Bruce Macintosh
for the GPI team
Presented at the “Spirit of Lyot”
conference June 7, 2007
2004: Gemini “Extreme AO Coronagraph” Conceptual design begins (CfAO-led)
2005: Gemini selects team and project
2006: (June): Project start
2007: (May): PDR pass

Team
LLNL: Project lead + AO
HIA: Optomechanical + software
UCB: Science modeling
UCLA: IR spectrograph
JPL: Interferometer WFS
AMNH: Coronagraph masks&design
UdM: Data pipeline
UCSC: Final integration&test
Key design requirements

- **Detectable point-source contrast \( \sim 10^{-7} \) in 1 hour**
  - Fast (2000 Hz+) AO system to minimize atmosphere timelag errors
- **Science reach for a large sample of targets**
  - \( I<8 \) mag (\( I<9 \) goal)
- **Minimal systematic errors**
  - Goal: not be limited by systematic errors in 1-hr exposure
  - High-quality optics (1 nm mid-frequency WFE)
  - Precision infrared interferometer
  - Require 5+1 nm static WFE
  - Differential imaging helps but requires minimal chromatic errors
- **Differential imaging capability**
  - Distinguish planets from artifact speckles
  - Polarimetry for study of circumstellar dust
  - Lenslet integral field spectrograph + polarimeter
- **Spectral capability for followup**
  - \( R\sim40-50 \) sufficient given models + available photons
GPI optical layout

3D LAYOUT

GPI AD RELAY, 2006-11-06, INCLUDING WINDOW, LINEAR ADC AND DICHROIC, GPI-AD-OPTI-000001
TUE MAR 20 2007

BRIAN BAUMAN
LAWRENCE LIVERMORE NATIONAL LABORATORY
AD RELAY, VERSION-CONTROLLED 22-11-2006 + CORONOGRAPH.ZM
CONFIGURATION 1 OF 2
High order high-speed AO (LLNL)

- **MEMS deformable mirror**
- **Optimized Fourier Controller (Predictive?)**
- **Spatially Filtered WFS 0.7-0.9 µm**
- **Focal stop spatial filter \( \lambda/d=0.9" \)**
- **Calibration/Alignment Unit**

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Deformable mirror</strong></td>
<td>349 actuators (240 active)</td>
<td>4096 actuators (1809 active)</td>
</tr>
<tr>
<td><strong>Subaperture</strong></td>
<td>56 cm</td>
<td>18 cm</td>
</tr>
<tr>
<td><strong>Control rate</strong></td>
<td>670 Hz</td>
<td>2000 Hz</td>
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<tr>
<td><strong>Wavefront sensor</strong></td>
<td>Shack-Hartmann 400 – 1000 nm</td>
<td>Spatially Filtered SH 700-900 nm</td>
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<tr>
<td><strong>Strehl @ 1.65 µm</strong></td>
<td>0.4</td>
<td>&gt;0.9</td>
</tr>
<tr>
<td><strong>Guide star mag</strong></td>
<td>( R&lt;13 )</td>
<td>( I&lt;8 ) (goal ( I&lt;9 )) (V&lt;11 aux.)</td>
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</tbody>
</table>
Optimized or predictive control

Residual error in dark hole, outside IWD

MSE (sq. radians at 1600 nm)

WFS noise propagation

WFS SNR

Uniform gain
Optimized gain
Predictor
Boston Micromachines
MEMS deformable mirror

Raw: 148 nm RMS WFE

Flattened: 6-12 nm WFE

In-band: 0.6 nm WFE

32x32 MEMS Evans et al 2006 Optics Exp. 14 5558

64x64 MEMS layout

64x64 MEMS unwired model
Apodized-pupil Lyot coronagraph (Soummer 2005)
Calibration interferometer

Invert coronagraph
Lyot invented the GPI CAL system!

- Coronagraph acts to convert phase signal to intensity
- CAL interferometer primarily measures intensity
- Coarse phase information needed to remove sign ambiguity and exclude pre-coronagraph amplitude errors
Integral field spectrograph
(UCLA+Montreal)

- Low spectral resolution (R~45)
- High spatial resolution (0.014 arcsec)
- Wide field of view (3x3 arcsec)
- Minimal scattered light
- One of Y J H K bands
- Dual-channel polarimetry
IFS Data

- Each spectrum is 16-17 pixels long (R~45).
- 68,000 spectra on a 2048x2048 detector.
- Spectra are separated by 4.5 pixels from their nearest neighbors.
GPI mechanical design

GPI enclosure

Gemini ISS

Electronics

Gort

“Klatuu Barada GPI”

Optics structure
GPI optical structure
GPI and SPHERE
CoDR analytic error budget

PSF components

Normalized intensity

- Atmos. Fitting
- Telescope
- Initial calibration
- Atmospheric bandwidth
- AO misalignments
- WFS measurement
- APLC chromatic error
- Post-coron: abers.
- Flexure/Beam shear
- Shear
- Shear
- Chromatic beam shear
- Cal system residuals
- Scintillation
- Polarization errors
- Tertiary intensity errors
- Residual diffraction
- Flat field errors
- Noise subtotal
- Total
GPI raw static contrast from each plane

Gray APLC at opt wavelength with Talbot propagated static aberrations (no SSDI & 2h ADI)
Perfect phase correction inside dark hole
M3 at pupil

Detection Limit (Δ mag)
Angular Separation (λ/D)
Detection limits from static and atmospheric speckles with and without spectral differencing

\[ H = 5 \quad I = 6 \text{ mag.} \]
Long exposures images

1.515 microns  1.57 microns  1.625 microns

Coro opt. wavelength

630K & 310K
ΔH = 12 & 17.4
(T8 spectrum)
Young associations

N=1000+ targets

Planet survey completeness

0–1 GYr solar–neighborhood sample

Mass (Jupiter masses)

N=1000+ targets

Semi-major-axis (AU)
• Exoplanet spectra indicate that $R \sim 40-100$ is suitable for measuring atmospheric parameters
  – [1.5] – [1.6] is a good effective temperature indicator
  – [1.5] – [2.2] is a good gravity indicator
  – Higher spectral resolution could address composition of hot Jupiters

100 Myr/1 $M_J$ planet convolved to $R = 40$ (Burrows et al. 2003). Dots represent sampling of the smoothed spectra in non-overlapping spectral channels. Ten independent flux measurements are combined to form to five colors in $H$ and three colors in $K$. Dotted lines show the transmission of the GPI H& K filters.
Spectral Resolution

• What spectral resolution is required for follow up
  – Can we measure first-order parameters?
  – $T_{\text{eff}}$ and $\log(g)$?

• Trade SNR & spectral resolution

Variation of fractional rms error in mass (left) and age (right) vs. $R$. Four curves are shown in each panel for $\text{SNR} \in \{10, 15, 20, 25\}$. 
• Fomalhaut analog
  – $\tau = 3 \times 10^{-4}$
  – $\theta = 0^\circ, 30^\circ, 60^\circ, 90^\circ$
• Edge-on disk is easily detected in Stokes $I$ in 90 s
  – Progressively less visible in Stokes $I$ in non edge-on configurations
• Dual channel polarimetry reveals face-on disks to $\tau = 10^{-5}$
Dual Channel Polarimetry Simulations

- Fomalhaut analog
  - $\tau = 3 \times 10^{-4}$
  - $\theta = 0^\circ, 30^\circ, 60^\circ, 90^\circ$
- Edge-on disk is easily detected in Stokes $I$ in $90$ s
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![Image of polarimetry simulations]
Dual Channel Polarimetry Simulations

- **Fomalhaut analog**
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- **Edge-on disk is easily detected in Stokes I in 90 s**
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- **Dual channel polarimetry reveals face-on disks to $\tau = 10^{-5}$**
Dual Channel Polarimetry Simulations

- Fomalhaut analog
  - $\tau = 3 \times 10^{-4}$
  - $\theta = 0^\circ$, $30^\circ$, $60^\circ$ & $90^\circ$
- Edge-on disk is easily detected in Stokes $I$ in 90 s
  - Progressively less visible in Stokes $I$ in non edge-on configurations
- Dual channel polarimetry reveals face-on disks to $\tau = 10^{-5}$
Gemini Planet Imager Science: Planets, moons, debris disks, evolved stars, binaries, etc.

Detected exoplanets for $I<8$ mag field survey

First light: late 2010 or early 2011

RY Scuti

$0.2''$ B0 V & M5 V

1+5 MJ

Disk $\tau=2\times10^{-4}$

Io

$1''$
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<tr>
<th>GPI</th>
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<tr>
<td><strong>AO Subaperture size</strong></td>
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<tr>
<td><strong>Primary deformable mirror</strong></td>
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<tr>
<td><strong>AO system update rate</strong></td>
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<td><strong>Limiting magnitude</strong></td>
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<td><strong>Coronagraph</strong></td>
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<td><strong>IWD</strong></td>
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<tr>
<td><strong>Science instrument</strong></td>
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<tr>
<td><strong>Wavelength coverage</strong></td>
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<tr>
<td><strong>Pixel size</strong></td>
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<tr>
<td><strong>Field of view</strong></td>
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<tr>
<td><strong>Spectral resolution</strong></td>
</tr>
<tr>
<td><strong>Polarimetry</strong></td>
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