Introduction to Adaptive Optics

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(with lots of help from Claire Max)
2004 Observatory Short Course
Outline

- Why do we need adaptive optics?
- How is it supposed to work?
- How does it really work?
- Astronomy with adaptive optics.
Why do we need adaptive optics?

Turbulence in earth’s atmosphere makes stars twinkle

More importantly, turbulence spreads out light; makes it a blob rather than a point

Even the largest ground-based astronomical telescopes have no better resolution than an 8" telescope!
Optical consequences of turbulence
Optical consequences of turbulence

- Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
- Light rays are refracted many times (by small amounts)
- When they reach telescope they are no longer parallel
- Hence rays can’t be focused to a point:

Parallel light rays

Light rays affected by turbulence
Kolmogorov turbulence cartoon

- Solar heating
- Convective processes
- Wind shear

Outer scale $L_0$

Inner scale $l_0$

Ground
Turbulence arises in several places

stratosphere

10-12 km

boundary layer

wind flow over dome

Heat sources w/in dome
Short exposures through the atmosphere

What a star really looks like through a large (6 m) telescope.
Long exposures through the atmosphere

Ground: Subaru (8m)  Space: HST (2.4m)
Light rays and the wavefront

Parallel light rays

Light rays affected by turbulence

Point focus

blur
Light rays and the wavefront

Parallel light rays

Light rays affected by turbulence

Point focus

blur
Characterize turbulence strength by quantity $r_0$

- Wavefront of light
- Primary mirror of telescope

$\leftrightarrow r_0$ “Fried’s parameter”

- “Coherence Length” $r_0$: distance over which optical phase distortion has mean square value of 1 rad$^2$

- $r_0 \sim 15 - 30$ cm on Mauna Kea
Imaging through a telescope

With no turbulence, FWHM is the diffraction limit of telescope, \( \vartheta \sim \frac{\lambda}{D} \)

Example:

\[ \frac{\lambda}{D} = 0.02 \text{ arc sec for} \]

\[ \lambda = 1 \, \mu m, \, D = 10 \, m \]

Point Spread Function (PSF): intensity profile from point source
Imaging through a telescope

With turbulence, FWHM is diffraction limit of regions of coherent phase, $\varnothing \sim \lambda / r_0$

Example:

$\lambda / r_0 = 0.80$ arc sec for $\lambda = 1 \, \mu m$, $r_0 = 25 \, cm$

Point Spread Function (PSF): intensity profile from point source

FWHM $\sim \lambda / r_0$
How does adaptive optics help? (cartoon approximation)

Measure details of blurring from “guide star” near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed
Simplified AO system diagram

Light From Telescope

Adaptive Mirror

Distorted Wavefront

Control System

Beamsplitter

Corrected Wavefront

Wavefront Sensor

High-resolution Camera
How a deformable mirror works (idealization)

BEFORE

Incoming Wave with Aberration

Deformable Mirror

AFTER

Corrected Wavefront
Most deformable mirrors today have thin glass face-sheets.

Glass face-sheet

Cables leading to mirror’s power supply (where voltage is applied)

PZT or PMN actuators: get longer and shorter as voltage is changed

Anti-reflection coating

Light
How to measure turbulent distortions (one method among many)

Shack-Hartmann wavefront sensor
Simplified AO system diagram

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High-resolution Camera
A real AO system: Keck 1 & 2

Tip-tilt mirror
Wavefront sensor
Deformable mirror
Keck II Left Nasmyth Platform

Enclosure with roof removed

Elevation Ring

Adaptive Optics Bench

Electronics Racks

Science cameras

Nasmyth Platform
The adaptive optics bench

IR Dichroic

To wavefront sensor

Deformable Mirror

Tip/tilt Mirror

To near-infrared camera
Deformable mirror

Front view

Rear view

15cm
Wavefront Sensor

Field Steering Mirrors (2 gimbals)  Sodium dichroic/beamsplitter

AOA Camera

Camera Focus

Wavefront Sensor Focus

Wavefront Sensor Optics: field stop, pupil relay, lenslet, reducer optics
6 AO systems on Mauna Kea!

Summit of Mauna Kea volcano in Hawaii:

- Subaru
- 2 Kecks
- UH 88"
- Gemini North
- CFHT
An adaptive optics system in action: Keck 2

The Galactic Center at 2.2 microns (without adaptive optics)

Total exposure for mosaic for similar SNR ~ 20 minutes

Average resolution: (brightest stars): 0.4''

Resolved source

Keck Adaptive Optics
Neptune in infra-red light
(1.65 microns)

Without adaptive optics
May 24, 1999

With Keck adaptive optics
June 27, 1999

2.3 arc sec
Adaptive optics in astronomy

- **Planetary science**
  - Volcanoes on Io
  - Methane storms on Titan

- **Dense star fields**
  - Black hole at the center of our galaxy
  - Star population in globular clusters

- **High-contrast imaging**
  - Faint material around bright stars (disks of dust, etc.)
  - Extra-solar planets and super-planets

- **Studying very distant galaxies.**
Occultation of a binary star by Titan

Hubble Space Telescope image
Occultation of a binary star by Titan

- Images taken with the Palomar Observatory 200" AO system.
- One image taken every 0.843 seconds - 4700 images total.
- Titan's atmosphere refracts the starlight, forming multiple images of each star!
- Result: winds in Titan's stratosphere are very strong: ~250 m/s in a jet-stream type pattern.
Orbits of stars around the black hole at the center of our galaxy

Result: Black hole at center of the galaxy has a mass of 2.6 million suns.
Mid-infrared flares from the black hole at the center of our galaxy

Result: Direct detection of heat released by material falling on the accretion disk surrounding the black hole.
Searching for planets around Epsilon Eridani
Searching for planets around Epsilon Eridani

Result: They're all background stars!
Studying the star populations of galaxies at $z \sim 0.5$

Result: Galaxies were brighter than today, but about the same size.
Sodium laser guidestars

Light from Na layer at ~ 100 km

Max. altitude of Rayleigh ~ 35 km

Rayleigh scattered light
Keck 2 laser
First images with Keck laser-guidestar adaptive optics

HK Tau B hidden behind an edge-on disk of dust.

HK Tau A (10^6 yr old T-tauri star)