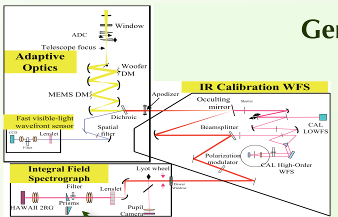
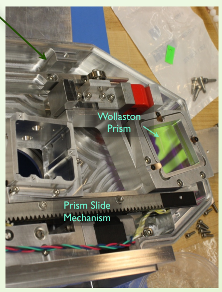
Imaging Polarimetry with the Gemini Planet Imager

Marshall D. Perrin[1], James R. Graham[2], James E. Larkin[1], Sloane Wictorowicz[2], Jerome Maire[4], Simon Thibault, Michael P. Fitzgerald[3], Rene Doyon[4], Bruce Macintosh[3], Donald T. Gavel[5], Ben R. Oppenheimer[7], David W. Palmer[3], Leslie Saddlemyer[8], J. Kent Wallace[6] and the Gemini Planet Imager team

1: UCLA, 2: UC Berkeley, 3: Lawrence Livermore National Lab, 4: Universite de Montreal, 5: UC Santa Cruz, 6: JPL, 7: American Museum of Natural History, 8: NRC/Herzberg Institute

Gemini Planet Imager Overview





Above: A schematic layout of GPI showing the major subsystems.

Right: This Wollaston polarizing prism mounted within the IR IFS enables the polarization analysis mode, along with an achromatic half wave plate and rotation mechanism mounted in the Cal WFS assembly.

GPI is a high-contrast AO system being built for the Gemini Observatory (Macintosh et al. 2006, 2008). GPI combines

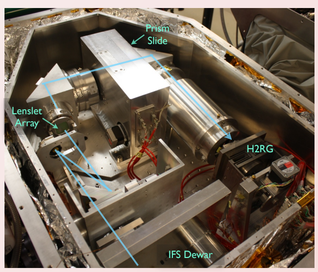
- high order AO wavefront control
- coronagraphic diffraction suppression
- precision IR wavefront calibration
- a speckle-suppressing science camera

GPI is nearing completion of construction, and first light is planned for 2011.

GPI's primary science goal is the direct **imaging and characterization of young, Jovian-mass exoplanets** in thermal emission. GPI also seeks to **image scattered light from debris disks** with an optical depths down to $4{\times}10^{-5}$. To achieve this, GPI will include an imaging polarimetry mode that suppresses unpolarized speckles by a factor of >100.

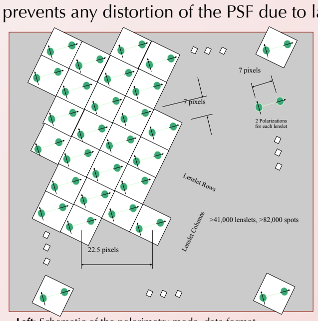
Integral Field Polarimetry

GPI's science instrument is a lenslet-based near-infrared imaging spectrograph (shown at right). In spectral mode, the dispersed spectra have R~45 at H band, with a spatial sampling of 0.014″/pixel across a 2.8″x2.8″ field of view. In **dual channel polarimetry mode**, the dispersing prism is replaced with a Wollaston prism, gaining sensitivity to orthogonal linear polarizations (though at reduced spectral resolution).



Above: The GPI IFS, shown with the dewar cover removed. The light path is shown in blue.

The polarizations are dispersed only after the lenslet array has pixellated the field of view, as shown below. This **novel "integral field polarimetry" design** minimizes differential wavefront error between the two polarizations, eliminates the need for precise image registration which has limited previous AO imaging polarimeters (e.g. Apai et al. 2004, Perrin et al. 2004, 2008), and does not require any reduction in field of view. It also prevents any distortion of the PSF due to lateral chromatism of the Wollaston prism, thus removing any need for exotic materials with low birefringent chromaticity like YLF.



Left: Schematic of the polarimetry mode data format, showing individually dispersed polarizations for each lenslet.

Linear Stokes polarimetry is achieved by modulation with a rotating half-wave plate. Because coronagraphic observations are more sensitive to wavefront errors prior to the occulting mask, the waveplate is mounted after the AO and coronagraphic optics. Hence the instrumental polarization is not modulated, and must instead be calibrated via observations of standards, and removed during data reduction. (see discussion at right.)

GPI remains stationary with respect to the telescope pupil—so the sky appears to constantly rotate. This allows angular differential imaging to reduce the residual speckle halo. However, it complicates polarimetry because each exposure has unique sky-projected polarization axes and rotation. The standard double-differencing data reduction will not suffice. Instead we adopt a **forward-modeling approach to data reduction**: Using the known instrumental response Mueller matrix for all exposure in a sequence, we derive the modulation matrix for the observation sequence. We then solve the resulting matrix equation via least-squares to derive the astronomical polarization for each pixel.

References

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Boccas et al. 2004 SPIE 5494 p. 239
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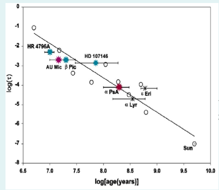
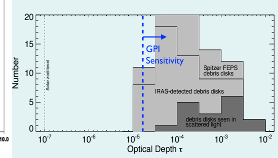
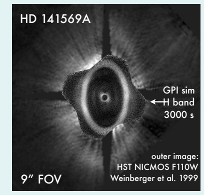
Disk Science with GPI





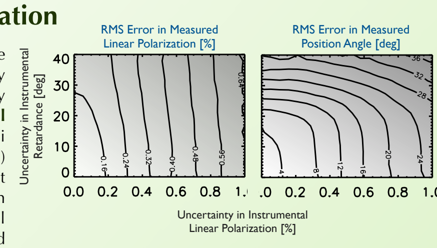


Above left: Disk optical depths (as measured by IR excess) tend to decrease with stellar age. (Adapted from Zuckerman 2001). **Center:** Currently, only a handful of the highest-optical-depth systems have been imaged with adaptive optics or space coronagraphy. **Right:** GPI's small inner working angle will enable observations of disk structure on scales comparable to the solar system for targets at ~100-150 pc distance. This figure shows simulated GPI observations of the inner regions of the transitional disk around HD 141569A. The inner working angle is ~ 3x better than HST NICMOS.

The majority of nearby disks have optical depths < 5e-4 (Zuckerman & Song 2004) yet only a handful of the highest optical depth systems have been imaged. Improved contrast is needed to enlarge the set of objects which can be resolved, allowing detections of fainter, older, and more face-on disks. **GPI polarimetry will enable studies of protoplanetary and debris disks with optical depths as low as $4{\times}10^{-5}$ (about 1/50 the optical depth of AU Mic)** on scales of 0.15-2.0″. These data will provide insights into disk architectures, tidal interactions between disks and planets, and the formation and evolution of planetary systems.

Instrumental Polarization

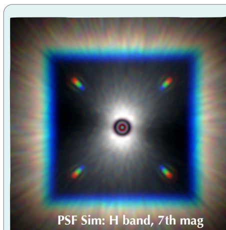
We have investigated the systematic errors caused by instrumental polarization. By **calibrating the instrumental polarization** (of the Gemini telescope plus GPI AO system) with an accuracy of at least <0.3% in degree and <20° in phase, we can ensure that final uncertainties are not dominated by systematics.



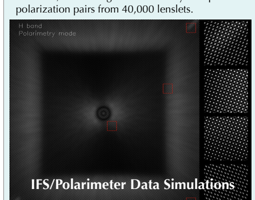
Above: Errors in recovered polarization signal as a function of calibration uncertainties, derived from Monte Carlo observation models.

The Gemini telescopes use protected silver coatings (Boccas et al. 2004) for all mirrors, including the 45°-incidence tertiary fold that likely dominates instrumental polarization. We have developed a high-fidelity model of the **polarization properties of protected silver** (Graham 2008), and find that a 45° reflection from protected silver induces a small linear polarization and phase shift: 0.99% and −164.5° at 1μm. This is almost as good as bare gold. This polarization changes slowly with wavelength and will be straightforward ot calibrate. Empirical measurements will be made during system integration and on the sky.

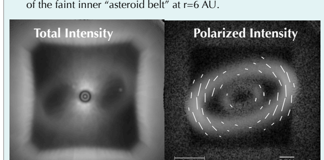
Integrated End-to-end Modeling



Above: Simulated H band GPI PSF. The dark hole is 1.8″ across. **Below:** Simulated raw data from the IFS, showing individually dispersed polarization pairs from 40,000 lenslets.



Below: Simulated 1-hour H-band observation of an I=6 star at 20 pc. Differential polarimetry suppresses the stellar PSF, enabling the detection of the faint inner "asteroid belt" at r=6 AU.



To verify the expected performance of GPI, we have carried out extensive modeling. Our **detailed simulations of the AO control loop** model multi-layer atmospheres, woofer/tweeter correction, and the full GPI AOC algorithm set to evaluate the effects of residual speckles on timescales of up to 30 seconds. Our static wave-optics model then uses a Fresnel optics code to propagate phase and intensity from arbitrary surfaces within the system, to evaluate the contribution of quasi-static components to the long-exposure PSF.

The derived PSF then is sent through our **spectrograph/polarimeter data simulator**, which propagates each individual lenslet's light along the full optical path of the IFS through the dispersing elements and onto the detector, including effects such as sky rotation, instrumental polarization and modulation, and detector flat fielding, read noise, and photon noise. This simulator allows arbitrarily complicated scenes to be modeled, with any number of planetary companions, scattered light debris disks, and/or background stars.

Lastly, we reduce the data through our draft **data reduction pipeline** (see Maire et al., this meeting) to extract spectral and polarimetric datacubes, including speckle-suppression algorithms. These simulations verify that GPI will be achieve contrasts for planetary companions of < 10^{-7} in 1 hour (5 sigma) in spectral mode, or to resolve scattered light from debris disks with optical depths as faint as a few x 10^{-5} in polarimetric mode.