The Adaptive Optics and Extremely Large Telescope Perspective

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(TMT: James Graham, Paul Hickson, James Larkin, Tim Davidge)

Non-redundant people: Peter Tuthill, John Monnier, Jamie Lloyd
• AO problems and promise in a single slide

• Quick ELT introduction
  – Major science roles

• Adaptive optics on ELTs

• Extrasolar planet detection with ELT AO:
  – TMT Planet Formation Imager

• Aperture masking interferometry on large telescopes
Early Keck AO images of Uranus (de Pater et al 2002)

- a) PA=0°
- b) PA=90°
- c) Cleaned Combined
AO PSFs have strong quasi-static structures (but this may improve in the future)

Keck AO PSFs
(0.01 arcsec/pixel)

Deep Keck AO PSF
4 arcsec FOV
Sky coverage => Science
Extremely Large Telescopes

Thirty Meter Telescope
• 30-m resolution + collecting area
• 1.2 – 1.5 m hexagonal segments

Giant Magellan Telescope
• 7 x 8-m segments
• 25-m resolution + 21 m area
• Adaptive secondary

Both architectures (and European 30 - 42 m ELT) have very similar capabilities
TMT Key Science Areas
(Paul Hickson from TMT CoDR)

- Cosmology and fundamental physics
- The early universe and first light
- Intergalactic medium beyond $z = 7$
- Galaxy formation and evolution
- Black holes and active galactic nuclei
- Stellar populations and star-formation histories in the local Universe
- Evolution of star clusters and the IMF
- Physics of star and planet formation
- Characterization of extrasolar planets
- Solar System studies

First-light instruments: wide-field optical spectrograph; high-strehl narrow-field AO; mid-IR spectroscopy + AO; high-resolution optical spectrograph

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• Key first-light AO instruments are integral field spectrographs
• Pixel and detector limitations will lead to operation below diffraction limit
  – Structure / velocities require 0.10~0.05” resolution
• Extragalactic / high Z targets are ~1”, very faint
  2”x2” at 0.008”/pix => 40-160 million pixels
• Multiplexing (multiple IFS deployed across wide field of view) is high priority
• Other science missions do require full diffraction limit

GOODS-N galaxies 1.5<z<2. Each image is 3”x3”

Figures from James Larkin + Tim Davidge
Next-generation AO can provide very good visible-light Strehl and high resolution.

Some care is needed for diffraction-limited performance. Extensive processing is required to achieve "HST-like" performance.
Inner working distance (IWD) \( \sim 2-4 \lambda/D \)
Systematic errors must be controlled at the nanometer level
Instrument overview

Starlight
DM1
Dichroic
Beamsplitter
WFS1
Diffraction
Suppression
System IFU
Neutral
Beamsplitter
WFS2
Reject
Light
(bright
beam)
DM2
Controller 1
Controller 2
Offset vector (calibration)
IR
Controller 2
WFS2
Neutral
Beamsplitter
IFU
Nulling interferometer + WFS

Starlight from pre-AO Mach-Zender Nuller (DSS)

Deformable Mirror

Spatial Filter

Modulator

DM Controller

Processor

WFS Camera

Science IFU

Stop
Nuller transmittance/sky response

Instantaneous Transmission

2-hour exposure 1.2x1.2 arcsec
Monte Carlo Extrasolar Planet Populations

- $H = 8-11$ mag
- $H = 5-8$ mag
- $H = 4-6$ mag

"Hot jupiters" Interferometer

Taurus protoplanets
Self-luminous jovians
Reflected-light jovians
Terrestrial planets

Gemini Planet Imager
TMT Planet Formation Instrument
Spectral characterization: $R=1000$ for composition

- $R=100$ spectroscopy needed for $G / \text{Teff}$
- $R=1000$ spectroscopy could measure compositions
- Planet $H>24$ mag
- Require multi-hour exposures on 20-30m filled apertures

![Graph showing spectral characterization with different temperatures and magnitudes](image)
T Tauri star (150 pc) with a $\Delta H = 10$ mag. companion in an optically thick disk ($i = 66^\circ$)
- $M = 3 \ M_J$, $t = 10$ Myr
Non-redundant masking (Keck)
Speckles and Power Spectra

FFT
Pinwheels: Colliding-Wind Wolf-Rayet Binaries

WR 104  50 mas (75 AU)  WR 98a  100 mas

Tuthill, Monnier & Danchi 1999
LkHα 101: Our closest image of a starbirth

- Herbig Ae/Be star
- Settle debate: Disk vs Envelope
- SED fitting ambiguous: central cavities now proven
- Overturn power-law thermal

Tuthill et al 2000, 2002
Speckle Interferometry

Classical Masking (Fizeau)

Telescope Focal Plane

Pupil Mask

CCD Camera

Power Spectrum

Adaptive Optics

Masking + AO
Masking: No AO (Keck)
Masking + AO (PALAO+PHARO)
Sparse-Aperture AO results
Palomar Faint Companion Program

Detectability of a companion (SNR=5)

- GJ 802
- Aperture Masking + AO
- Full Aperature AO

Masking Superior
A.O. Superior
36-aperture geometry

- Non-redundant masking provides many more baselines than conventional interferometers, but lower resolution and sensitivity
- Complex targets with strong signals at 30-m spatial frequencies
- e.g. searching 2MASS for 30-m resolvable hot dust leads to 150 targets (up from 12 on 10-m)
Insufficiently justified conclusions

- 20-40m ELTs with adaptive optics are almost inevitable
  - AO performance will improve for shorter wavelengths / high Strehl
- Many ELT science missions require large collecting areas but not necessarily diffraction-limited resolution
- Systematic errors complicate interpretation of AO data at the smallest angular scales and moderate contrasts
  - AO needs new ways of thinking about systematic calibration problem
- Sample ELT roles: Photon-starved, complex objects
  - Multiplexed extragalactic science, Crowded and complex fields
  - Planet detection at >0.1”, mapping systems, and high-resolution exoplanet spectroscopy
    - Astrometry is highly complementary
- Interferometer roles: measuring sets of numbers
  - Objects with complex structure that can be parametrized
  - Planet detection at <0.03” for some systems
  - SKY COVERAGE is a key for the broad community
- AO aperture masking provides intermediate capabilities
Diffraction
TMT PSFs: Gaps vs M2

Gaps only

M2 supports only
2-stage nuller output pupil
Inner working distance $\sim 3-5 \lambda/D$

Outer working distance $\sim N \lambda/D$