text{m}$ . The capabilities of the NGAO IFS match these criteria very well, and of course the integral field feature obviates the need to carry out repeated observations with offset slits in order to fully characterize the two-dimensional velocity field. The observations would not be sensitivity-limited, so one could relatively rapidly survey a sample of a dozen or so of the youngest preplanetary nebulae in order to capture and follow the ejection events in as many systems as

possible, and to periodically repeat these observations in order to constrain the limit cycle of these events.

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#### IV. THE LONG-TERM PERSPECTIVE ON NGAO

Upon entering the phase of routine operations at its target date in 2015, NGAO will be a preeminent facility benefitting the broad Keck community by enabling discoveries across a wide range of scientific investigations. It will have a window of at least 3 or 4 years, and very possibly more, before the start of science operations with TMT, GMT, or ELT, and during this time, it will have a clear opportunity to make substantial contributions to the science cases mentioned above and in the SCRD.

There is a particularly strong synergy between NGAO and TMT because the investments of funds and personnel required for the development of the AO technology necessitated by NGAO pave the way for the development and construction of the technologically similar facility at the TMT: NFIRAOS. Many of the technical challenges that need to be faced for TMT will already have been resolved in the development of NGAO, so in fact an investment in NGAO represents a substantial cost benefit for almost every aspect of the NFIRAOS, including the development costs of both hardware (e.g., CCDs, laser designs) and software (simulation tools, wavefront correction algorithms), and for formulating error budgets and cost assessments.

Once TMT enters its phase of routine operations, the science emphasis of NGAO is likely to evolve. NGAO will offer Strehls similar to those of TMT's first-light AO system, but with lower spatial resolution (at a common wavelength), and it will offer similar spatial resolution for IFS science, but with lower sensitivity. As TMT arrives on the scene NGAO could be reconfigured to move to new areas such as shorter wavelengths or multiple object spectroscopy. Even in the GSMT era NGAO will remain an ideal platform for long-term precision synoptic science, from astrometric and radial velocity measurements of the Galactic Center to weather monitoring of solar system planets and moons. It is also likely to play a staging role that is complementary to TMT, as the most compelling and tantalizing research results from NGAO are likely to stimulate follow-up work with TMT where higher spatial resolution and sensitivity are called for. Such a role might be anticipated in crafting surveys with NGAO, with the specific intent of selecting sources for investigation by TMT.

NGAO will very probably be operating in the era of JWST, so a comparison with that platform is warranted. JWST's sensitivity is  $\sim 200$  times higher than NGAO at K-band, but NGAO offers higher sensitivity than JWST for imaging at, or bluer than, J-band (by  $\sim 6$  times at J) and for spectroscopy between the OH-lines at H-band or bluer. Also, NGAO offers higher spatial resolution for both imaging and spectroscopy (from 0.7 to 2.4  $\mu\text{m}$ ) due to the larger primary mirror and to higher spatial sampling (0.009"/pixel versus 0.032"/pixel for JWST). This latter advantage of NGAO is of primary importance for the key science cases

NGAO will also coexist with ALMA, which operates at millimeter and submillimeter wavelengths, so is not in direct competition. Both NGAO and ALMA will bring to bear comparably high spatial resolution on their scientific subjects, but ALMA will typically be investigating regions or objects that are colder, denser, and often more obscured than those that will be studied by NGAO. ALMA and NGAO observations will likely be complementary for thorough investigations of spatially resolved

galaxy kinematics at  $z < 3$ , of planetary and preplanetary nebulae, and of debris disks, protostellar disks and young stellar objects. ALMA will often be employed to study the composition and dynamics of cool interstellar gas in sources where NGAO will be used to study hot gas and warm dust.

## V. CONCLUSIONS

Given the variety of exciting and fundamental science that can be addressed with NGAO, the NSAT projects that it will become the workhorse instrument for the growing community for which diffraction-limited resolution provides a scientific premium. This community includes those exploring the solar system, those investigating the stellar and interstellar contents of our Galaxy, those examining the resolvable stellar populations and the nuclear regions of galaxies in the nearby universe, and those doing research on galaxy assembly and the dynamics of galactic systems in the early universe.

In this document, we have highlighted selected science cases for which NGAO will be a powerful tool that facilitates pathbreaking scientific advances. We emphasize that there are many more such cases than we have had the time or expertise to address. These would include compact HII regions and bow shocks, Wolf-Rayet winds (including the binary “pinwheels”), novae, the dynamics of protostellar disks and their jets, debris disks, the internal dynamics of star clusters – both young and old, coherent stellar dynamics in galactic nuclei, methane in the Martian atmosphere, wind dynamics in gas giants, Kuiper belt objects, comets, exoplanet atmospheres, circumnuclear disks in galaxies, and much more. The scientific impact of NGAO will be both broad and deep.

NGAO is also an important evolutionary step for advancing the technique of adaptive optics. By itself, it is a natural and pivotal next step for the WMKO to undertake in order to maintain its leadership in the development and deployment of AO, *and* it would be a powerful link between the current state of the observatory and the advent of the TMT.