Chap 6: The Tools of the Astronomer
Chapter 6: The Tools of the Astronomer

- Spectroscopy
  - Dispersion element: *Prism, Grating, Grism*
  - Ancillary optics: *Collimator & Focuser*
  - Doppler shift
- Timekeeping devices
- Computer programs

- Telescope & Camera
  - Light gathering power
  - Angular resolution:
    - Diffraction limit
    - Atmospheric seeing
  - Optical design
  - Plate Scale & Field of View
  - Atmospheric Transmission
  - Interferometers
How spectroscopy works?
DIFFRACTION GRATINGS:
TRANSMITTING / REFLECTING

Equal mixture of red and blue

Grating

Incident plane wave

Diffraction envelope

m = 2
m = 2

m = 1
m = 1

m = 0
m = 0

m = 1
m = 1

m = 2
m = 2

The original object is visible straight through the grating.
GRATING EQUATION FOR NORMAL INCIDENCE

Path difference between adjacent slits: \( l = g \sin d \)
Condition for constructive interference: \( \frac{l}{l} = m\lambda \Rightarrow g \sin d = m\lambda \)

Figure 3.5. Light diffraction at three equidistant parallel slits.
A spectrograph using lenses as collimator and focuser
A spectrograph using mirrors as collimator and focuser
Atomic Transitions

use quantum mechanics to predict the specific wavelengths of emission lines
An atom consists of a small, dense nucleus surrounded by electrons.

- The **nucleus** contains *protons* and *neutrons*
- All atoms with the same number of *protons* have the same name (called an element).
- Atoms with varying numbers of *neutrons* are called **isotopes**.
- Atoms with a varying numbers of *electrons* are called **ions**.
Rutherford’s Experiment (1915)

*atoms are largely empty space!*

Alpha particles from a radioactive source are channeled through a very thin sheet of gold foil. Most pass through showing that atoms are mostly empty space, but a few are rejected showing the tiny nucleus is very massive.
Atoms and Light – 1

- Atoms have a dense nucleus of **protons** and **neutrons**.
- **Electrons** surround the nucleus in a “cloud.”

![Diagram of parts of an atom and Bohr model](image-url)
Electrons can have certain quantized energies; other energies are not allowed.

Each type of atom has a unique set of energies.

When electrons change energy levels, they absorb or emit light.

Electrons not in the ground state are said to be in excited states.

We use energy level diagrams to represent the allowed states of an atom. Analogously, atoms exist in one allowed energy state or another, but never in between.
Absorption Spectra

- **Absorption**: An electron absorbs the energy of a photon, moving the electron to a higher energy level.
- The photon’s energy has to be equal to the energy difference.
- This will absorb a photon with a specific wavelength.
Absorption Spectra

When white light passes through a cool gas containing hypothetical two-state atoms with energy $E_1$...

...photons with energy $E_2 - E_1$ may be absorbed...

...and are missing in a spectrum of the light.
Emission Spectra

- **Emission**: An electron in an excited state emits a photon and drops to a lower energy state, losing energy.

- The photon’s energy is equal to the energy difference between the two levels.

- This produces a photon with a specific wavelength (color).

A hypothetical atom has two allowed energy states with energies $E_1$ and $E_2$.

An atom with energy $E_2$ decays to the lower state with energy $E_1$...

...by emitting a photon that carries off the extra energy ($E_2 - E_1$).
The Emission-Line Spectrum of Hydrogen

Visible emission spectrum from hydrogen

Hydrogen emission spectrum
Bohr’s model predicts wavelengths of hydrogen lines

\[ \frac{1}{\lambda} = \left( \frac{1}{n_{\text{low}}^2} - \frac{1}{n_{\text{high}}^2} \right) \frac{13.6 \text{eV}}{hc} \]

- \( n_{\text{low}} = \) quantum number of lower orbit
- \( n_{\text{high}} = \) quantum number of higher orbit
- \( \lambda = \) wavelength of emitted photon

Excited state | Ground state
--- | ---
6 | 2
5 | 2
4 | 2
3 | 2

Wavelengths:
- 410 nm
- 434 nm
- 486 nm
- 656 nm

Energy absorbed | Energy emitted
--- | ---

\( n = 2 \)
Hydrogen Spectral Series
Emission Line Spectra from Different Elements Can Be Calculated

Visible emission spectrum from hydrogen

Emission spectra for sodium, helium, neon, and mercury

Each type of atom has a unique spectral fingerprint.
Spectroscopy allows study of chemical composition of a planetary nebula.
The Mean UV Spectrum of Quasars

taken by a ground-based telescope
(Wavelength unit: 1 Angstrom = 0.1 nm)
Doppler Shift

How spectroscopy tells velocity?
In 1676, Danish astronomer Olaus Røemer discovered that the exact time of eclipses of Jupiter’s moons varied based on how near or far Jupiter was to Earth.

This occurs because it takes varying amounts of time for light to travel the varying distance between Earth and Jupiter.
Doppler effect is widely used by law enforcement.
**Doppler shift:** The motion of a light source toward or away from us changes our perception of the wavelength of the waves reaching us.

Waves that reach this observer are spread out to longer “redshifted” wavelengths (lower frequency).

Waves that reach this observer are squeezed to shorter “blueshifted” wavelengths (higher frequency).

Moving source of light

This observer sees no Doppler shift.

Speed of light, $c$
Doppler shift – 2

- Light from approaching objects is **blueshifted**; the waves crowd together.
- Light from receding objects is **redshifted**; the waves are spaced farther apart.
Doppler shift measured by comparing spectra (e.g., Arcturus)
Doppler shift measured by comparing spectra of Arcturus & Sun
Derivation - Doppler shift equation

how exactly wavelength shifts with velocity?

$$\frac{V_r}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\text{obs}}}{\nu_{\text{obs}}}$$
Doppler Shift Practice

*How spectroscopy tells velocity?*
Doppler Shift Equation

- **Red Shift**: The distance between the observer and the source is *increasing (positive velocity)*
- **Blue Shift**: The distance between the observer and the source is *decreasing (negative velocity)*

\[
\frac{V_r}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\text{obs}}}{\nu_0}
\]

- \(\lambda_o\) = wavelength at rest frame
- \(\lambda_{\text{obs}}\) = wavelength seen by observer

\(V_r\) = velocity of source *along the line-of-sight*

\(c\) = speed of light
Practice: Wavelength shift to velocity

- In a lab room, you measure the wavelength of a strong Hydrogen line at 656.3 nm; at telescope, you detect the same Hydrogen line from a nebula and its wavelength has been shifted to 659.0 nm. What is the velocity of the nebula relative to us along the line-of-sight?

\[
\frac{V_r}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\text{obs}}}{\nu_{\text{obs}}}
\]

\[
\nu_r = \frac{\lambda_{\text{obs}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}} \times c = \frac{659.0 \text{ nm} - 656.3 \text{ nm}}{656.3 \text{ nm}} \times (3 \times 10^8 \text{ m/s})
\]

\[= 1.2 \times 10^6 \text{ m/s}\]
Practice: Frequency shift to velocity

• A spacecraft transmits a signal at 98.75 MHz. It is received on Earth at 98.76 MHz. How fast is the spacecraft moving relative to Earth and in which direction (away or towards us)?

\[
\frac{V}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\text{obs}}}{\nu_{\text{obs}}}
\]

Answer: \( V = (98.75 - 98.76)/98.76 \times c = -30 \text{ km/s} \)
Doppler Shift Application: Speed of light

- If we know the velocity $V$, the wavelength shift, and the rest-frame wavelength, we can use these measurements to infer speed of light:

$$\frac{V_r}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0}$$

$$\Rightarrow c = V_r \frac{\lambda_0}{\lambda_{\text{obs}} - \lambda_0}$$
Why Do We Need Large Telescopes?

• Greater light gathering power => higher sensitivity (see fainter sources)
• Smaller diffraction pattern => higher angular resolution (when equipped with adaptive optics or launched to space)
• Longer focal length => smaller plate scale (higher definition images)
Telescope: Light gathering power
Telescopes are like rain buckets but for photons
Received Power from EM Flux

\[ P = F \times \text{Projected Area} \]

- Because **most** telescopes are designed to be pointed at the source, its **projected area** equals to its **aperture size**

![Diagram showing the calculation of received power from EM flux with an equation and a telescope illustration.]

The same amount of sunlight strikes the ground at a shallower angle and so is spread out over a larger area.
One of the exceptions: the FAST Observatory in China Five-hundred-meter Aperture Spherical Telescope
The light-gathering power of a telescope is proportional to the square of the aperture size.

\[
\frac{\text{Light-gathering power of Keck}}{\text{Light-gathering power of 8-inch telescope}} = \frac{(10 \text{ m})^2}{(0.2 \text{ m})^2} = \left(\frac{10}{0.2}\right)^2 = 2,500
\]

Each 10-m primary mirror is comprised of 36 hexagonal segments. Each segment is 1.8 meters in diameter, weighs 880 pounds or roughly 0.4 metric tons and is covered with a thin, reflective layer of aluminum.

\[
A = \frac{3 \sqrt{3}}{2} a^2
\]
LBT (Large Binocular Telescope)
Two 8.4 m wide mirrors
ELT (Extremely Large Telescope) [future project]
OLT (Overwhelmingly Large Telescope) [future project]
Great Paris Exhibition Telescope
Paris, France (1900)

Yerkes Observatory
40" refractor
Williams Bay, Wisconsin (1893)

Hooker (100"
Mt Wilson, California (1917)

Hale (200"
Mt Palomar, California (1948)

Multi Mirror Telescope

BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)

Large Zenith Telescope
British Columbia, Canada (2003)

Gaia

Kepler

Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)

Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)

Keck Telescope

Gemini North
Mauna Kea, Hawaii (1999)

Subaru Telescope
Mauna Kea, Hawaii (1999)

Hobby-Eberly Telescope
Davis Mountains, Texas (1996)

Southern African Large Telescope
Sutherland, South Africa (2005)

Gemini South
Cerro Pachón, Chile (2000)

Large Binocular Telescope
Mount Graham, Arizona (2005)

Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)

Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2021)
Telescope: Max Resolution

\textit{diffraction limit} = \textit{\lambda}/\textit{Diameter}
Diffraction pattern of a long slit

\[ \theta = \frac{\lambda}{a} \]

\[ \Delta \theta = \frac{2\lambda}{a} \]
Diffraction pattern of a narrow slit
Diffraction pattern of a circular aperture

\[ \Delta \theta = \frac{1.22 \lambda}{D} \]

“Airy Disc”

\[ \langle I \rangle \]

\[ r \]

\[ 0 \]

\[ \frac{1.22 \lambda L}{D} \]

\[ L \gg a, \lambda \]

\[ a_x \]

\[ a_y \]
Diffraction pattern of a circular aperture that focuses light

The Airy Disk

\[ \Delta \theta = \frac{1.22 \lambda}{D} \]

\[ 2 \Delta \theta \]

\[ \langle \ell \rangle \]

\[ 0 \quad \frac{1.22 \lambda L}{D} \]
The Diffraction Limit of A Circular Lens/Mirror

The **diffraction limit** is defined as the *radius* of the Airy disk:

\[ \theta = 1.22 \frac{\lambda}{D} \]

where \( \lambda \) is the wavelength and \( D \) is the lens/mirror diameter.
The diffraction limit determines the closest separation between two point sources that is resolvable

\[ \theta = 1.22 \frac{\lambda}{D} \]
The ultimate resolution of a telescope is set by the **diffraction limit**.

The angle subtended by the smallest resolution, $\theta$, is determined by the ratio of the wavelength of light being studied to the aperture diameter.

$$\theta = 2.06 \times 10^5 \left( \frac{\lambda}{D} \right) \text{arcsec}$$

- 1 arcsecond = $1/3,600$ of a degree
- Human eye (assuming 4 mm pupil diameter):

$$\theta = 2.06 \times 10^5 \left( \frac{5.5 \times 10^{-7} \text{ m}}{0.004 \text{ m}} \right) \text{arcsec} = 28.3 \text{ arcsec}$$
Practice: Calculating Diffraction Limit

\[ \theta = 1.22 \frac{\lambda}{D} \text{ radian} = 206265 \times 1.22 \frac{\lambda}{D} \text{ arcsec} \]

Practice: Hubble Space Telescope

What is the diffraction limit of the HST at a wavelength of 500 nm? The diameter of HST’s primary mirror is 2.4 meter.

Answer: 0.052 arcsec
NGC 2174, the Monkey Head Nebula
Based on *Fourier* Optics, we can calculate the diffraction patterns of differently shaped apertures.
BUT, GROUND-BASED OPTICAL AND INFRARED OBSERVATIONS ARE LIMITED BY ATMOSPHERIC SEEING

Twinkling of stars and the moon caused by pockets of air at different densities
Seeing quantifies the amount of aberrations from atmosphere turbulence

- Large-scale T gradients trigger subsonic turbulences. The T differences between turbulent eddies then cause variations of density and refractive index.

- Most of the turbulence that blurs your image originate from the lowest and most massive atmosphere layer: the troposphere at altitudes < 15 km.

- Typical seeing blurs the Airy pattern to a Gaussian with a FWHM of ~2 arcsec.
Telescope + Camera:

detector, plate scale, & field of view
Silicon-based Detectors: e.g., CCD and CMOS

- **CCDs:** charge-coupled devices (such as digital cameras)
- Electronic detectors record photons on **pixels**.
- Photons create a signal in the array.
- The electronically recorded images can greatly exceed photographs in quality.
- CCDs are the astronomer’s detector of choice.
How to calculate how large an area this image covers?
We need to know (1) the angular size of each pixel and (2) the number of pixels on each side.
Plate Scale is defined as the angular size of a pixel, it has a unit of arcsec/pixel

$$\text{plate scale} = \frac{\text{pixel size}}{\text{focal length}} \quad \Rightarrow \quad \text{plate scale}(''/\text{pixel}) = 206265''/\text{radian} \times \frac{\text{pixel size}(\mu\text{m}/\text{pixel})}{\text{focal length}(\text{m}) \times 10^6}$$

often the focal length is not provided, but the focal ratio is:

Focal Ratio = Focal Length / Aperture Diameter

$$s = F \times \theta \quad \rightarrow \quad \theta = s/F$$
The Field of View of a camera is defined as the angular dimension of the full detector:

$$\text{FoV} = \text{Plate Scale} \times [N_x, N_y]$$
• The Meade LX200GPS in the small dome has an aperture diameter of 10 inch (25.4 cm) and a focal ratio of F/10 (which is defined as the ratio between focal length and aperture diameter).
• The Panasonic GF2 digital camera that you’ll mount on it has a sensor with a dimension of 17.3mm x 13mm and 4000 x 3000 pixels (12 Megapixels).
• What is the pixel size in µm/pixel?
• What is the plate scale in arcsec/pixel?
• What is the field of view in arcmin?

plate scale(′′/pixel) = 206265′′ × \( \frac{\text{pixel size}(\mu\text{m/pixel})}{\text{focal length}(\text{m}) \times 10^6} \)
Why Do We Need Large Telescopes?

- Greater light gathering power => higher sensitivity (see fainter sources)
- Smaller diffraction pattern => higher angular resolution (when equipped with adaptive optics or launched to space)
- Longer focal length => smaller plate scale (higher definition images)
Telescope

*typical optical designs*
Two Basic Types of Telescopes

- **Refractors**
  - Use lenses to concentrate incoming light at a focus.

- **Reflectors**
  - Use mirrors to concentrate incoming light at a focus.

*The goal is always the same – gather as much light as possible and form an image at a focus.*
The Eye

- The eye is like a refracting telescope.
- It collects light and focuses an image.
- It collects a limited amount of light.
- The eye suffers from (relatively) poor angular resolution, because the pupil is small.
Refractors – 1

- Refracting telescopes use lenses to bend the light to focus it.
- The **objective lens** refracts the light.
- The **aperture** is the diameter of the objective lens. A larger aperture gathers more light.
- The objective lens is placed in the end of the telescope facing the sky.
Refractors – 2

- The **focal length** is the distance between lens and the image (longer = larger image).
- The aperture sets the light-collecting power.
- The focal length determines the image size.
Refractors – 3

The largest refracting telescope has a 1-meter aperture and a focal length of 20 meters (Yerkes Obs.)

Problems with refractors:
- need to be large structures to have a long focal length
- lenses suffer from chromatic aberration
- difficult to polish lenses
Specially designed compound lenses and lens coatings can reduce chromatic aberration.
Newton invented reflecting telescopes (~1666 CE)

A concave mirror causes parallel rays of light to converge to a focus at the focal point.
The *Late* Arecibo Observatory, Puerto Rico

a single-mirror reflector, 305 m in diameter

Science instruments

Primary Mirror
Advantages of reflecting telescopes

- Reflectors have advantages over refractors:
  - There is no chromatic aberration.
  - Mirrors can be made lighter than lenses.
  - They are more compact.

- The largest telescopes in the world are all reflectors.
The Original Newtonian Design (~1666)

- A Newtonian reflector originally uses a **spherical primary mirror** and a **flat secondary mirror**.
- But it suffers from **spherical aberration**
- The solution is to adopt a **parabolic** primary mirror
The most successful update to the original reflector design

- Laurent Cassegrain (1672)
- a French Catholic priest
Cassegrain Reflectors Examples
A Cassegrain reflector has three focuses:

- **Prime focus**
- **Coudé or Nasmyth focus**
- **Cassegrain focus**

**Diagram Elements:**
- Parabolic primary
- Hyperbolic secondary
- Flat tertiary

The diagram illustrates the path of light through the Cassegrain reflector, showing how it converges at the different focuses.
Cassegrain Reflectors: The 8-meter Subaru Telescope
Subaru Telescope 8.2-m alt-azimuth mount

Mirrors:
Primary, Secondary, Tertiary

Focuses:
Primary, Cassegrain, Nasmyth

Primary Focus
Focal ratio: 2.0 (with corrector)
Field of view: 30 arcmin

Nasmyth Focus (Optical)
Focal ratio: 12.6

Cassegrain Focus
Focal ratio: 12.2
Field of view: 6 arcmin

Illustration by Takaetsu Endo, taken from Nikkei Science 1996
THE FOCAL LENGTH OF A CASSEGRAIN REFLECTOR CAN BE MUCH LONGER THAN THE LENGTH OF THE TELESCOPE.
• Keck: $D = 10\text{m}$, $F = 150\text{ m}$ (or an F ratio of f/15)
Atmospheric Transmission

the windows of EM waves
The thin atmosphere that protects all of life

- upper atmosphere
- stratosphere
- troposphere
- limb
- Indian Ocean

outer space
The Three Transmission Windows of the Atmosphere

- The atmosphere does not transmit all light: only visible, some infrared, and radio wavelengths are allowed to come in.
- Nearly all X-ray, ultraviolet, and mid-to-far infrared wavelengths are blocked.

![Diagram showing the transmission windows of the atmosphere with labeled windows for visible, infrared, and radio wavelengths.](image-url)
Atmosphere Opacity (1-Transparency) vs. Wavelength

Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.
Atmosphere absorption

Absorption from various molecules

Dowgoing Solar Radiation
70-75% Transmitted

Upgoing Thermal Radiation
15-30% Transmitted

Spectral Intensity

UV | Visible | Infrared

Total Absorption and Scattering

Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering

Wavelength (μm)
Site Selection Considerations

» Atmospheric transparency
» Atmospheric seeing
» Number of clear nights per year
» Visible fraction of the celestial sphere
» Light pollution

Winners:
Mauna Kea (Hawaii, USA)
Las Campanas, Cerro Paranal, Cerro Tololo (Chile)
Interferometers

maximizing resolution by synthesizing multiple apertures
If segmented mirrors can work together as one, do we really need to fill the aperture with mirrors?
VLA (Very Large Array)

27 parabolic dishes, each 25 meters (82 feet) in diameter.
A Single VLA Dish (25 m in diameter)
The Diffraction Limit of A Circular Lens/Mirror

The **diffraction limit** is defined as the **radius** of the Airy disk:

\[
\theta = 1.22 \frac{\lambda}{D}
\]

where \( \lambda \) is the wavelength and \( D \) is the lens/mirror diameter.
Based on *Fourier* Optics, we can calculate the diffraction patterns of differently shaped apertures.
We can calculate the diffraction patterns of differently shaped apertures, even for the fragmented aperture of the VLA.
diffraction pattern of the VLA interferometer
The diffraction limit is the *radius* of the *central* disk:

\[ \theta = 1.22 \frac{\lambda}{D} \]

where \( \lambda \) is the wavelength and \( D \) is the *widest separation* between two elements in the interferometer.
16 Mpc away
Atmospheric Turbulence

need Adaptive Optics to achieve the maximum angular resolution
THE DREAM OF OPTICAL ASTRONOMERS: MAKE A LARGE MIRROR INTERFERE
If we had the means of continually measuring the deviation of rays from all parts of the mirror, and of amplifying and feeding back this information so as to correct locally the figure of the mirror in response to the schlieren pattern, we could expect to compensate both for the seeing and for any inherent imperfection of the optical figure.

(Horace Babcock 1953 PASP)
During the cold war, it was part of the strategic defense thinking of the US, of what we could do to get better images of what was out in space — R. Duffner, *The Adaptive Optics Revolution: A History*

The purposes of “Compensated Imaging systems”:

- **Surveillance**: To obtain clearer images of Soviet satellites and missiles
- **Strike**: To improve the performance of laser weapons on incoming missiles
1989, THE BREAK-THROUGH

- In 1989, the first AO for astronomy worked: **COME-ON** on the 1.5-m telescope of Haute-Provence Observatory in southern France.

- In 1991, the US military declassified most of the development work on AO to astronomers.

“An old dream of ground-based astronomers has finally come true”, Merkle+1989
Adaptive Optics: Basic Principles

Deformable Mirror (DM)
**ADAPTIVE VS. ACTIVE OPTICS**

- **Active Optics** control wavefront distortions introduced by the telescope itself, and use the large primary mirror for the slow correction (~1 Hz).

- **Adaptive Optics** compensate for the rapidly varying atmospheric wavefront distortion and use smaller deformable mirrors for the fast correction (~1000 Hz)
ATMOSPHERE PARAMETERS THAT DETERMINE AO DESIGN

- The Fried/seeing parameter, 
  \[ r_0 = \frac{\lambda}{\text{seeing}} \sim \lambda^{1.2} \cos(ZA)^{0.6} \sim 500 \text{ nm}/1 \text{ arcsec} = 10 \text{ cm}, \]
  defines the coarsest sampling of the telescope pupil to achieve good AO corrections.

- The isoplanatic angle, 
  \[ \Theta_0 \sim \cos(ZA) \frac{r_0}{h} \sim 20'', \]
  defines the field of view that can be corrected by AO.

- The coherent time, 
  \[ \tau_0 \sim \frac{r_0}{V_{\text{wind}}} \sim 10 \text{ cm}/10 \text{ m/s} = 10 \text{ ms}, \]
  defines the required AO temporal correction bandwidth

- All parameters get larger at longer \( \lambda \)!
DEFORMABLE MIRRORS

- Vibrates just like speakers
- Fast response: $<< 0.1 \text{ ms}$; Small strokes: $< 10\text{ s \mu m}$
MOST EXPENSIVE DMs

- This example shows a DM as the secondary mirror of the LBT
- 672 voice-coil actuators with spacings of a few cms
- The Beryllium shell is ~1 meter across but only 1-2 mm thick — this is the most challenging part to manufacture
- Costs ~$1 million each
INEXPENSIVE DMs

- micro-optical-electrical-mechanical system (MOEMS), ready-made units costs $1-10 k.
- thousands of actuators in just 1 cm²
- small strokes: ~2 µm, needs to be coupled with another large-stroke DM (i.e., a woofer) for large telescopes
A SIMPLIFIED AO OPTICAL BENCH
RAYLEIGH LASER GUIDE STARS

- Pulsed UV laser beam, reflects off air molecules through Rayleigh scattering

- Pros: no harm to airplane pilots, easier to make

- Cons: Elevation only 10 km (vs. 90 km from the Sodium layer). Because of the low elevation, wavefront aberrations due to the atmosphere is only partly corrected

- Laser: ~12 W 355nm (e.g., RoboAO, Baranec+2014)
SODIUM LASER GUIDE STARS

- Sodium layer: 90 km high, 5-10 km thick. Origin - micrometeorites
- Laser wavelength: 589 nm, Na D
- Laser power: e.g., 10-14 W for the Keck system, but consumes **6-50 kW** of energy
- Return power: \( V = 8.8-10.0 \) mag
- Spot size \( \sim 1-2'' \)
Deformable secondary mirror of LBT, 1-m across, costs $1m!

Esposito+2010
Remember this Hubble image of Jupiter? We can get it from the ground with adaptive optics.
EXAMPLE AO IMAGES

Persistent rings in and around Jupiter’s anticyclones

AO image (1.58, 1.29, & 1.65μm)

AO mosaic (5μm)

de Pater+(2010)
EXAMPLE AO IMAGES

Volcanic eruptions on Jupiter’s moon Io

20 Feb. 2001

Keck II AO/NIRSPEC images of Io

22 Feb. 2001

Recent outburst 010222A (Surt)
Emission area $T_1=1470$ K (90 km$^2$) and $T_2=880$ K (1760 km$^2$)

Marchis+2002, see also de Pater+2014
Discovery of the SMBH at the Galactic Center

Nobel Prize in Physics, 2020

The Galactic Center at 2.2 microns

Adaptive Optics OFF

Adaptive Optics ON
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Chap 6: Equations

**Doppler Shift**

\[ \frac{V_r}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\text{obs}}}{\nu_{\text{obs}}} \]

**Diffraction Limit**

\[ \theta = 1.22 \frac{\lambda}{D} \text{ radian} = 206265 \times 1.22 \frac{\lambda}{D} \text{ arcsec} \]

**CCD Plate Scale**

\[ \text{plate scale} (\arcsec/\text{pixel}) = 206265\arcsec \times \frac{\text{pixel size}(\mu\text{m}/\text{pixel})}{\text{focal length}(\text{m}) \times 10^6} \]

**Focal Ratio**

\[ F = f/D \]