Development of an Adaptive Optics System for the Baade 6.5m Telescope

We propose to duplicate the MMT's f/15 chopping/AO meniscus secondary for the Magellan I (Baade) Telescope. This would immediately enable diffraction-limited mid-IR astronomy at the Baade Telescope and would lay the foundation for additional planned and funded adaptive optics (AO) efforts in the near and mid-IR. The deformable meniscus secondary proposed here has important advantages for AO over conventional deformable, reimaged, mirrors: fewer warm reflecting and transmitting optical elements, lower emissivity, smooth deformable mirror surface, and absolute position sensors to help maintain the figure of the mirror. With this mirror, the Baade Telescope will operate at the state of the art for many important programs in infrared astronomy. The telescope will provide a large portion of the U.S. access to AO in the southern hemisphere. More than 300 American astronomers in the Magellan consortium will be able to take advantage of this capability for a broad range of programs, including: determining asteroid masses; detecting "zodiacal" clouds, disks, and planets around both nearby and young stars; determining fundamental parameters affecting star formation in dense regions; measuring black hole masses in active galaxy nuclei; probing the morphology of galaxies at the most distant edge of the observable Universe; and constraining cosmological constants. Access to diffraction-limited imaging in the southern hemisphere is critical to provide overlap with ALMA, which can observe at similar angular resolution, as well as for observations of the nearest young stars and access to our nearest extragalactic neighbors, the Magellanic Clouds.

1. Results from Previous NSF Support

1.1 Tip-tilt secondaries

The PI (L. Close) has been involved with several AO instrumentation projects over the last 10 years that were supported at least in part by NSF. In the spring of 1992 we carried out an experiment in high resolution near IR imaging without increasing the thermal background. We built a novel tip-tilt secondary mirror (called FASTTRAC, see Close & McCarthy 1994) for the Steward Observatory 90-inch (2.3m) telescope at Kitt Peak. This led to 0.25" imaging of the Galactic Center, some of the sharpest images of this crowded region at that time (see Close et al. 1995, Hollywood et al 1995, Tamblyn et al. 1996 & Haller et al. 1996). Observations were also obtained of faint field galaxies and of the lensed IRAS galaxy FSC 10214+4724 (c.f. Mutz et al. 1997; Close et al. 1995). It was found that infrared imaging at 0.25" resolution (even with low Strehl) was scientifically fruitful.

1.2 Adaptive optics

Close was a Co-PI on the very successful University of Hawaii NSF grant "A High-Performance Adaptive Optics Imager for Astronomy" (PI F. Roddier). This grant allowed the construction and utilization of the first 36-element curvature AO system (mainly built by E. Graves and M. Northcott). This new AO system, called Hokupa'a ("immovable star" in Hawaiian), allowed one to obtain diffraction-limited images at 1.2 μm with resolutions of 0.1" in 1" seeing at the CFHT. The strehl ratios were typically 30% at J, 50% at H, 70% at K, and 98% at N (10 um); see Graves et al. (1998) for more details.

With the new adaptive optical surface called a "bimorph deformable mirror," our point spread function (PSF) was noticeably "smoother" and artifact-free than images produced from the older style "stacked actuator deformable mirrors" (SAMs) even if the strehl ratios were identical. A demonstration of the benefits is that, to our knowledge, only bimorph mirror AO systems (so called curvature AO systems) have been able to see faint scattered light from circumstellar disks around young stars (see Roddier et al. 1996, Close et al. 1997a, Close et al. 1998, Potter et al 2000). The reason for the improved image quality and PSF smoothness was likely due to the new bimorph mirrors using radial grid geometry (very similar to that of the proposed adaptive secondary - see Figure 3.2). Additionally, and perhaps most importantly, these new mirrors did not have individual rigid PZT stacks pressing on the mirror surface such as SAMs use (and which can lower image smoothness by scattering light off a local "bump" print-through).

1.3 Circumstellar Disks

The PI's NSF SAA grant "A Survey of Circumstellar Disks and Young Stars with Adaptive Optics" exploited the improvement in PSF fidelity to image extremely faint (up to 10^6 times fainter than the primary star) circumstellar disks. These studies yielded many new insights into circumstellar disks reviewed by McCaughrean, Stapelfeldt, & Close (2000). We were able to observe all the T Tauri disks imaged to date in the IR (c.f. see Roddier et al. 1996 -GG Tau, Close et al. 1997a -HL Tau, Close et al. 1998 -UY Aur, Potter et al 2000 -UY Aur in polarized light, & Potter et al. 2001 -HV Tau C and HK Tau/C, plus the circumbinary disk source GG Tau, all in polarized light). We capitalized on the smooth PSF to measure the size, shape, inclination, and morphology of all these disks at 0.1" resolution. We were also able to estimate the extinction to the central sources, and to estimate the mass of dust in the disks. In addition, our complex Mie scattering models showed that the dust in these disks was composed of small grains with ISM like composition (Close et al. 1998), an important constraint for planetary formation models. Some of the results of this work are presented in Figure 1.1.

As part of our NSF-funded research we developed (Close et al. 1997b) the first AO IR polarizer coupled to the Hokupa'a system. The very steady AO PSF allowed polarization maps to be made of these disks at the 0.2" resolution level. D. Potter (a graduate student at IfA, Honolulu under the past supervision of the PI) developed the first Wollaston AO polarizer to produce even better simultaneous differential polarization maps. These maps of UY Aur, GG Tau, HV Tau C & HK Tau/C have all confirmed (for the first time directly) that their disks are indeed flattened distributions of dust orbiting these young stars, possibly in the process of forming planets (Potter et al. 2001).

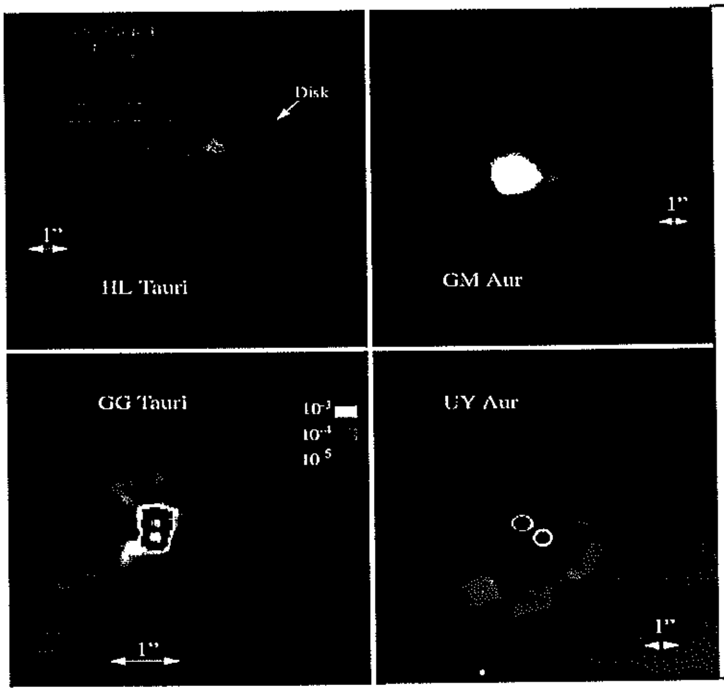


Figure 1.1. Adaptive Images of Disk Systems. The images were obtained by L. Close and collaborators at the CFHT and have been combined with an HST R image in the case of HL Tau.

HL Tau: R from HST (blue), J (green), and H (red). Scattered light above the disk plane dominates the R image.

GM Aur: J

GG Tau: J, intensities "wrapped" to show resolution of central binary (Roddier et al. 1996).

UY Aur: J (blue), H (green), and K (red).

1.4 Solar System Objects

We have collaborated with PI W. Merline of SWRI (Boulder) on an NSF-funded project to detect faint moons in orbit close to much brighter parent asteroids. Until we started this search no orbits for asteroidal moons were known, and only one moon had been glimpsed as the Galileo spacecraft took a snapshot of a small ~1km body orbiting near the asteroid Ida. We used a smooth bimorph deformable mirror on the 3.6m CFHT PEUO AO system (Rigaut et al 1998) to detect a small (11km) moon orbiting 45 Eugenia in a 6.406 day orbit (Merline et al. 1999; Close et al. 2000a), see Figure 1.2. To detect this moon required the AO PSF to be smooth enough to distinguish a point source 200 times fainter than the parent body and located only 0.75" away. However, this was quite easily accomplished with PUEO, and since then we have detected 3 more asteroidal moons and determined their orbits (Merline et al. 2000). The significance of these orbits is that we can measure for the first time the mass (and hence density) of the parent asteroid bodies to 10% accuracy. These densities have been as small as 1.2 ± 0.1 g/cm^3 for Eugenia (suggesting a "rubble-pile" structure) and as high as 1.8 g/cm^3 for asteroid 762 Pulcova (Merline et al. 2000), indicating a range of asteroid internal structures.

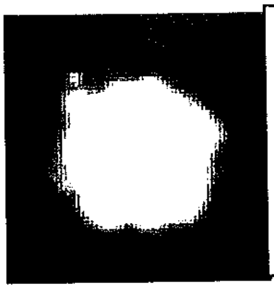


Figure 1.2. 45 Eugenia with its moon (to the upper left)

We have also observed the active volcanism on Jupiter's moon Io (Roddier et al. 1998). Imaging the hot volcanism in the thermal IR allows for a steady tracking of the ever changing face of the solar system's most active body. In addition, the strong mineral/molecular absorption bands in the IR have allowed us to map the minerals on several solar system bodies to locate H_2O, CH_4, olivine, & pyroxene on large asteroids like Vesta (Dumas et al 1998), Saturn's moon Titan (Roddier et al. 1998), and the Pluto Charon system (Close et al. 2000b).

1.5 Crowded and Obscured Star Fields with AO

The ability of AO systems to detect faint point sources near bright objects is also extremely helpful when imaging crowded, obscured star fields such as sites of star formation. In particular, AO imaging in the Orion Trapezium cluster allowed the detection of 294 pre main sequence stars in the IR in just 5 square arcminutes (Simon, Close, & Beck 1999). Such observations determine fundamental parameters such as the binary fraction, luminosity function, and mass function. In the Trapezium cluster we found that the binarity was similar to that of the field and significantly lower than that of similarly aged (1-2x10^6 yr) stars forming in the less dense Taurus molecular cloud (Simon, Close, & Beck 1999). A larger survey of many star formation clusters with AO showed that in general, higher density clusters have a lower binary fraction (Duchene et al. 1998a,b; Bouvier 1998; Eisloffel 2000a,b). This difficulty in forming and keeping binaries in dense clusters (where most stars are thought to form) is an interesting constraint for models of both binary star and planet formation.

1.6 Low mass companion detection with AO

An ideal application of AO with smooth PSFs is the direct detection of very low mass companions to nearby stars. Figure 1.3 is an illustration. It was possible to detect companions 10^6 times fainter than their primaries within 3" in the case of MWC480 at the 3.6m CFHT (Close et al. 1999; Close 2000c). Moreover, we have found that proper motions of such faint companions can be measured to 0.005"/yr with AO at the CFHT (Close 2000c). Only after a faint companion is confirmed to have a common proper motion can it be believed to be a physical companion. It takes 1-2 years to confirm that faint companions pass this test. We have several interesting objects that are being followed to see if they are true common proper motion pairs; without AO resolutions such proper motions would take ten times as long to measure.

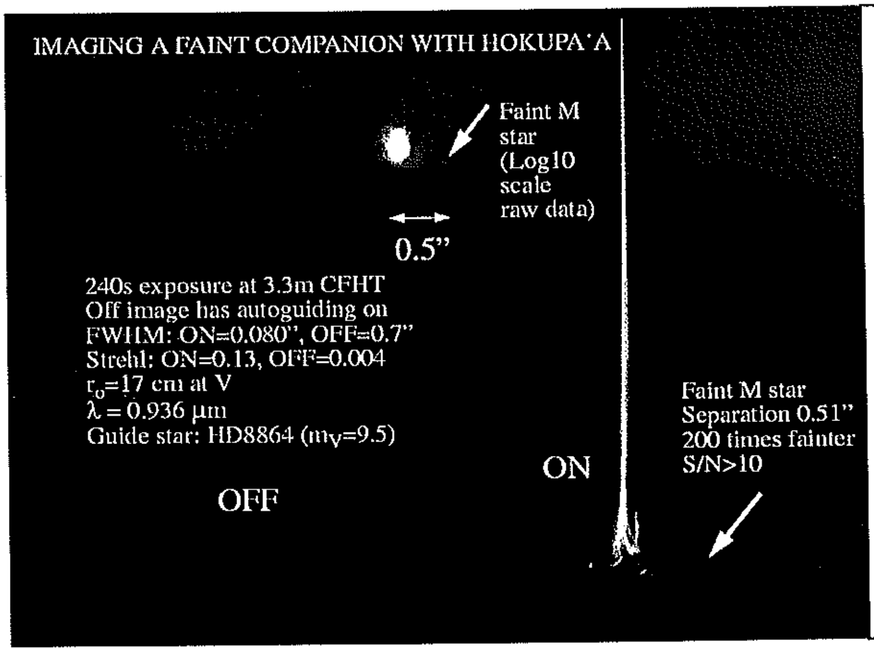


Figure 1.3. AO corrected image of HD8864 obtained by L. Close and collaborators at the CFHT. The adaptive correction allows detection of a very faint companion, 200 times fainter than the primary and only 0.51" away.

2. Science Applications of the Proposed System

Groundbased optical-infrared astronomy is being re-invigorated and even revolutionized by the new generation of 6.5 to 10-m telescopes. The power of the new generation of telescopes is derived at least as much from their improved image quality as from their large apertures. The improved images result from better site selection, reduction of dome seeing effects, maintaining the mirrors close to ambient temperature, and adaptive optics. It is becoming possible to put substantial amounts of energy into a diffraction-limited central image in the near infrared (see Section 1). The resulting new science opportunities have made AO a high priority in both the previous and current decadal surveys of astronomy. Moreover, a main recommendation of the NSF "First Workshop on the Ground-Based O/IR System" was to focus on AO systems in the IR on 6-10m class telescopes.

We plan an incremental approach to implementing AO on the Baade Telescope. This proposal and existing instrumentation will complete Phase I, equipping the telescope for deep thermal infrared imaging with the Mid Infrared Array Camera (MIRAC – see Hoffmann et al. 1998) and nulling interferometry (BLINC -- Hinz et al. 2000) (neither capability is in the immediate plans for VLT instrumentation). In Phase II we will establish diffraction-limited near infrared imaging; through a generous gift to MIT, most of the resources are also in hand. We will develop near infrared spectroscopy in Phase III. We illustrated some specific science interests in Section 1 and list more below, with a broader accounting in Section 4. The science discussion is illustrated by examples provided by the indicated consortium members. There is a high level of interest, and a broad range of important problems will be addressed with this capability.

2.1 Deep Cosmological Diffraction-Limited Imaging (P. McCarthy, OCIW)

One of the principal challenges to our present understanding of galaxy evolution at high redshifts is distinguishing between luminosity evolution and mass accumulation. One of the primary processes in galaxy building, star formation, produces radiation with clearly recognizable signatures. Other processes (e.g. mergers) do not necessarily produce any radiation and the light from the accumulated mass and evolved stars is often lost in the glare from newly formed massive stars at visible and UV wavelengths.

Diffraction limited near-IR observations provide one means of gauging the buildup of galaxy mass both from determinations of galaxy scale lengths and from determinations of luminosities at wavelengths dominated by large numbers of evolved stars. These studies are well adapted to natural reference star AO systems because the exact field on the sky is not critical and can be selected to provide a suitable reference star. The Kormendy relations (projections of the fundamental plane) provide a powerful tool for gauging the dynamical state of early-type galaxies, even in the absence of velocity information (e.g. the scale-length/mean-surface-brightness relationship). The effective radii of L* ellipticals at z ~ 1 - 2 are expected to be ~ 2 - 3kpc, or roughly 0.5". To measure the scale length for galaxies with integrated magnitudes of K ~ 19 - 21 requires both the high angular resolution and the low backgrounds provided by an AO system based on a deformable secondary as proposed for the Baade Telescope.

The sub-L* galaxies that dominate the faint galaxy counts are know to have smaller half-light radii but little is know about them. Deep HST images reveal compact morphologies for many galaxies with H > 23. In Phase III, an AO fed cryogenic spectrograph on the Baade Telescope with entrance apertures matched to the image sizes (~ 0.1") could provide gains of 1 to 3 magnitudes in sensitivity compared to conventional spectrographs, allowing us to reach rest frame optical emission lines in both the sub-L* galaxies that comprise the faint counts as well as the luminous Lyman-break galaxies that dominate the global star formation rate at 2 < z < 4.

2.2 Gravitational Lensing (B. McLeod, CfA; P. Schechter, MIT)

Gravitational lensing is an important astrophysical tool that requires high angular resolution infrared imaging to exploit fully. A typical scenario has light rays from a background quasar deflected by a closer galaxy, causing multiple images of the quasar. The separations are typically 1", making high-resolution imaging a requirement. Such systems permit the measurement of cosmological parameters (e.g. Blandford and Narayan 1992) and measurement of the gravitational potentials of lensing objects (e.g. Keeton, Kochanek and Falco 1998). For example, if the quasar brightness varies, the time delay between the multiple images can be determined, in principle providing a direct measure of the Hubble Constant (H_0) independent of other distance ladder rungs. However, in many cases the lensing galaxy is blended with and overwhelmed by one or more of the quasar images, making it difficult to determine relative positions and the shape and redshift of the galaxy. Without good positions and a redshift, one cannot model the lensing potential and the expected time delay. Working in the near-IR brings up the lensing galaxy with respect to the quasar and can solve these problems. An illustration is the use of the AO bonnette on the CFHT by Crampton, Schechter and Bezuit(1998) to obtain images of SBS1520+530, finding a previously undetected lensing galaxy (see Figure 2.1).

Another approach depends only on the bending of the light depending on the mass of the lens. NICMOS observations by the CASTLES group showed that many lensed quasars have host galaxies that are lensed into Einstein rings. Given the distances to the lens galaxy and the quasar, the shape and size of the ring can constrain the mass of the lens and provide the information necessary to pin down H_0. Observations of the ring are best made in the near IR, where the quasar-galaxy contrast is optimal. The NICMOS observations sufficed to show the lensed hosts and to derive basic photometry. Very deep AO observations on a 6.5m telescope can trace the shapes of the rings adequately to constrain H_0.

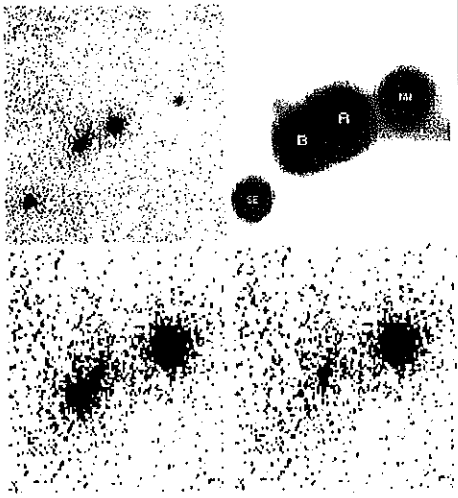


Figure 2.1. Identifying the lensing galaxy in a lensed QSO (Crampton, Schechter, & Beuzit 1998): upper left, corrected image; upper right uncorrected; lower left, expanded view, lower right PSF subtracted to show galaxy (as a faint smudge to the left and just below a brighter stellar image).

In many cases, gravitationally lensed quasars include bright, well isolated, compact images that can be used as wavefront reference sources. For example, nearly half the CASTLES lenses could be observed in this way (based on data in Lehár et al. 2000), and additional examples are being discovered, particularly in the southern hemisphere (e.g., Morgan et al. 1999; Gregg et al. 2000). A few additional systems have adequate nearby reference stars. Nonetheless, the number of suitable systems is modest, making further searches desirable. Schechter, with collaborators at MPIA-Heidelberg and the University of Potsdam, is involved in two major searches for southern hemisphere lenses. The proposed Baade Telescope system would be ideal for following up on the lensing galaxies, first with direct imaging both to confirm their nature and to determine their shapes and sizes, and then with low resolution spectroscopy to obtain redshifts and other parameters of the lens and quasar.

2.3 Nuclear Activity in Galaxies (G. Rieke, SO; D. Richstone, Mich)

Many forms of galaxy activity, such as starbursts, type 2 Seyfert nuclei, or ultraluminous nuclei, are shrouded in dust. To learn about the fundamental properties of the different manifestations of nuclear activity requires observation in the infrared and other spectral regimes not blocked by obscuration. Imaging active galaxies with the Baade Phase II system is an obvious example. In many cases, the galaxy nucleus itself is suitable as a reference object. Such studies can extend the study of the relation of the nucleus to nearby interstellar matter, critical to understand how mass is fed to the nuclear activity (see HST programs such as Regan and Mulchaey 1999).

In Phase III, we will have the added capability of determining the dynamics around the galaxy nuclei, both to constrain possible black hole masses (see Richstone et al. 1998, Gebhardt et al. 2000) and to determine starburst characteristics (e.g., Engelbracht et al. 1998). Figure 2.2 shows an example from a study of the dynamics of the nearby starburst NGC 253, from the latter reference. This galaxy not only has huge amounts of circumnuclear interstellar material, but is nearly edge on, so its true nucleus is not apparent in the optical.

2.4 Circumstellar Disks and Planets (D. Wilner, S. Kenyon CfA; P. Hinz, L. Close SO)

Surveys of young stars at infrared and millimeter wavelengths show that most exhibit emission from small particles thought to be distributed in disks with properties similar to the young Solar System. Models of spectral energy distributions indicate disk sizes from 10's to 100's of AU, consistent with the gravitational collapse of slowly rotating dense molecular cloud cores.

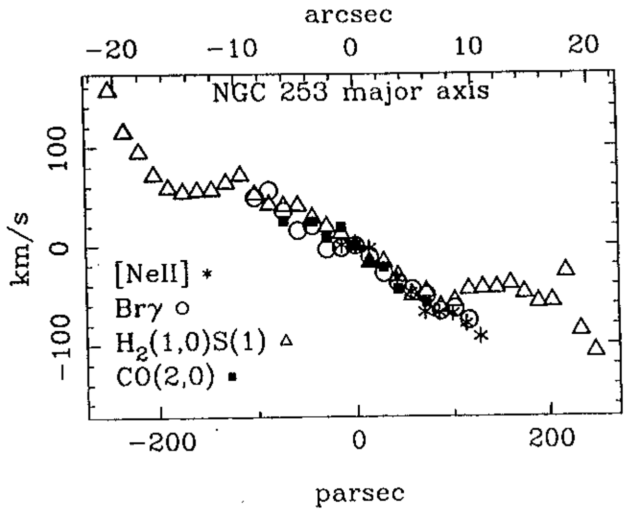


Figure 2.2. Infrared dynamics indicators through the nucleus of NGC 253, from Engelbracht et al. (1998). The NeII line is at 12.8μm, the Brγ and H_2 lines are near 2.1μm, and the CO feature is an absorption bandhead in the spectra of cool stars at 2.3μm.

Despite recent progress, many important questions remain about the structure and evolution of disks around young stars. The benefits of high angular resolution are readily apparent in images of disks made with existing AO systems, as shown in Figure 1.1 and discussed in section 1.3.

These systems have the advantage for AO that the primary star provides a satisfactory wavefront reference. A fiducial scale is that a disk with a radius of 50AU at a distance of 100pc would subtend 1". Therefore, resolution of these systems places a premium on observation of nearby ones, and many of the closest star forming regions are in the southern hemisphere. Even more important, ALMA will provide a unique capability to resolve (at similar 0.1" resolutions) southern hemisphere systems in the mm- and submm-wave regions, enabling one to compare with the structures measured with the Baade Telescope in the near and mid infrared. Such comparisons can test ideas about the process of mass accretion and the agglomeration into planetessimals. For example, in the case of UY Aur 0.1" AO images at J, H, & K were compared to the best CO 2-1 maps made by the Plateau de Bure mm Interferometer to show that the dust in this disk traces the CO gas distribution very closely (Close et al. 1998). The most readily accessible signatures of the presence of companion bodies around young stars may come from their gravitational influence on disks. While the interpretation in terms of planetary systems is not unique, millimeter interferometry and infrared imaging have already directly imaged huge inner holes in the disks that surround some young stellar systems, for example the 200 AU radius cavity in the circumbinary disk of GG Tau shown in Figure 1.1 (Roddier et al. 1996).

Disk imaging in the mid infrared is also a high priority for the Baade Telescope. Many systems of interest will be identified in SIRTF GTO programs (G. Fazio at CfA is PI of IRAC, and G. Rieke of SO is PI of MIPS, two of the three SIRTF instruments) and in the relevant Legacy program (M. Meyer of SO is PI). The ideal approach to imaging these systems is to use nulling interferometry, so that the glare of the primary star is cancelled and very sensitive examination can be made for faint extended emission and point-like planetary images close to the star (Hinz et al. 1998, 1999). BLINC (the Bracewell Infrared Nulling Cryostat) provides this capability and would be the only such instrument in the south. BLINC is designed so the images from each arm are identical and the instrument produces direct images of the object under study (not an image combined with a mirror image). The path length is adjusted by a ZnSe plate, which allows approximate achromatization of the null and hence use of wide bandpasses near 10μm, achieving high sensitivity. However, over large wavelength baselines, the achromatism breaks down making it possible to control the null by observing the signal at shorter wavelengths, e.g., 2μm (Hinz et al. 2000). Using the built-in near infrared wavefront sensor, BLINC can achieve deep nulls operating in the Phase I configuration of the Baade AO system, with suppression by factors up to 10^4 of the light from the primary star but constructive interference (and hence full sensitivity) 0.2" away. Thus, BLINC is an ideal way to probe the environments of nearby stars in the few AU radius region, observing both the structure of the inner parts of the circumstellar debris and searching for any giant planets.

BLINC will also be very effective in finding faint companions, since in only 1000 seconds it can detect (5 σ) a 1 Gyr old object of 10 M_J.

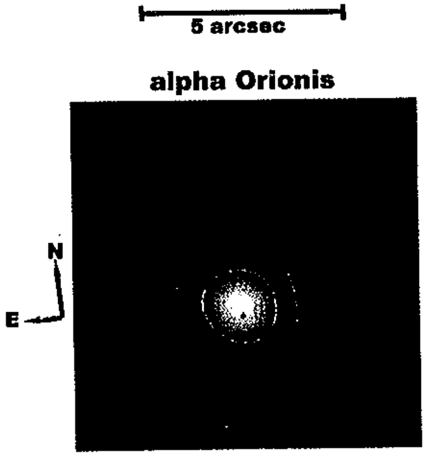


Figure 2.3. Image of the dust cloud surrounding α Ori, obtained with BLINC (Hinz et al. 1998). The position of the star is shown by the black dot; it makes negligible contribution to the image. The dust cloud is asymmetric around this position.

3. Requested Research Instrumentation

3.1 Overview

All the partners in the Magellan Telescopes have a significant interest in adaptive optics (see Section 4). As a result, many critical features have already been built into the Baade Telescope. We summarize in this section the requirements for a state of the art system, the features of the proposed adaptive secondary, and then the other aspects of the system.

3.2 Infrared Optimization

The optical design of the Baade Telescope incorporates all the elements for optimal infrared performance originally described by Low and Rieke (1974) and now proven on many telescopes. The central feature is an undersized secondary mirror that defines the entrance pupil against the cold background of the sky. A thorough optimization of the Magellan infrared focus guided the design of the telescope (Rieke 1987), balancing 1.) optical aberrations; 2.) rapid image motion compensation; 3.) chopping requirements; and 4.) alignment tolerances. The optimization process led to a well defined telescope design with primary f/ratio (f_p) of 1.25 and Cassegrain f/ratio (f_c) of 15.

3.3 Requirements on AO/Chopping System

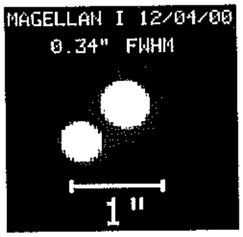
To take advantage of the infrared optimization of the Magellan telescope requires an adaptive optics (AO) mirror system to correct the atmospheric wavefront distortions, allowing operation at the full diffraction limit ($\lambda/D = 0.06$ arcsec at 2μm). In addition, in the deep thermal infrared it is necessary to chop the images rapidly over a small angle to aid in removing sky emission fluctuations and in flatfielding the images. We derive requirements for these operations in this section.

3.3.1 Optical Design

To preserve the intrinsic low emissivity performance of the telescope, no additional warm optical surfaces should be added to the optical train. For ease in construction, a number of AO systems form a re-imaged pupil and place a warm, flexible mirror there, adding a number of warm optical surfaces. Lloyd-Hart (2000) has compared conventional focal plane AO systems with the performance of a deformable-secondary-mirror. He shows that the lower infrared foregrounds allow the latter to reach faint sources in factors of 2 to 3 less integration time in the infrared atmospheric windows at 2.2 (K), 3.5 (L), and 5(M), and 10(N) μm. This gain will make the Baade telescope nominally more sensitive by factors of 1.1 – 1.4 than the somewhat larger southern hemisphere telescopes with conventional AO systems (e.g., NAOS which adds 7 extra warm mirrors and one extra warm dichroic), given equal integration times.

3.3.2 Adaptive Optics

The median seeing at the Magellan Telescope in the visible has proven to be spectacularly good -- see figure to right -- with images of 0.5" or less occurring frequently. Thus, nearly full correction of the typical wavefront distortions at all wavelengths > 1μm can be provided with an adaptive mirror with ≥ 300 actuators. Experiments at the MMT and elsewhere show that



optimal image stabilization requires a servo bandwidth of ≥ 50 Hz, corresponding to a step and settle time of < 2 msec. The diffraction limit can be achieved at 1μm if the surface error of the mirror is ≤ 35nm rms. The typical incremental stroke of a single actuator will be ≤ 0.1μm of wavefront correction, corresponding to a motion of ≤ 0.05μm, in a single 2msec period. As discussed in Section 1, the mirror should be smoothly deformable to provide a smooth PSF.

3.3.3 Chopping

Chopping with the secondary mirror is well known to give the best results in the mid infrared, since it minimizes path differences in the telescope dome and in the atmosphere near the ground compared with any form of focal plane chopper (Low and Rieke 1974, Rieke 1987). In addition, focal plane choppers involve additional warm reflections with performance penalties similar to those discussed above for AO systems.

We base our derived requirements for chopping frequency from experiments with the Mid-Infrared Array Camera (MIRAC) on the IRTF (Hoffmann 1993; see also Gezari et al. 1992), which were obtained to help set the Gemini chopping frequency specification. The system noise was measured observing the inside of the telescope dome and with the instrument adjusted to equalize the background on the detector, and subtracting the resulting noise from the total to derive the component from the sky. Modulation at ≥ 3 Hz was needed to extract the best signal to noise from the detector, regardless of the behavior of the sky. This frequency is far lower than would be conventional with a single detector because of the degree of monitoring of the sky achieved in staring mode with an array. The chopper throw as a minimum should be a few times the diameter of the Airy disk, i.e., $> 5\,\lambda/D \sim 2''$ at 12μm on the Baade Telescope, where λ is the wavelength of operation and D the telescope diameter. A larger chopper throw is highly desirable, both at 20μm and to improve the performance on extended sources.

3.3.4 Summary

The requirements for the infrared secondary are summarized to the right.

Secondary Mirror Diameter (2.6% undersized)	63.9 cm., f/15
Number of actuators	> 300
Actuator speed	step 0.05μm and settle in < 2ms
Accuracy	< 35nm rms mirror surface error
Chopping frequency	up to 3 Hz
Chopper throw on sky	> 2" (10" goal)
Thermal control	≤ 2C from ambient

3.4. Implementation

3.4.1 Adaptive Correction

The proposed AO system for the Baade Telescope will be modeled on the system now being completed for the MMT, whose primary mirror is identical to the Baade primary. As part of the Large Binocular Telescope project, Steward and Arcetri Observatories have collaborated in developing a new and powerful technique for adaptive optics, in which the adaptive correction is made directly at a deformable Cassegrain secondary mirror. A series of prototype mirrors has been built and tested, leading to construction of the 336 actuator MMT secondary (see figs 3.1 and 3.2) as the first application. The highly aspheric and very thin glass meniscus face sheet of the 64cm secondary was figured at the Steward Observatory Mirror Lab, by new techniques developed especially for the purpose. The Lab also made the rigid ULE glass reference body, which is pierced by 336 holes for actuators, each with the annular electrode of a capacitive gap sensor to allow servoing the actuator to maintain the 50μm gap between meniscus and reference. The rest of the secondary, including the supporting structure, the voice coil actuators, and the control system, were designed and built in Italy by three firms: Media Lario, ADS, and Microgate. The MMT AO secondary has now been accepted in Arizona, and will soon (Mar. 3, 2001) have its final system checks on the optical testbed in the mirror lab. First light at the telescope is scheduled for July 2001. Given the excellent performance demonstrated in acceptance testing in Italy and Arizona, we propose to replicate this system for use on Magellan.

In this design, the meniscus is restrained against in-plane motions by a thin steel pivot attached to the inner hub of the secondary, leaving almost free the focus, tilt, and higher degrees of freedom. Each actuator is controlled by a 20 kHz position servo operating off the corresponding sensor, and by external WFS commands (updated at 770Hz) that indicate how to bend the meniscus sufficiently to carry out full wavefront correction. To avoid hard contacts that can ruin the small scale smoothness of conventional SAM mirrors, the actuators do not make contact with the meniscus. Their voice coils simply drive a magnetic field that passes through the air gap and pushes or pulls small magnets attached on the backside of the meniscus directly above each voice coil. To increase the system robustness the air gap is closed by a fine latex seal that prevents dust from entering the sealed area containing the gap. A similar system was found to be very robust with the FASTTRAC2 capacitive sensors (Lloyd-Hart et al. 2000), which utilized a similar gap size on many nights (~45) at the MMT without a failure. This concept provides a very smooth adaptive surface since the deformable mirror "shell" rides on a cushion of air everywhere except in the central hub --which itself sees no light and so does not effect the PSF.

The glass meniscus itself has a resonance of ~30 Hz when not under servo control (and about 300 Hz for tip/tilt under servo control); the stability of the system is greatly enhanced by making use of the damping provided by the thin layer of air trapped (with few exit paths) between the meniscus and plate. Tests of the system show it to have a rise time of ~ 0.5 msec and 18nm rms error. The servos are very stable at least up to meniscus/plate gaps of 80μm. The operation has been shown to be independent of the gravity direction. The system also seldom requires recalibration and is robust. The performance of the mirror is illustrated in Figure 3.3.

3.4.2 Chopping

The traditional approach to chopping between source and sky with mid infrared instruments is to tilt a rigid secondary mirror between two fixed positions (Low & Rieke 1974). The control power is minimized by tilting around the center of mass, in which case it is approximately:

$$P = C\,B\,\rho \frac{f_p^3 A^5}{f_c^3} \nu^3 \theta^2,$$

where C is a constant, B is the thickness to diameter ratio of the mirror, ρ is its density, A is the telescope aperture, f_p is the primary f/ratio, f_c is the Cassegrain f/ratio, ν the chop frequency, and θ the chop angle on the sky (Rieke 1987). As equation (1) shows, the requirements for articulation have been made very difficult with large telescopes. In addition to the rapid scaling with telescope aperture, field curvature must be controlled for good imaging over large-format arrays. We have carried out ray traces for a number of possible instruments, finding that the delivered image quality suffers due to field curvature if the Cassegrain f/ratio, f_c, is > 15 (Rieke 1987). A solution has been demonstrated for the Keck and VLT telescopes with an expensive beryllium mirror and placement of instruments at a forward Cassegrain focus (to limit the secondary size), requiring significant constraints on their design.

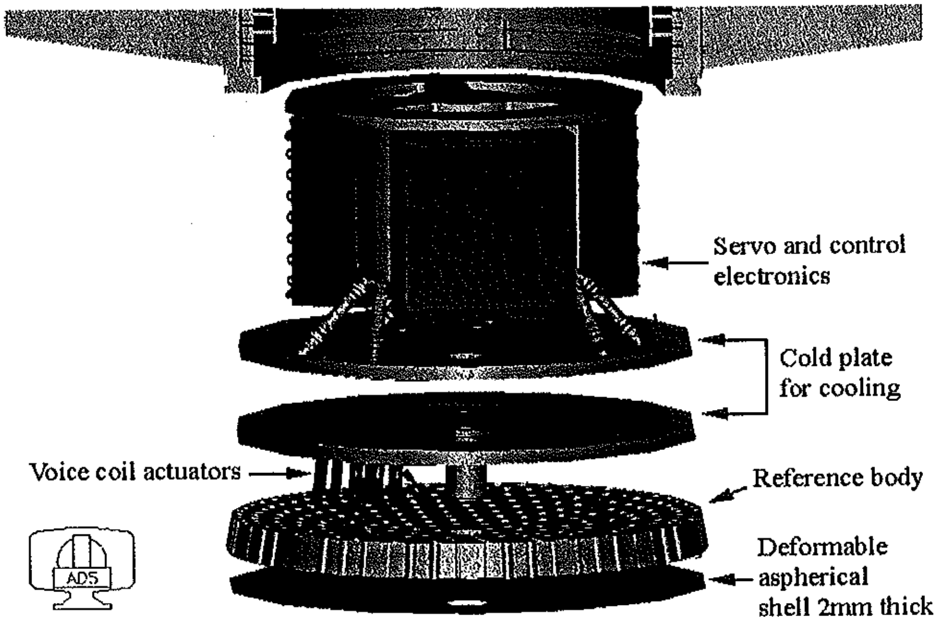


Figure 3.1. An exploded diagram of the MMT 336 actuator secondary (Brusa et al. 1999).

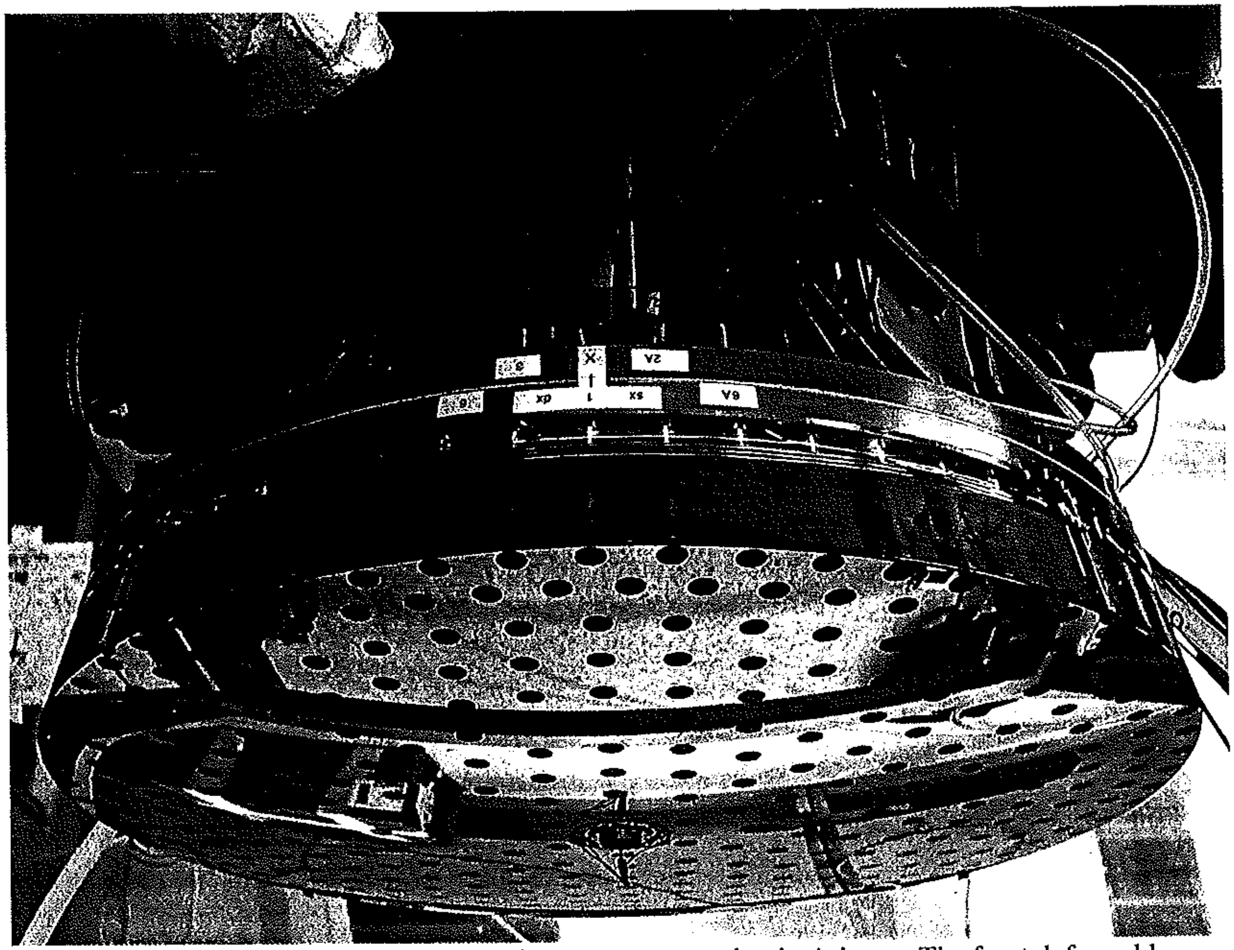


Figure 3.2. The MMT AO secondary under acceptance testing in Arizona. The front deformable meniscus is not yet aluminized.

These problems can be circumvented by using a thin meniscus secondary mirror to carry out chopping as well as AO correction. In this approach, the rigidity requirement is met by the reference body, which can have a conventional thickness to diameter ratio and can be constructed of conventional, well-behaved optical materials. The low inertia of the meniscus allows for chopping with a minimum of power and hence with a tractable control problem. The mirror figure is maintained during the chop action by monitoring the gap between meniscus and reference body. We have an ongoing effort with Media Lario, ADS, and Microgate to use such mirrors for chopping, and the Magellan mirror can benefit from this study.

The action of air damping decreases rapidly as the gap between the backup plate and the meniscus is increased. However, to allow chopping, this gap has to be larger than required for adaptive corrections. Already in acceptance testing, with no attempt to optimize the system for chopping, the mirror has been chopped over an angle corresponding to a throw of 2" in the focal plane, and with a rise time of < 1 ms. Measurements on the mirror show its servos to be very stable with a gap of 80μm (Riccardi et al. 2000). Thus, with a nominal gap of 50μm, a chop corresponding to ± 30μm of motion at the meniscus edge is possible. Such a motion corresponds to a total chop of 7.5" in the telescope focal plane.

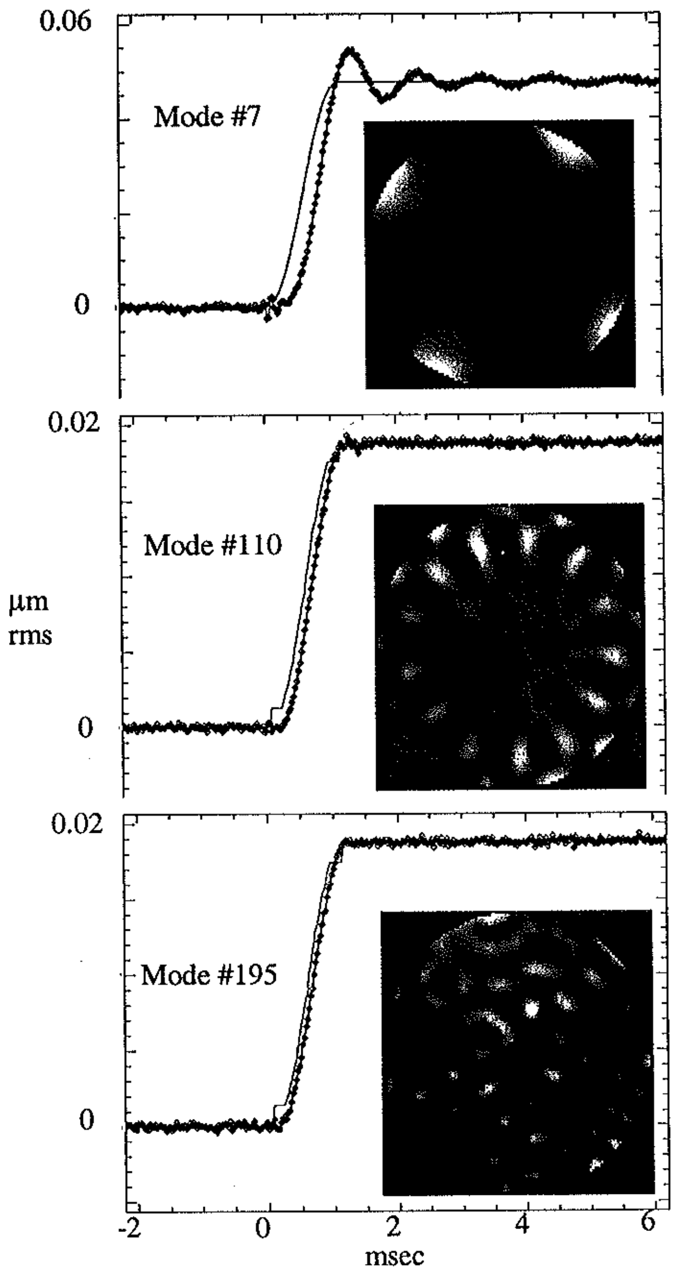


Figure 3.3. Operation of MMT AO Secondary Mirror. The top frame shows the results using the actuators to move the mirror in its 7th mechanical mode. In this mode, the mirror has low stiffness and most of the 'work' is done by the closed loop control. A low order mode such as this one is expected to require motions up to 0.05µm (see requirements), close to the amplitude demonstrated in this figure. The middle frame shows similar results, but with the mirror distorted according to the 110th mechanical mode. In this mode, the mirror has medium stiffness and both closed loop control and open loop (feedforward) 'work' are important. The bottom frame shows the 195th mechanical mode, where the mirror has high stiffness (about three orders of magnitude above the 7th mode). Here, the open loop control (feedforward) does the work. All the responses have short risetimes and rapid settling, demonstrating the quality of the servo control.

3.4.3 Other system components

Two features will assist in maintenance of the adaptive secondary. The first is a grid of 24 absolute gap sensors that are built into the device, interspersed with the linear actuators and their capacitive relative gap sensors. Each of these devices is a miniature interferometer with a silicon PIN diode sensor, and each is fed from a single monochromator via fiber optics (see Johnson et al. 1999). They allow setting the figure of the meniscus without reference to a star. Second, an optical testbed has been developed at Arizona to test the MMT mirror, utilizing a large doublet lens to allow operation with an artificial test source and turbulence simulator coupled to an interferometer and WFS (cf McGuire et al. 2000; Lloyd-Hart et al. 2000). Before shipping the Baade secondary to Chile, we will bring it to Arizona to perform end-to-end testing of the entire system in the optical test bed to verify and optimize its performance. In addition, we have included in the budget a duplicate doublet lens to be mounted on the telescope as needed with the secondary mirror. This lens allows the AO optical train -- secondary and guider box optics -- to be illuminated artificially (with the dome closed) to allow detailed trouble shooting and tuning up of the electronics on site.

The telescope already includes an instrument rotator and focus and collimation adjustments for the adaptive secondary. The adaptive system will need a guider box to be provided by the telescope project budget. As with the secondary mirror itself, the design of this unit will benefit substantially from experience with the MMT, for which the AO guider box is shown in Figure 3.4. The focal plane instrumentation is mounted on the bottom of the box with an up-looking optical system that accepts the light from the telescope without a single additional warm reflection. The cryostat window is a dichroic that reflects the visible light into the guider optical train. For the Baade Telescope, we will provide "railroad tracks" for mounting two instruments so we can switch quickly between them while maintaining exactly the same feed to the guider optics. The optics feed a Shack-Hartmann wavefront sensor, which can operate on axis because of the dichroic feed, or anywhere over a field of 150" in diameter. In Phase I, we will use a wavefront analyzer provided by the project to allow optimizing mirror figure, but without the bandwidth required for realtime wavefront correction. A separate high speed optical sensor will be used for tip-tilt correction, adequate to achieve the diffraction limit at 10 and 20μm over nearly the whole sky given the excellent seeing at the Baade Telescope site and the large tip-tilt isoplanatic patch. This device will be upgraded to a high bandwidth wavefront sensor when the AO is to be used for near infrared observations, along with the necessary computer hardware and software for real-time wavefront reconstruction and control of the adaptive secondary at 770Hz like the current MMT system (Lloyd-Hart et al. 2000).

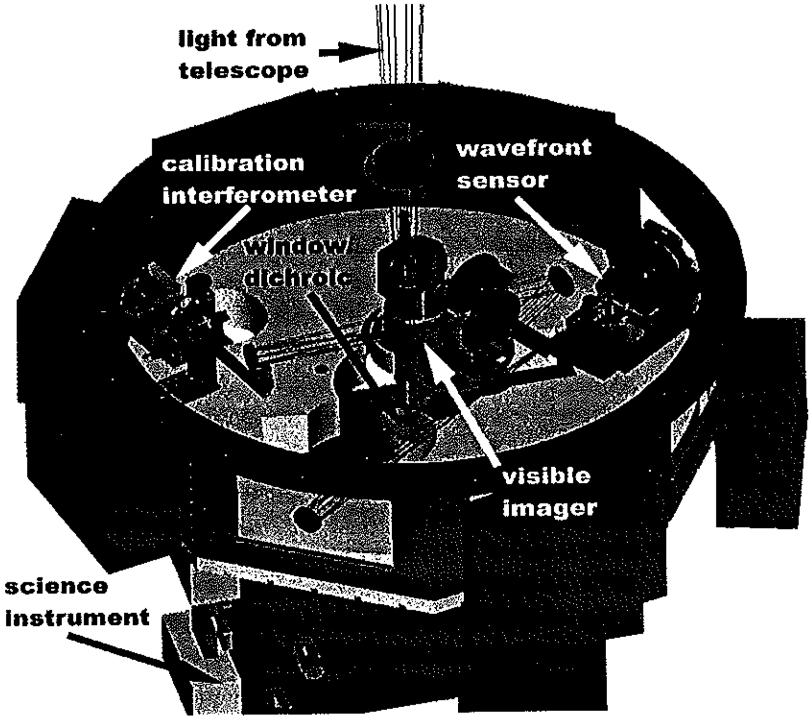


Figure 3.4. MMT adaptive optics guider box shown as built. We will replicate this design for Magellan. Note that the science instrument window/dichroic is the first optical element in the AO system; therefore the instrument sees no increase in the thermal background from the AO system.

4. Impact on research infrastructure

The United States has a huge investment in new-generation large telescopes in the north: two 10-m Keck Telescopes, 50% of the twin 8.4-m Large Binocular Telescope, the 9-m Hobby-Eberly Telescope, 52% of the 8-m Gemini(N) Telescope, and the 6.5-m Multiple Mirror Telescope. U.S. access in the south is more limited, with 42% of the 8-m Gemini (S) Telescope, about half of the 9-m South African Large Telescope (SALT), and the two 6.5-m Magellan Telescopes. In terms of mirror area weighted by share, the two Magellan Telescopes represent more than half of the U.S. presence in the south. Since the SALT is of an inappropriate design, the only other southern new generation U.S. telescope that will allow use of AO is Gemini (S). The implementation on that telescope may be delayed due to the breakup of Laplacian Optics, the main contractors of the NICI AO system. This will place the US significantly behind the VLT which should have its facility AO system (NAOS; a classical SAM AO system) available at the end of 2001.

This proposal will not only provide an important capability for U.S. astronomy in the form of AO on Magellan I/Baade Telescope, but also a world class AO capability. The obvious standard of comparison in the south is the VLT with NAOS. Although the resolution of the Baade Telescope compared with a single VLT will be reduced by the aperture ratio of 8/6.5=1.23, we show in Section 3.3.1 that our approach will allow IR point source sensitivity greater than with a VLT telescope by factors of 1.1 – 1.4. In addition, the Baade Telescope will benefit from the smooth deformable mirror compared with the SAM on the VLT.

The Magellan consortium includes five major observatories: Carnegie Observatories (OCIW), Harvard-Smithsonian Center for Astronomy (CfA), Massachusetts Institute of Technology (MIT), the University of Michigan (Mich), and Steward Observatory of the University of Arizona (SO). The consortium includes more than 300 research astronomers, divided roughly equally among permanent faculty/staff; research faculty and postdoctoral fellows; and graduate students.

Infrared astronomy and the new possibilities through adaptive optics are a high priority with all the members of the Magellan consortium. The infrared instrument for HST was managed at SO and two of the three instrument teams for NASA's next infrared mission, SIRTF, are centered at consortium members. Contributions for the science applications section of this proposal were made by members of the staffs of all the consortium members, and are based on extending and expanding their ongoing programs. Thus, the availability of adaptive optics at the Baade Telescope is viewed as an exciting addition to its capabilities, and one that would be used immediately by all consortium members for a broad variety of science objectives.

To illustrate this point in more detail, the following table lists faculty/staff members, their affiliation, their relevant science interest, and a recent publication reporting research where observations with the proposed AO system would have been useful. Each faculty/staff member is backed, on average, by a research faculty member and a graduate student, so the table shows that research programs of about 100 members of the consortium would benefit immediately from the implementation of the adaptive optics system. Of course, interests will change, and the availability of AO is likely to attract other members of the consortium into research projects using it.

Four members of the Magellan consortium -- Harvard, Michigan, MIT, and Arizona -- have large graduate student programs. These programs together total well over 100 students, all of whom potentially have access to the Baade Telescope. Given the faculty interest, many graduate student research programs will in fact take advantage of this opportunity. The faculties have also been very successful in engaging undergraduates in research, with nearly 100 in an active status at any one time. We estimate that about a third of these student programs will make active use of the Baade Telescope or data from it. Thus, the Baade AO system will have an important educational dimension, through providing state of the art data for undergraduate projects and a major research capability for Ph.D. theses.

Name	Org.	Program	
Angel, R.	SO	extrasolar planets	IAU Symp. 202, 102 (2000)
Bechtold, J.	SO	emission lines in high z galaxies	ApJL, 477, L29 (1997)
Bernstein, G.	Mich	gravtationally lensed quasars	AJ, 118, 14 (1999)
Binzel, R.	MIT	surface composition of asteroids	Icarus, 128, 95 (1997)
Brown, R.	SO	debris disks	ApJ, 529, 499 (2000)
Butler, R. P.	OCIW	extrasolar planetary systems	ApJ, 545, 504 (2000)
Canizares, C.	MIT	xray source identification/grav. Lenses	ApJL, 543, L119
Chakrabarty, D.	MIT	xray source identification/pulsars	ApJL, 498, L37 (1998)
Close, L.	SO	extrasolar planets, circumstellar disks	A&A, 364, L13 (2000)

Dressler, A.	OCIW	galaxy clusters, surface bright fluctuations	ApJ, 530, 625 (2000)
Elliot, J.	MIT	outer solar system	Nature, 393, 765 (1998)
Fazio, G.	CfA	SIRTF followup, mid-IR imaging	ApJL, 541, L63 (2000)
Freedman, W.	OCIW	tip of red giant branch for distances	ApJ, 480, 589 (1997)
Hartmann, L.	CfA	star formation, circumstellar disks	ApJL, 521, L129 (1999)
Ho, L.	OCIW	near IR observations of low lum. AGNs	ApJ, 516, 672 (1999)
Ho, P.	CfA	circumstellar disks, Galactic Center	ApJ, 513, 752 (1999)
Hoffmann, W.	SO	mid-IR imaging, planetary nebulae	ApJ, 492, 603 (1998)
Huchra, J.	CfA	extragalactic globular clusters	ApJL, 531, L29 (1999)
Impey, C.	SO	lensed quasar host galaxies	ApJ, 541, 74 (2000)
Kenyon, S.	CfA	circumstellar disks	ApJL, 524, 119 (1999)
Kirshner, R.	CfA	supernovae, gamma ray bursts	ApJ, 543, 61 (2000)
McCarthy, D.	SO	brown dwarfs, low mass stars	ApJ, 481, 378 (1997)
McCarthy, P.	OCIW	deep cosmological imaging	AJ, 120. 575 (2000)
Meyer, M.	SO	circumstllr disk evolution/mid-IR features	ApJ, 534, 838 (2000)
Mulchaey, J.	OCIW	AGN and environments imaging	AJ, 117, 2676 (1999)
Persson, S. E.	OCIW	deep cosmological imaging	AJ, 112, 1612 (2000)
Phillips, M.	OCIW	supernova spectral energy distributions	ApJ, 536, 62 (2000)
Richstone, D.	Mich	dynamics of galactic nuclei	ApJL, 539, L13 (2000)
Rieke, G.	SO	SIRTF followup, star formation	ApJ, 510, 1016 (2000)
Rieke, M.	SO	starburst galaxies, SIRTF followup	ApJ, 532, 845 (2000)
Schechter, P.	MIT	new gravitational lenses	AJ, 120, 2868 (2000)
Schmidt, G.	SO	optical polarimetry	ApJ, 545, 117 (2000)
Steel, S.	CfA	star formation in blue compact galaxies	A&A, 315, L105 (1996)
Thompson, R.	SO	NICMOS followup, cosmology	AJ, 119, 1062 (2000)
Wilner, D.	CfA	circumstellar disks	ApJL, 534, L101 (2000)
Young, E.	SO	circumstellar disks, SIRTF followup	ApJL, 492, L157 (1998)
Zaritsky, D.	SO	Magellanic Cloud stellar populations	AJ, 118, 2824 (1999)

5. Management Plans

We plan to implement adaptive optics on the Baade Telescope incrementally, to obtain experience and to train personnel as we go. At the same time, the system needs to be scientifically compelling from the start, and each part of the system needs to be of high quality so we do not have to spend resources building replacements. To meet these goals, we will use a phased approach:

Phase I combines the requested \$0.99M from NSF, \$0.4M of matching funds from the University of Arizona and from a portion of a gift to MIT, \$0.4M of project funds, and existing instrumentation to to establish science capability for the deep thermal infrared. Instrumentation will include MIRAC, BLINC, and IRIS (respectively, a 5 - 25μm camera with a 128x128 detector array, a nulling interferometer based on the same camera, and a camera/high resolution spectrometer based on a 256x256 array - the first would be a facility instrument and the latter two available on a visiting basis).

Phase II will follow quickly, with its core funding derived from the gift of \$1.5M to MIT. It will provide near infrared imaging (requiring a suitable focal plane instrument and improvements in the wavefront sensor). In addition, at this time use of the MMT's AO science camera/spectrometer ARIES (McCarthy et al. 2000) will become possible on a visiting basis.

Phase III will provide for near infrared spectroscopy on a facility basis.

Phase IV would include upgrades to the AO system, such as use of artificial guide stars. In this way, the Baade Telescope can leverage off the NSF investment in advanced AO at the MMT. We will be careful to anticipate such upgrades as the initial system is designed, but will be cautious about introducing them to the Baade Telescope until they have been proven on the MMT.

The phased approach has been carefully evaluated to be sure that each step leads to a self-contained powerful scientific capability, building on the capabilities established in previous phases. It also divides the tasks into well-focussed systems that allow most of the implementation to be carried out by a single group, with carefully considered and relatively straightforward interfaces. Thus, this implementation allows the different consortium members to contribute to the overall AO system without creating overly complex interactions or problems of interface control.

Upon approval of this proposal, work would proceed on the following schedule:

1. Negotiate contract	2 months	includes final interface definition
2. AO secondary const.	15 months	includes optics @ UA plus electronics, assembly, & test in Italy
3. Shipping to UA	1 month	
3. End-to-end testing	3 months	system level testing in the AO simulator at Arizona
4. Shipping to Chile	2 months	
5. Install at telescope	2 months	includes time for system testing and personnel training
6. Operation in mid-IR	6 months	completes Phase I - science operations, fine tuning
7. Initial tests of WFS	6 months	wavefront sensor testing begins Phase II (can overlap with mid-IR operation)
8. Operation in near-IR		delivery of near IR camera completes Phase II

A budget is attached; by leveraging the Baade AO system as much as possible off the large investments by the Air Force, Steward and Arcetri Observatories, and the NSF, we can provide a powerful system for much less than it would cost for a new development.

Our management approach can best be understood by reference to the budget. The contract to Media Lario/ADS/Microgate is managed in Italy by Media Lario, who serve as the primary point of contact. The Steward Observatory optical work will be managed by S. Miller, who has overall responsibility for the mirror laboratory and hence the authority to be sure that the work proceeds. We have also included a line item for partial support of a technical manager who will be responsible for the systems overview of the mirror/electronics/telescope interface and will also be responsible for contract administration. The work in Italy will be further managed through a series of technical reviews and incremental funding based on success in them. Thus, contract negotiation will end with a kick-off review to be sure that all the boundary conditions for the work are understood on both sides. There will be a mid-term review prior to the beginning of assembly of the electronics with the optics, and a pre-ship review to be sure that all test data and documentation are satisfactory before delivery.

We have also addressed management issues in the composition of the proposing team. The PI, Laird Close, was manager of AO systems for the VLT prior to taking a faculty position at AO. Co-I Bill Hoffmann will represent MIRAC, which will be the first instrument to be used extensively with the new hardware. George Rieke has been involved closely with the infrared optimization of the Baade Telescope and is the SO representative on the Magellan Science Advisory Committee. Paul Schechter represents the MIT interest in the program and will coordinate activities with the implementation there of Phase II. Matt Johns is the project scientist for the telescope and will advise us on issues regarding interfaces with it.

References

Blandford, R. D. and Narayan, R., Cosmological applications of gravitational lensing, 1992 ARA&A 30, 311

Bouvier, J., Duchene, G., Simon, T., Close, L.M., & Eisloffel, J., The Binary Fraction in Different star forming Regions, Protostars & Planets IV, 1998 July 6-13th Santa Barbara.

Brusa, G., Riccardi, A., Biliotti, V., Del Vecchio, C., Salinari, P. Stefanini, P. Mantegazza, P., Biasi, R., Andrighettoni, M., Franchini, C., and Gallieni, D. SPIE Conference on Adaptive Optics Systems and Technology, 1999, eds. Robert K. Tyson and Robert Q. Fugate, 3762, Denver.

Close, L.M. and D.W. McCarthy, High Resolution Imaging with a Tip-Tilt Cassegrain Secondary, PASP, 1994, 106, 77-86.

Close, L., D. McCarthy, and F. Melia, Infrared Photometry of the Black Hole Candidate Sgr A* ApJ, 1995, 439, p 682-686.

Close, L.M., P., Hall, C. Liu, and K. Hege, Spectroscopic and Morphological Evidence that IRAS FSC 10214 +4724 is a Gravitational Lens, 1995, ApJ, 452, L9

Close, L.M., F. Roddier, M.J. Northcott, C. Roddier, J.E. Graves, Adaptive Optics 0.2" Resolution Infrared Images of HL Tauri: Direct Images of an Active Accretion Disk Around a Protostar, 1997a, ApJ 478 766.

Close L.M., et al., Adaptive Optics Infrared Imaging-Polarimetry and Optical HST Imaging of Hubble's Variable Nebula (R Mon / NGC 2261): A Close Look at a Very Young Active Herbig Ae/Be star, 1997b, ApJ 489, 210-221.

Close L.M., et al., Adaptive Optics Imaging of the Circumbinary Disk Around The T Tauri Binary UY Aur: Estimates of the binary Mass and Circumbinary Dust Grain Size Distribution, 1998, ApJ 499, 883

Close L., Dan Potter, and Alan Tokunaga, Adaptive Optics Imaging of Faint Companions: Test Case of MWC480, 1999 ESO VLT first Light Sym., Chile, p518

Close L.M. et al., A Search for Asteroidal Satellites Using Adaptive Optics, SPIE proc. 4007, Munich, March 2000a, p796-802

Close L.M., et al., Adaptive Optics Imaging of Pluto-Charon and the Discovery of a Moon Around the Asteroid 45 Eugenia: The potential of Adaptive Optics in Planetary Astronomy, SPIE proc. 4007, Munich, March 2000b, p787-795

Close, L.M., A Review of Published Galactic and Solar System Science: A Bright Future for Adaptive Optics Science, 2000c, SPIE proc. 4007, p 758-772

Crampton, D., Schechter, P. L., and Beuzit, J.-L., Detection of the Galaxy Lensing the Doubly Imaged Quasar SBS 1520+530, 1998 AJ, 115, 1383

Duchene, G., Bouvier J., Simon, T., Close, L.M., & Eisloffel, J., The Binary Fraction in Different star forming Regions, CFHT Users Meeting 1998a, Quebec City.

Duchene, G., J. Bouvier, T. Simon, L. Close, & J. Eisloffel, Low-mass stars in young open clusters: a deep near-infrared adaptive optics binary survey, 1998b, ESO/OSA Astronomical Adaptive Optics Sept. 6-11th Sonthofen, Germany, p185

Dumas, C., Owen, T., and Barucci, M. A., Near-Infrared Spectroscopy of Low-Albedo Surfaces of the Solar System: Search for the Spectral Signature of Dark Material, Icarus, 133, 221

Eisloffel, J., Theodore Simon, Laird Close, Jerome Bouvier, Binarity in the Young Open Cluster a Persei 2000a, Cool stars conference.

Eisloffel, J., Theodore Simon, Laird Close, Jerome Bouvier, Binarity in the Young Open Cluster α Persei , 2000b, IAU 200, "Binary Star Formation", Potsdam, Germany, April 2000.

Engelbracht, C. W., Rieke, M. J., Rieke, G. H., Kelly, D. M., and Achtermann, J. M., The Nuclear Starburst in NGC 253, 1998, ApJ, 505, 639

Gebhardt, K. et al., A Relationship between Nuclear Black Hole Mass and Galaxy Velocity Dispersion, 2000, ApJL, 539, 13

Gezari, D. Y., Folz, W. C., Woods, L. A., and Varosi, F., A 5-18 micron array camera for high-background astronomical imaging, 1992, PASP, 104, 191.

Graves, J.E., Northcott, M. Roddier, F., Roddier, C., & Close, L.M First light for Hokupa'a: the 36 element Curvature AO system at UH, 1998, Proc. SPIE Vol. 3353, Adaptive Optical System Technologies, Domenico Bonaccini; Robert K. Tyson; Eds., p. 34-43

Gregg, M. D., et al., A Close-Separation Double Quasar Lensed by a Gas-rich Galaxy, 2000, AJ, 119, 2535

Haller, J., M.J. Rieke, G.H. Rieke, P. Tamblyn, L. Close and F.Melia, Stellar Kinematics and the Black Hole in the Galactic Center, 1996, ApJ, 456, p194.

Hinz, P. M., Angel, J. R. P., Woolf, N. J., Hoffmann, W. F., and McCarthy, D. W. 1999, PASP Conf. Ser. 194, 401

Hinz, P. M., Angel, J. R. P., Hoffmann, W. F., McCarthy, D. W., McGuire, P. C., Chelselka, M., Hora, J. L., and Woolf, N. J., Imaging circumstellar environments with a nulling interferometer. 1998, Nature, 395, 251

Hinz, P. M., Angel, J. R. P., Woolf, N. J., Hoffmann, W. F., and McCarthy, D. W., First results of nulling interferometry with the Multiple-Mirror Telescope, 2000, SPIE Conf. on Interferometry in Optical Astronomy, eds. P. J. Lena and A. Quirrenbach, in press.

Hoffmann, W. F. 1993, unpublished report to Gemini Project on sky noise

Hoffmann, W. F., Hora, J. L., Fazio, G. G., Deutsch, L. K., and Dayal, A., MIRAC2: a mid-infrared array camera for astronomy, 1998, Proc. SPIE, 3354, 647

Hollywood, J.M., F. Melia, L. M. Close, D. W. McCarthy, and T. A. DeKeyser, General Relativistic Flux Modulations in the Galactic Center Black Hole Candidate Sgr A*,1995, ApJ, 448, L21.

Johnson, R. L., Angel, J. R. P., Lloyd-Hart, M., and Angeli, G.Z., Miniature instrument for the measurement of gap thickness using polychromatic interferometry, 1999, Proc. SPIE, 3762, 245

Keeton, C. R., Kochanek, C. S. and Falco, E. E., The Optical Properties of Gravitational Lens Galaxies as a Probe of Galaxy Structure and Evolution, 1998, ApJ, 509,561

Lehár, J., et al., Hubble Space Telescope Observations of 10 Two-Image Gravitational Lenses, 2000, ApJ, 536, 584

Lloyd-Hart, M., Thermal Performance Enhancement of Adaptive Optics by Use of a Deformable Secondary Mirror, 2000, PASP, 112, 264

Lloyd-Hart, M., Wildi, F., Martin, H., McGuire, P., Kenworthy, M., Johnson, R., Fitz-Patrick, B., Angeli, G., Miller, S., Angel, J. R. P., Adaptive Optics at the 6.5 m MMT, 2000, SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 167-174, Munich.

Low, F. J., and Rieke, G. H., Methods of Infrared Astronomy, 1974, Methods of Experimental Physics, ed. M. Carleton, Pergamon Press.

McCaughrean, M. J., Stapelfeldt, K., and Close, L. M., High-Resolution Optical and Near-Infrared Imaging of Young Circumstellar Disks, 2000, Protostars and Planets IV, p. 485

McGuire, P. C., Langlois, M. P., Lloyd-Hart, M., Rhoadarmer, T. A., and Angel, J. R. P. , 2000, SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 713-716, Munich

Merline, W.J., L.M. Close, C. Dumas, C.R. Chapman, F. Roddier, F. Menard, W. Colwell, D.C. Slater, G. Duvert, C. Shelton, T. Morgan, Discovery of a Moon orbiting the asteroid 45 Eugenia 1999, NATURE, 401, 565

Merline, W. J.; Close, L. M.; Dumas, C.; Shelton, J. C.; Menard, F.; Chapman, C. R.; Slater, D. C., Discovery of Companions to Asteroids 762 Pulcova and 90 Antiope by Direct Imaging, 2000, American Astronomical Society, DPS meeting #32, #13.06

Morgan, N. D., Dressler, A., Maza, J., Schechter, P. L., & Winn, J. N., CTQ 414: A New Gravitational Lens, 1999, AJ, 118, 1444

Mutz, S.B., R. A. Windhorst, D. Wittman, L. Close, D. McCarthy, High-Resolution V,I, and K-Band Imaging of Faint Field Galaxies from the HST Medium-Deep Survey, 1997, AJ 113, 1537

Potter, D., L.M. Close, F. Roddier, C. Roddier, J.E. Graves, M. Northcott, A High-Resolution Polarimetry Map of the Circumbinary Disk around UY Aur, 2000, ApJ, 540, 422

Potter, D.; Baudoz, P.; Brandner, W.; Close, L.; Graves, B.; Guyon, O.; Northcott, M, Gemini/ Hokupa'a Adaptive Optics Observations of Circumstellar Disks, 2001, American Astronomical Society Meeting 197, #91.05

Regan, M. W., and Mulchaey, J. S., Using HUBBLE SPACE TELESCOPE Imaging of Nuclear Dust Morphology to Rule Out Bars Fueling Seyfert Nuclei, 1999, AJ, 117, 2676

Riccardi, A., Brusa, G., Bilotti, V., Del Vecchio, C., Salinari, P. Stefanini, P. Mantegazza, P.. Biasi, R., Andrighettoni, M., Franchini, C., Gallieni, D., Lloyd-Hart, M., McGuire, P., Miller, S., and Martin, H., Adaptive Secondary Mirror for the 6.5 m Conversion of the Multiple Mirror Telescope: Delivery Test Results, 1999, SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 524-531, Munich.

Richstone, D. et al., Supermassive black holes and the evolution of galaxies, 1998, Nature, 395, 14

Rieke, G. H., Infrared Optimization of 8-m Telescopes, 1987, unpublished report to the Magellan Project

Rigaut, F. et al., Performance of the Canada-France-Hawaii Telescope Adaptive Optics Bonnette, 1998, PASP, 110, 152

Roddier, C., Roddier, F., Northcott, M. J., Graves, J. E., and Jim, K., Adaptive Optics Imaging of GG Tauri: Optical Detection of the Circumbinary Ring, 1996, ApJ, 463, 326

Roddier, F., Roddier, C., Close, L.M., Dumas, C., Graves, J.E., Han B., Northcott, M., Owen, T., Tholen D., & Brahic, A., Planetary science with adaptive optics: results obtained with the University of Hawaii AO system, 1998 ESO/OSA Astronomical Adaptive Optics Sept. 6- 11th Sonthofen, Germany, p401

Simon, M., L.M. Close & T. Beck, Adaptive Optics Imaging of the Orion Trapezium Cluster, 1999, AJ 117, 1375

Tamblyn, P., G. Rieke, M.M., Hanson, L.M. Close, D. McCarthy, Rieke, M. The Peculiar Population of Hot Stars at the Galactic Center, ApJ, 1996, 456, p206.