PHYS 320

Lecture 6

Astronomical Telescope and Instrumentation

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Guiding Questions

1. Why is it important that telescopes be large?
2. Why do most modern telescopes use large mirrors rather than large lens?
3. Why are observatories in such remote locations?
4. How do astronomers use telescope to measure the parameters of distance objects?
5. Why do astronomers need telescopes that detect radio waves and other non-visible forms of light?
6. Why is it useful to put telescopes in orbit?

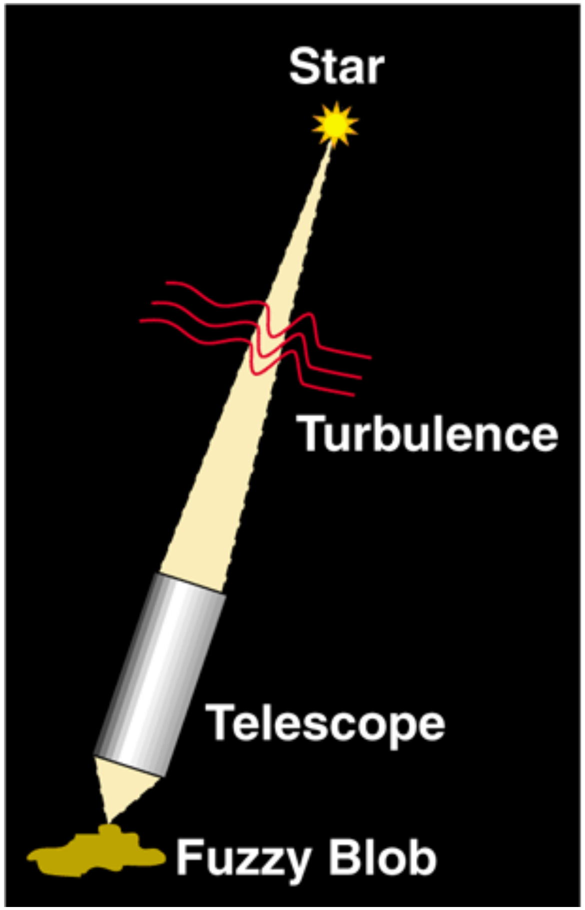
7.1 Telescope Sites

- Good transparency – freedom from haze, smog, dust, etc.
- Clarity – freedom from clouds and fog
- Good 'seeing' – freedom from atmospheric distortion
- Need all three for a good site

Ex.4: Big Bear Solar Observatory/ NJIT, build on a mountain top (7000 feet) in the middle of a lake to minimize effects by smog, clouds, and atmosphere turbulence. The best seeing at this site is around 1", i.e., one thousandths of the Sun's radius.

Q: limited by seeing, shall we operate big telescopes on the ground?

7.2 AO Introduction



- ***Why is adaptive optics needed?***
- ***Start from a kid's song …***

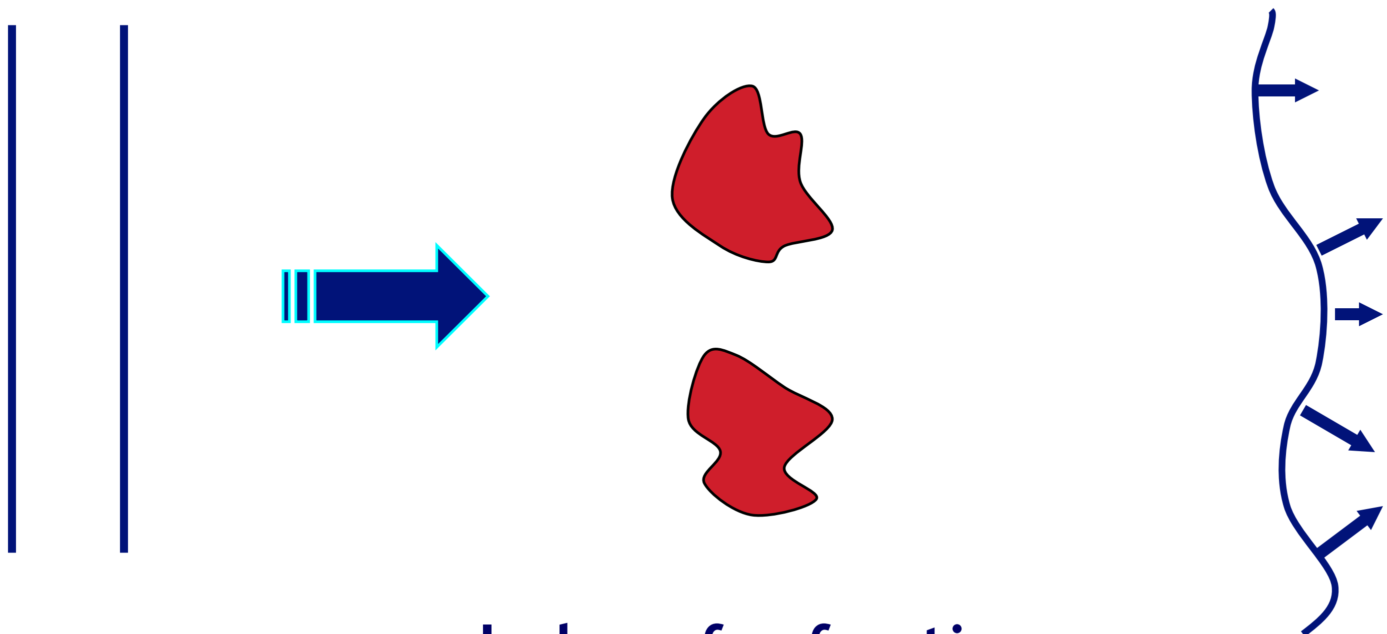
http://www.youtube.com/watch?v=yCjJyiqpAuU

"twinkle twinkle little star, how I wonder what you are ……"

- ***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 telescope have no better resolution than an 8-inch backyard telescope***

Light through Turbulence

- *Atmospheric perturbations cause distorted wavefronts*



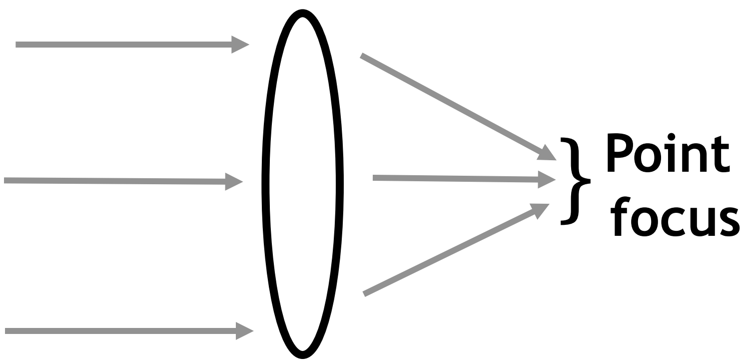
Plane Wave

Index of refraction variations

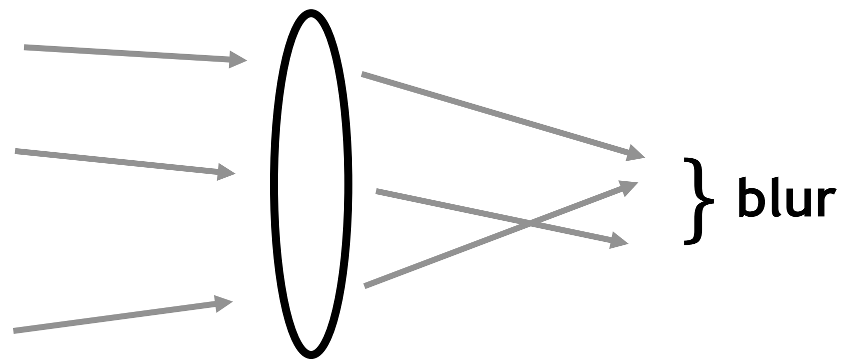
Distorted Wavefront

Light through 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:*

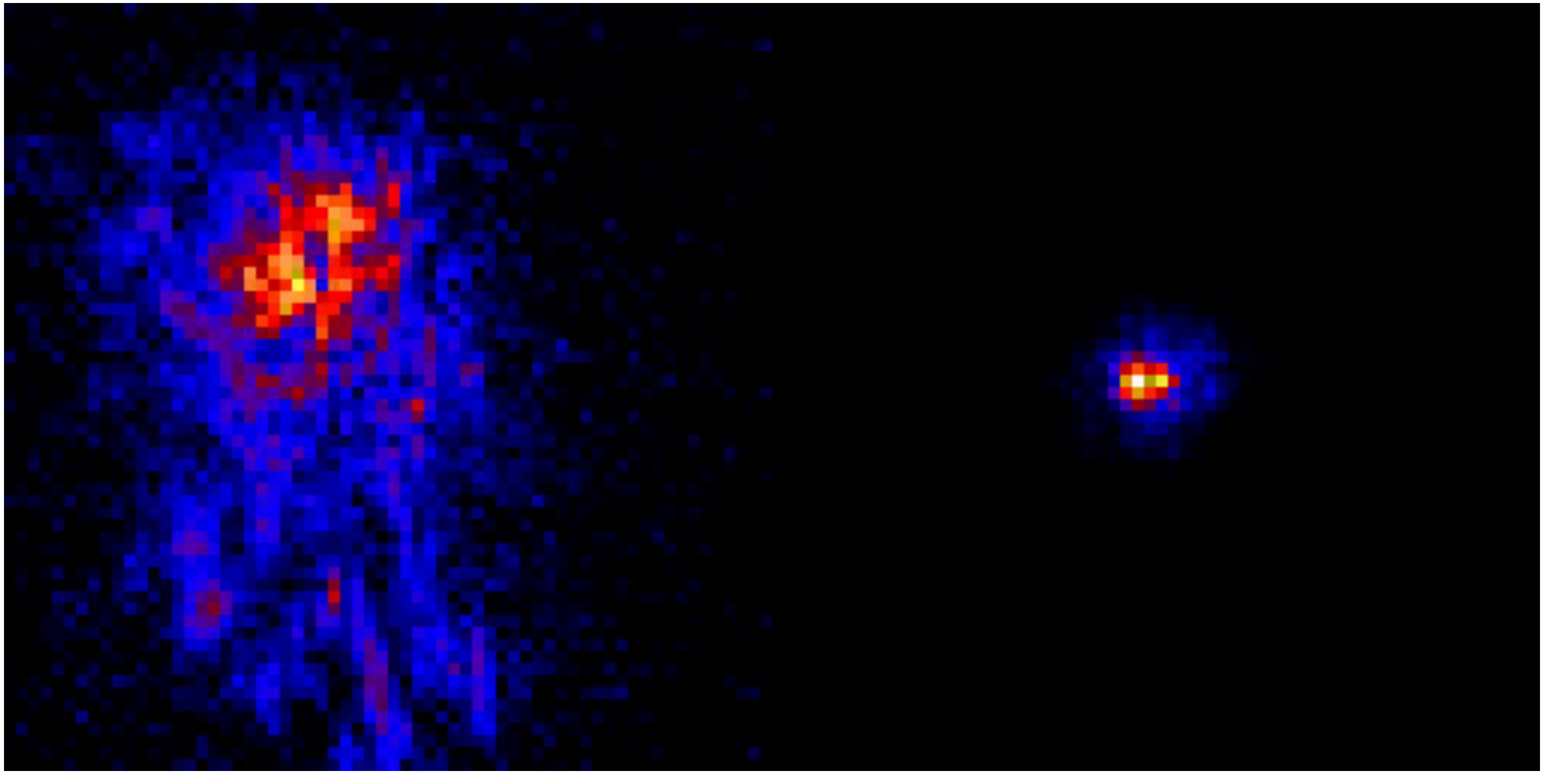


Parallel light rays



Light rays affected by turbulence

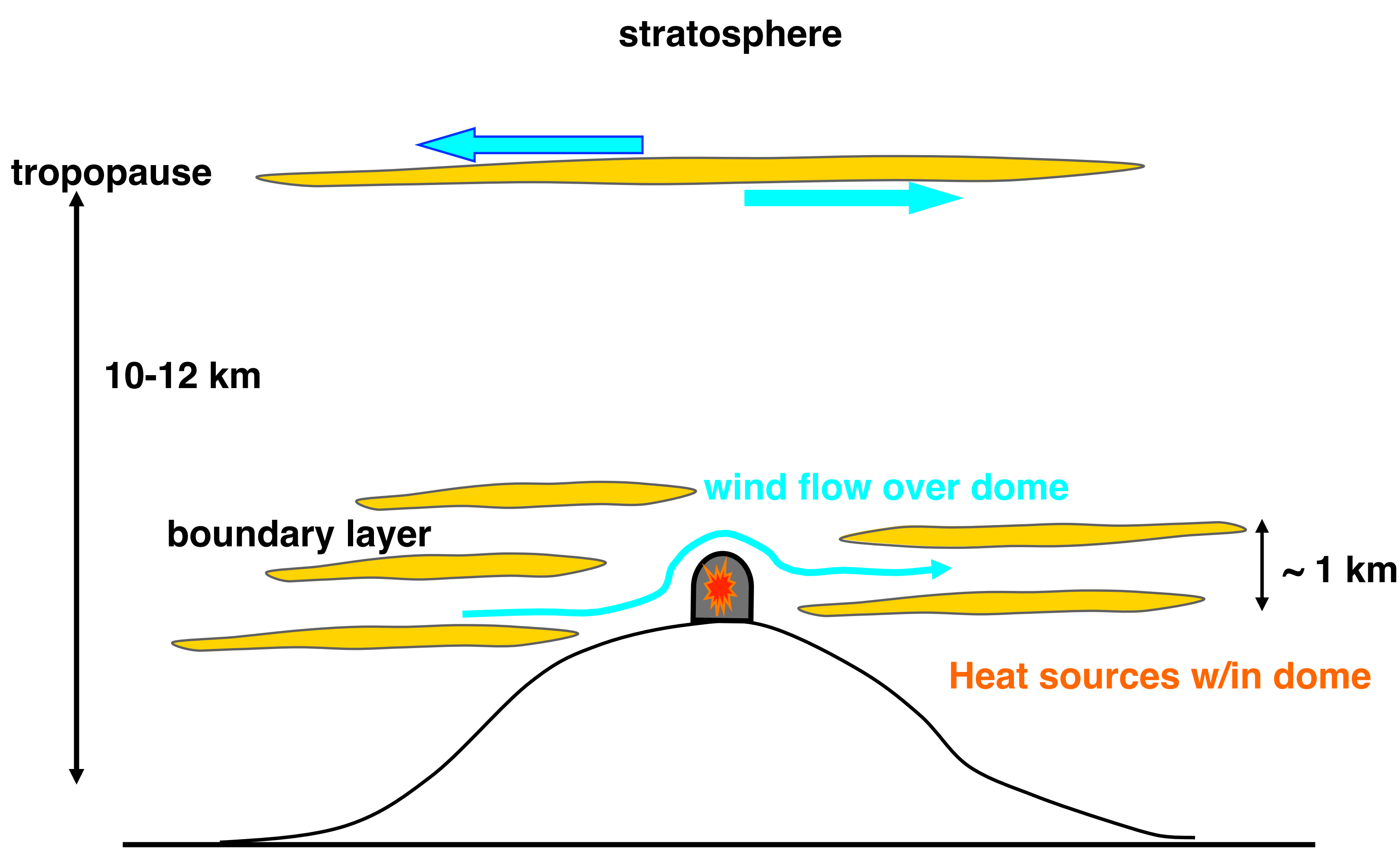
IR Images of a Star with AO



No adaptive optics With adaptive optics

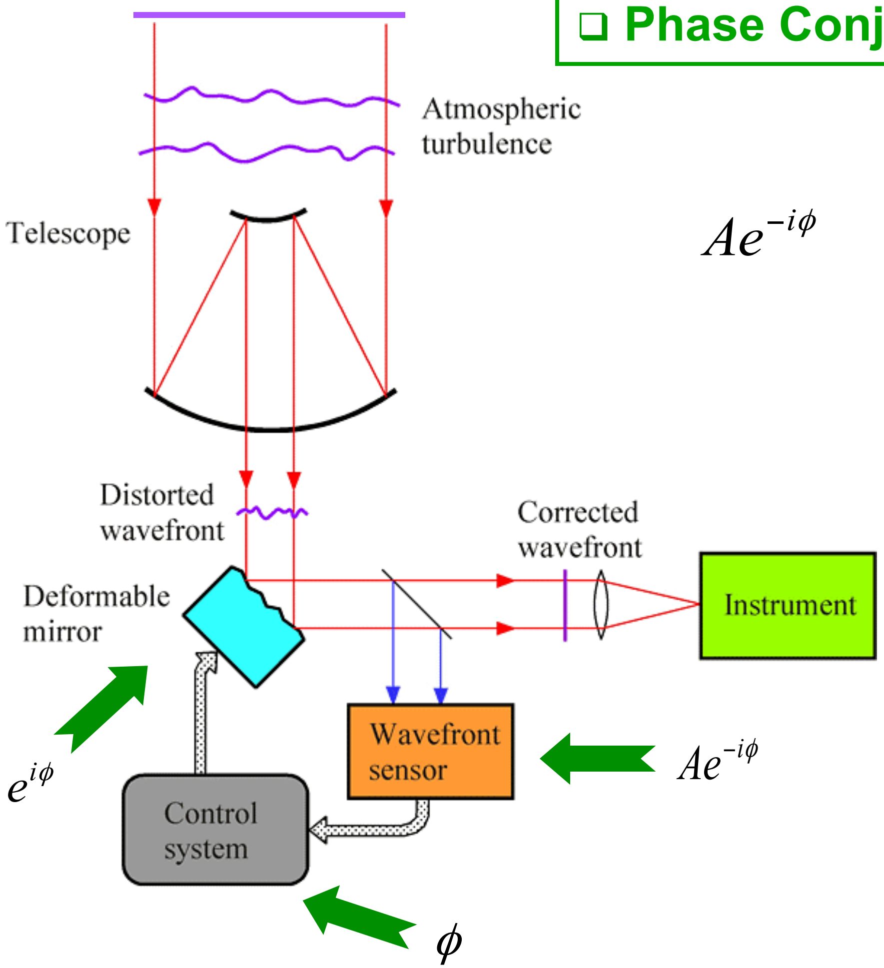
Note: "colors" (blue, red, yellow, white) indicate increasing intensity

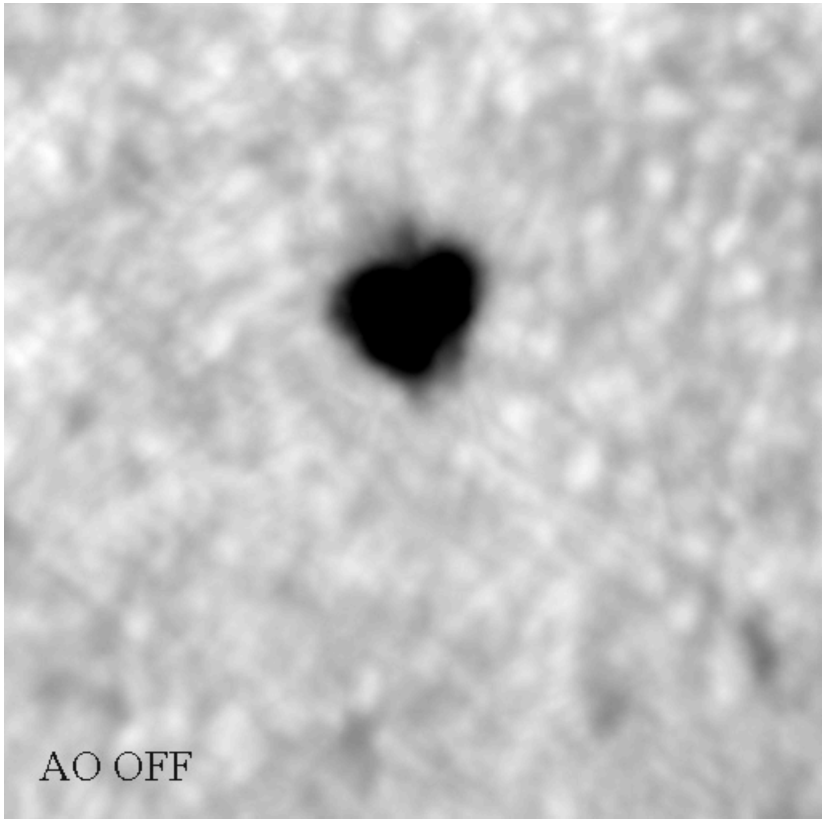
Turbulence Sources



Adaptive Optics Principle

❑ **Phase Conjugation:** $A\exp(-i\phi)\cdot\exp(+i\phi)$

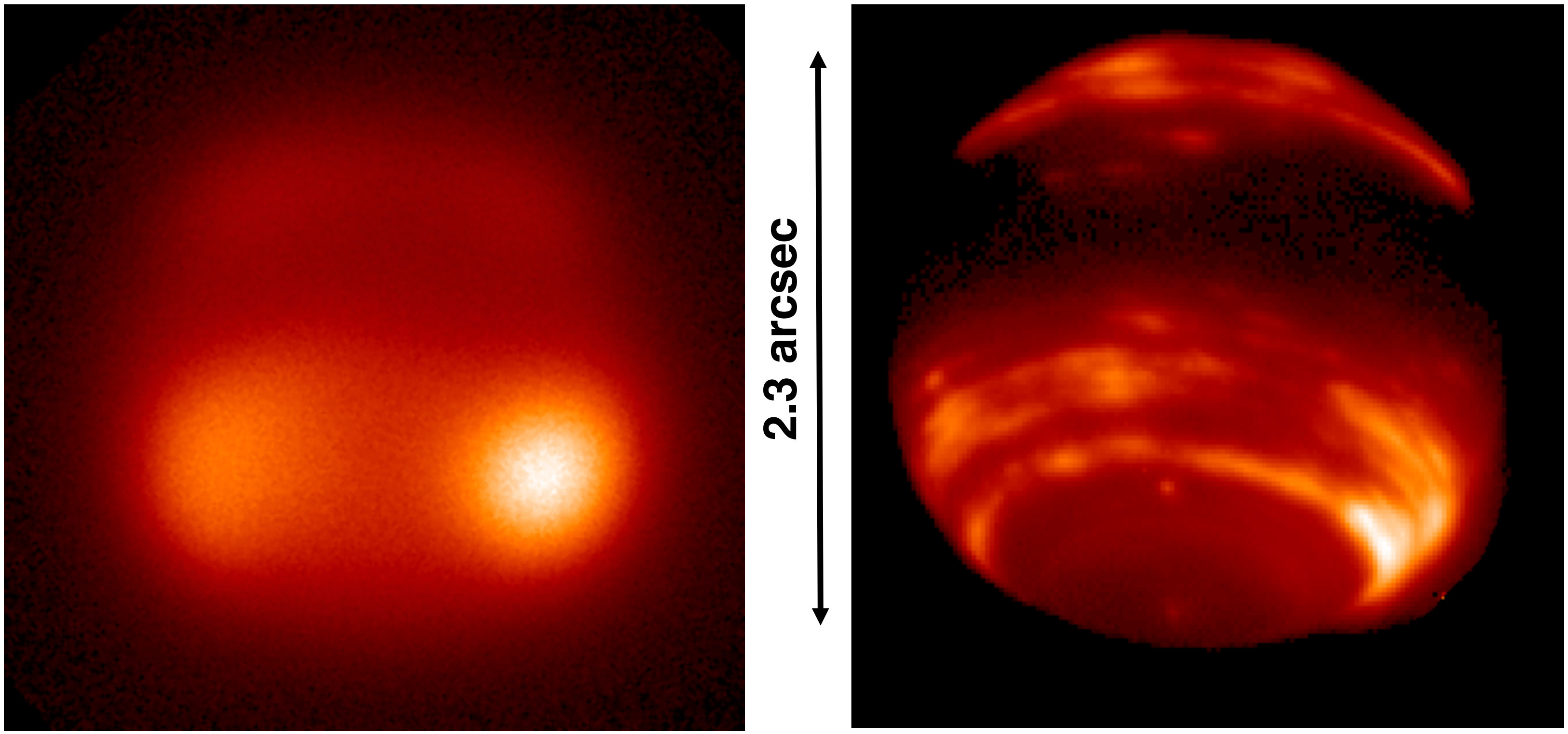




❑ Adaptive optics (AO) uses a deformable mirror to correct the distorted wave front by atmosphere turbulence.

New Discovery with AO

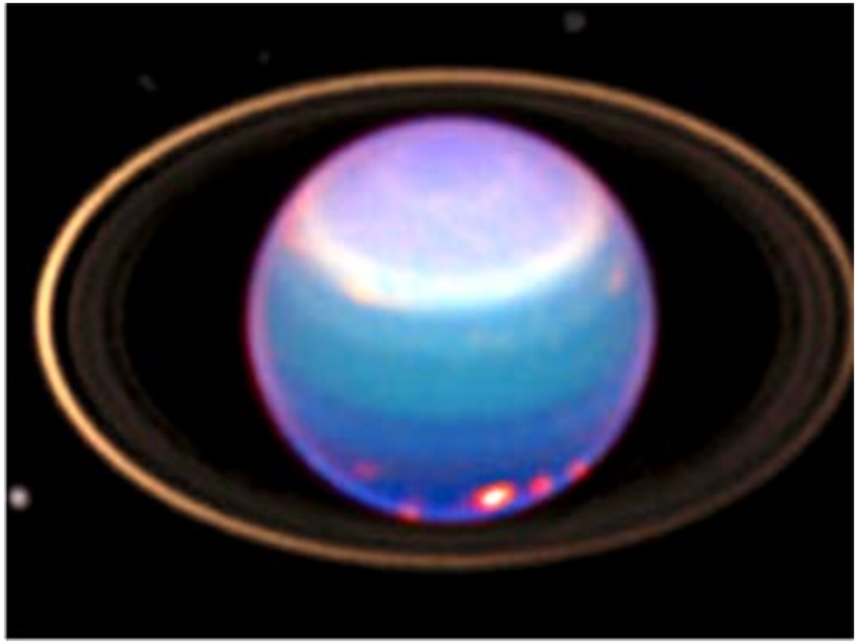
Neptune in infra-red light (1.65 microns)



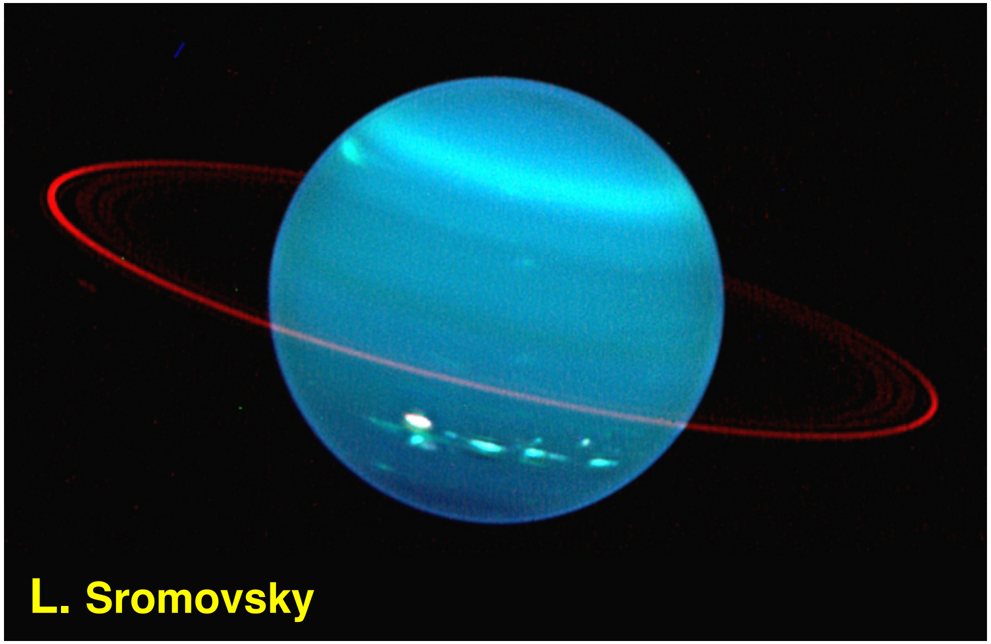
Without AO **With Keck AO**

New Discovery with AO

Uranus with Hubble Space Telescope and Keck AO



HST, Visible

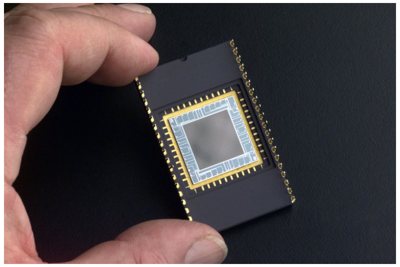


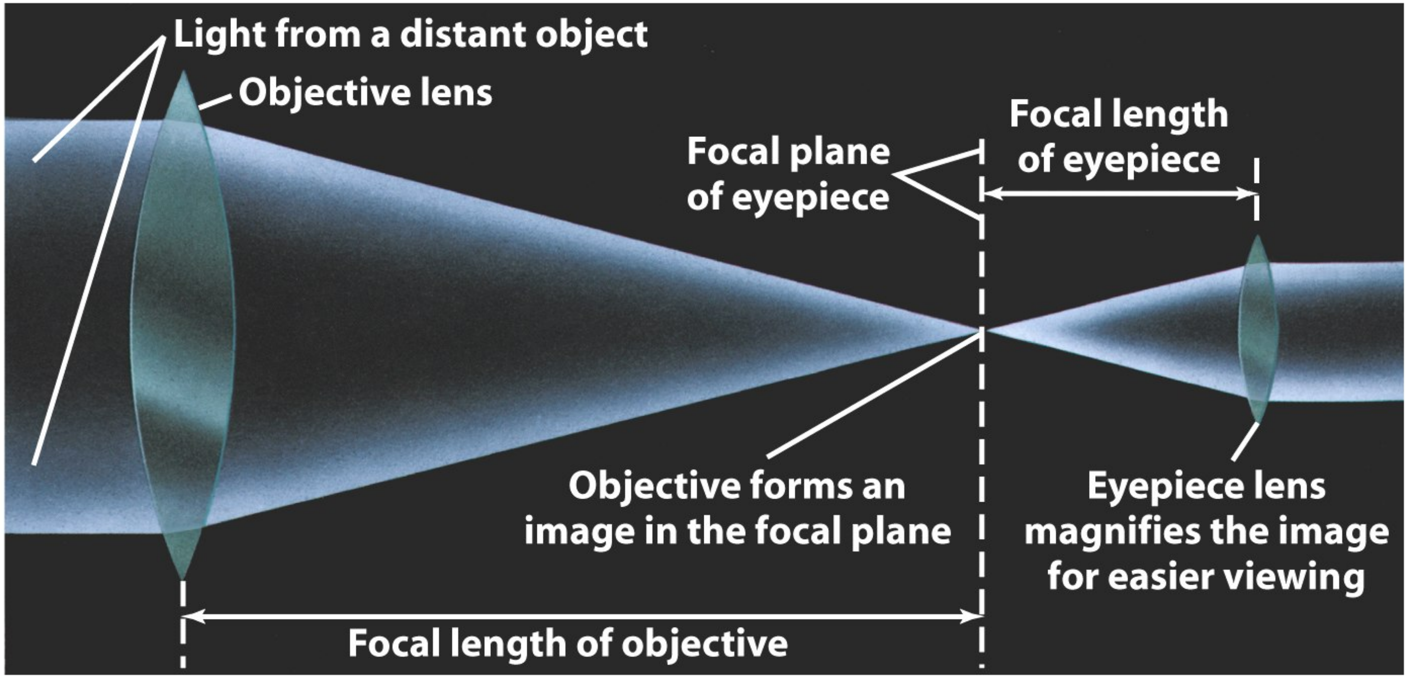
Keck AO, IR

Lesson: Keck in near IR has ~ same resolution as Hubble in visible

7.3 Astronomical Detector

- Photographic Film
- Photomultiplier Tubes
- Charge Coupled Devices (CCDs)





Pros and Cons

Films

- reciprocity failure beyond a few second exposure
- minimal light intensity required to detect a target at all
- low quantum efficiency (5 ~ 20% at optimal wavelengths)
- response to light is non-linear
- small dynamic range (6-bit)
- picture elements (grain) are randomly distributed
- needs to be processed in a chemical darkroom
- good MTF

Solid State Devices

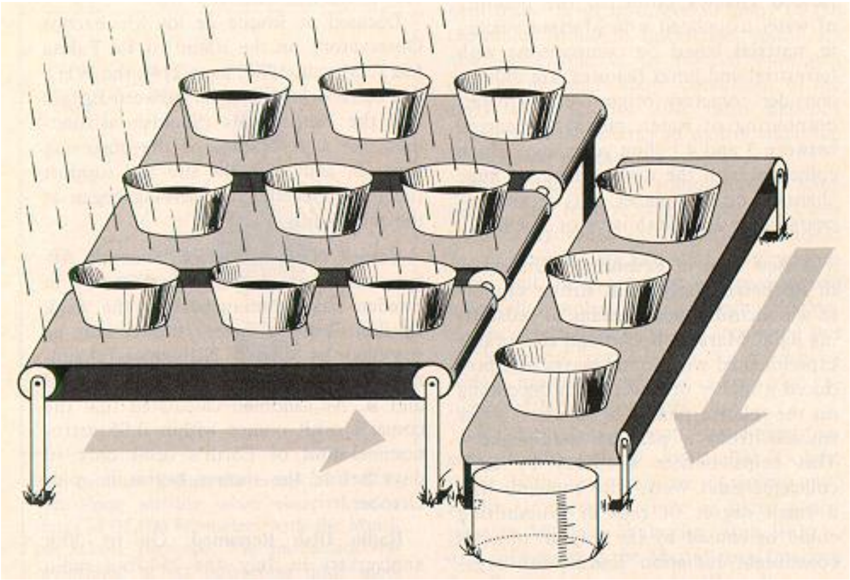
- no loss of sensitivity to light during exposure
- no minimal light intensity required to detect a target
- high efficiency of light detection (up to 50 ~ 90%, though device- and wavelength-dependent)
- signal is proportional to light intensity
- large dynamic range (typically 16-bit)
- picture elements (pixels) are regularly spaced
- ready for digital processing

CCD Basic Operating Principle

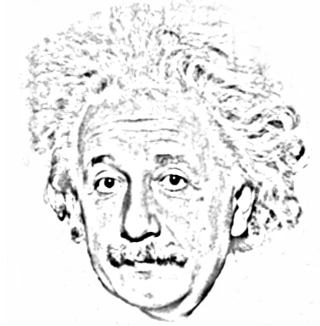
- *Step 0 - Light into Detector*
- *Step 1 - Charge Generation*
- *Step 2 - Charge Collection*
- *Step 3 - Charges Transfer*

λ

- *Step 4 - Charge-to-Voltage Conversion*
- *Step 5 - Digitization*



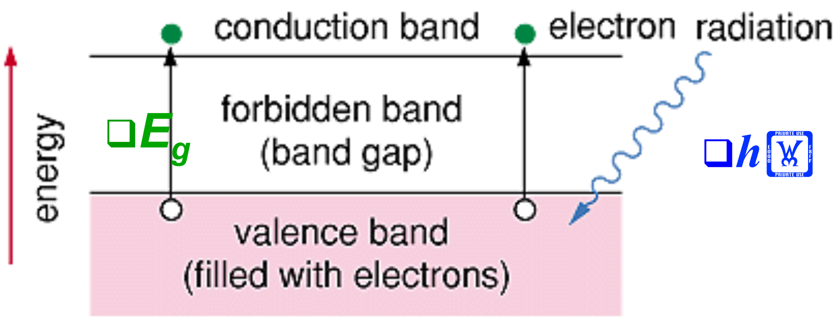
Photoelectric Effect



- *For an electron to be excited from valence band to conduction band*

$$h\nu \geq E_g$$

  - *h = 6.63×10^{-34} Joule·s (Planck constant)*
  - $\Upsilon = c / \lambda$ *(Frequency of light)*
  - *E_g: electron-volts (Energy gap of material)*



- *Long wavelength cut-off*

$$\lambda \leq \frac{1.238}{E_g(eV)} = \lambda_{cut-off}(\mu m)$$

- **Silicon: E_g = 1.12 eV, $\lambda_{cut\text{-}off}$ = ?**

NJIT Observatory

The NJIT observatory has a computer controlled 10" Meade LX200GPS telescope. We can use this telescope with an SBIG STL1301 CCD camera for "deep sky" imaging, or use a simple webcam for planetary and lunar imaging. The telescope is an f/10 system, and the two CCD cameras have the following specifications:

CCD	Kodak KAF-1301E	TouCAM II VGA CCD
Pixel Array	1280 x 1024 pixels 20.4 x 16.4 mm	640 x 480 pixels 3.58 x 2.69 mm
Total Pixels	1,310,720	307,200
Pixel Size	16 x 16 microns	5.6 x 5.6 microns
Full Well Capacity (NABG)	~120,000 e-	?
Dark Current	0.5e^-/pixel/sec at -30° C	?

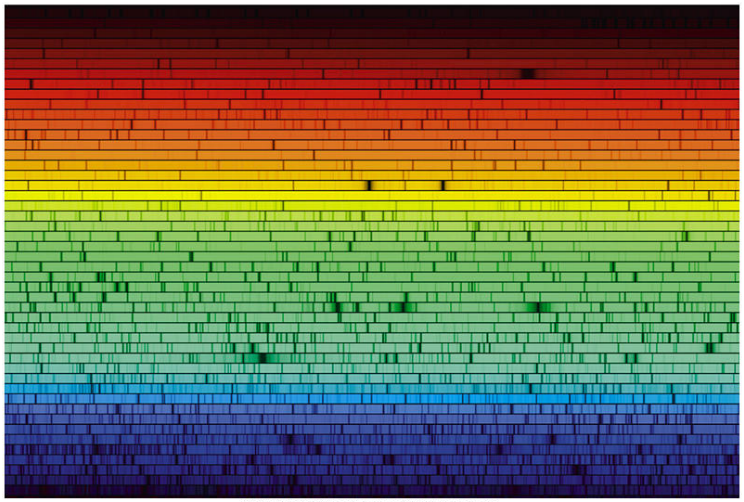
What is the image scale of the KAF1301E CCD (arcsec/pixel)?

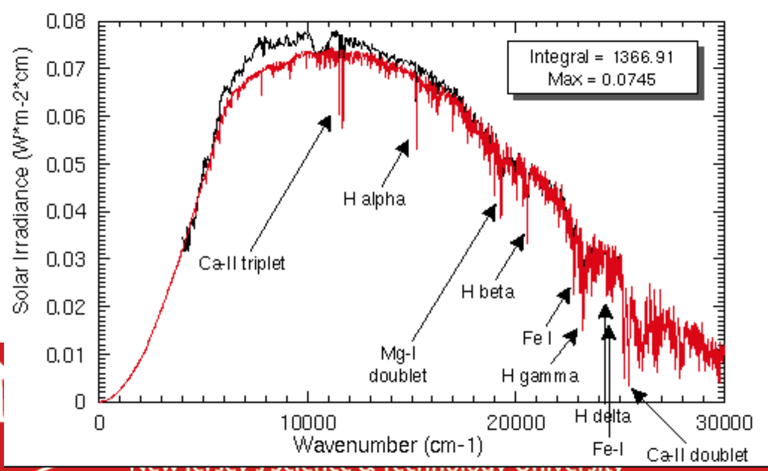
What is the field of view of the CCD camera, in arc-minutes?

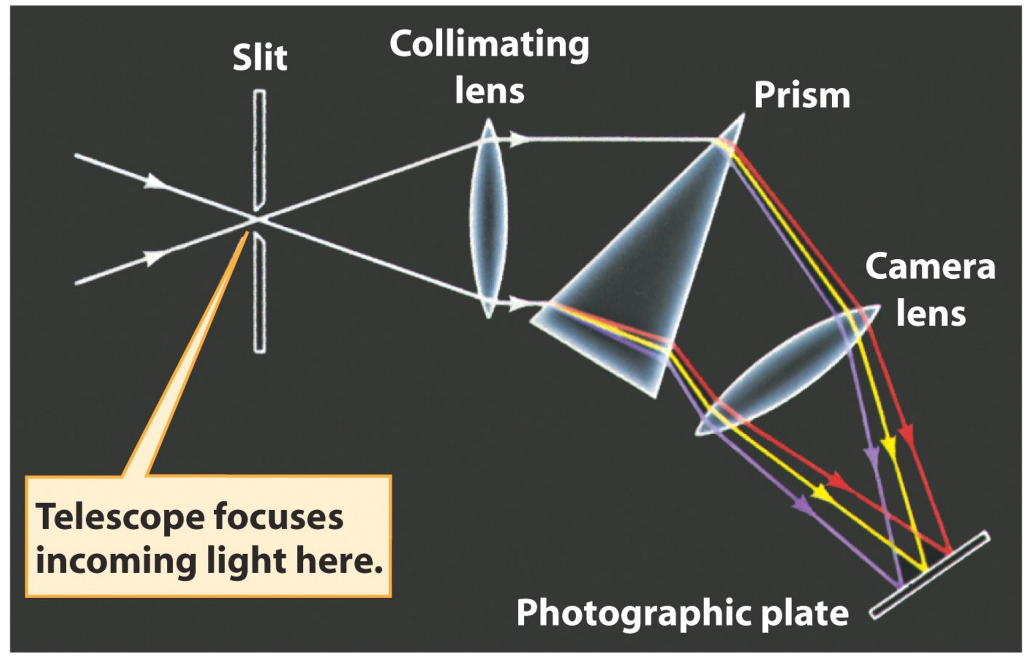
Will the Moon fit into the field of view of the CCD camera?

7.5 Spectrograph

Spectroscopy is one of the most important parts of observational astronomy. Spectral observations can tell us the **temperature**, **chemical composition**, and **motion** of remote celestial objects.



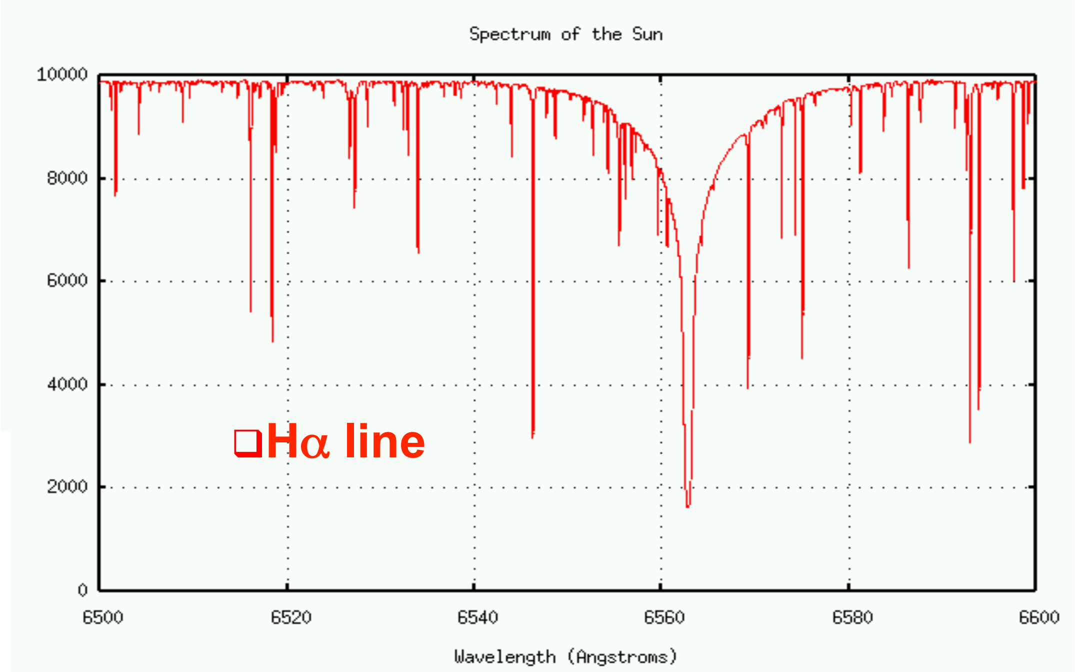


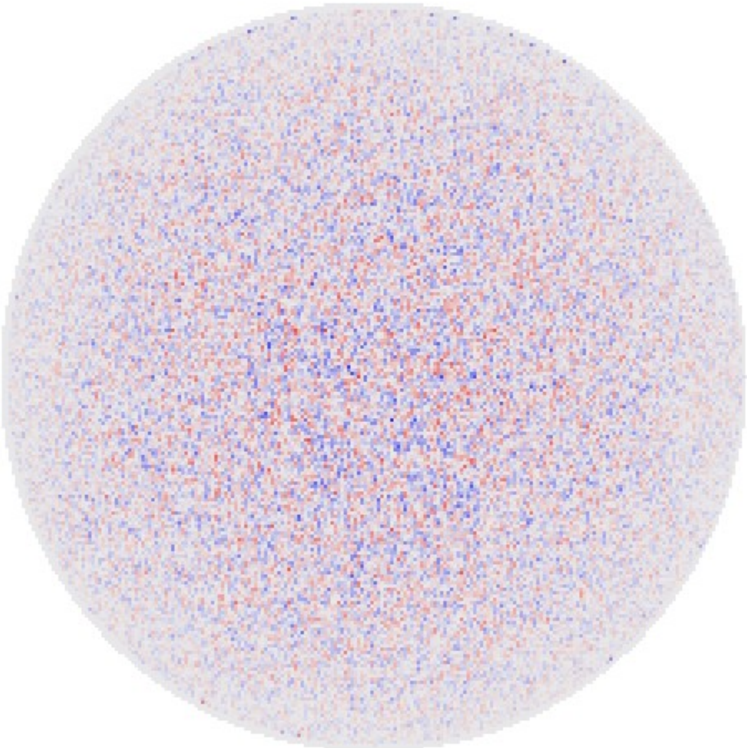


A prism spectrograph

Ex.7: Spectral observations of the Sun.

Ex.8 Hα line observed in the Sun's atmosphere.





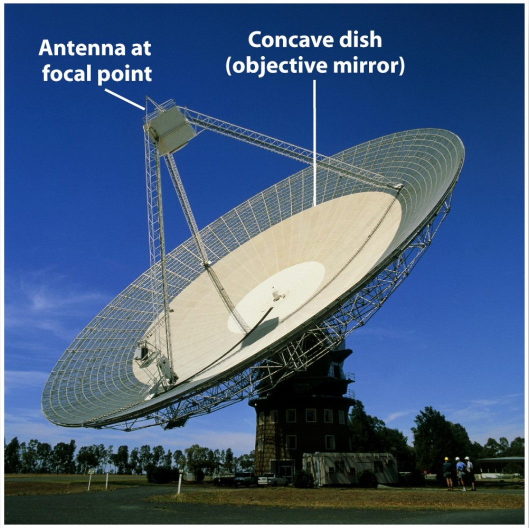
Ex.9: Dopplergram showing oscillations in the Sun's photosphere.

7.6 Interferometry - radio telescopes

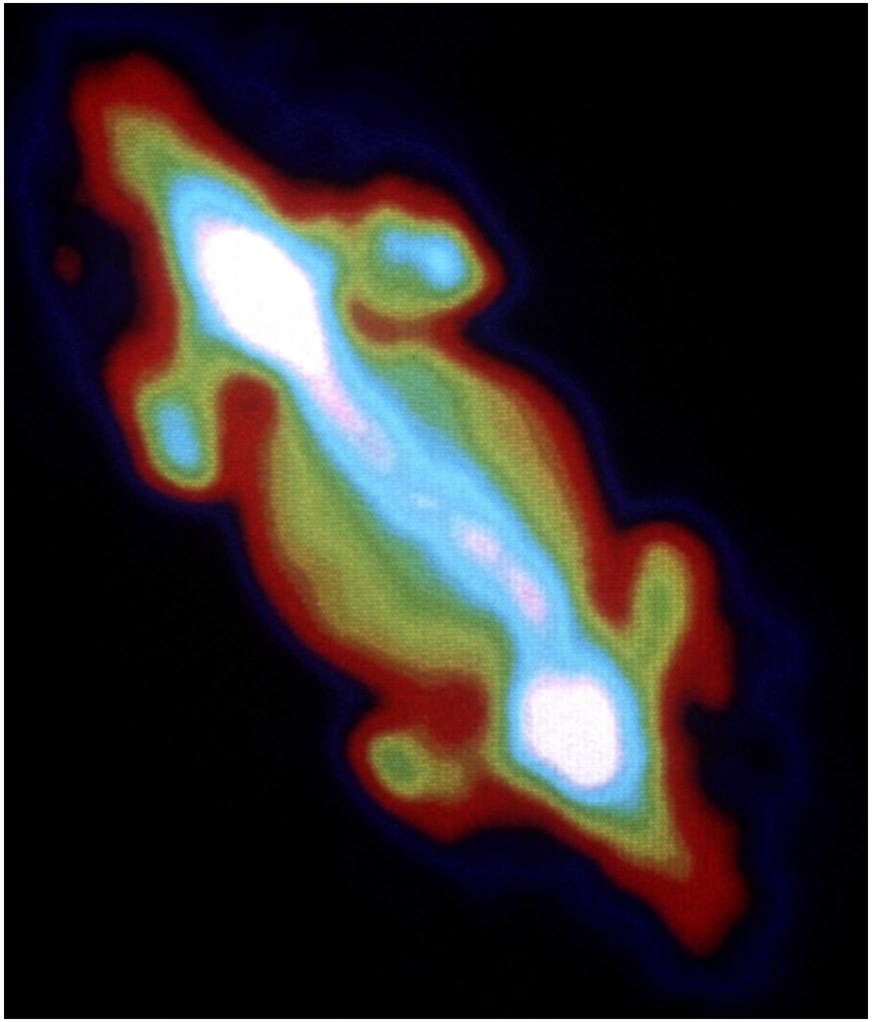
Radio telescopes make images with **interfering** radio signals from many radio telescopes separated by many kilometers. The distance between the telescopes is a **baseline**. The longer the baseline, the higher the resolution.

$$\theta \sim \frac{\lambda}{D} \rightarrow \frac{\lambda}{b}$$

The Very Large Array (VLA, New Mexico) consists of 27 radio telescopes.



Ex.10: Radio Jupiter recorded at VLA, New Mexico. The radio waves mapped in this false-color image are produced by energetic electrons trapped within Jupiter's intense magnetic field. The radio emitting region extends far beyond Jupiter's cloud tops and surrounds Jupiter. While it glows strongly at radio wavelengths, Jupiter's radiation belt is invisible in the more familiar optical and infrared views which show the Jovian cloud tops and atmospheric features in reflected sunlight.

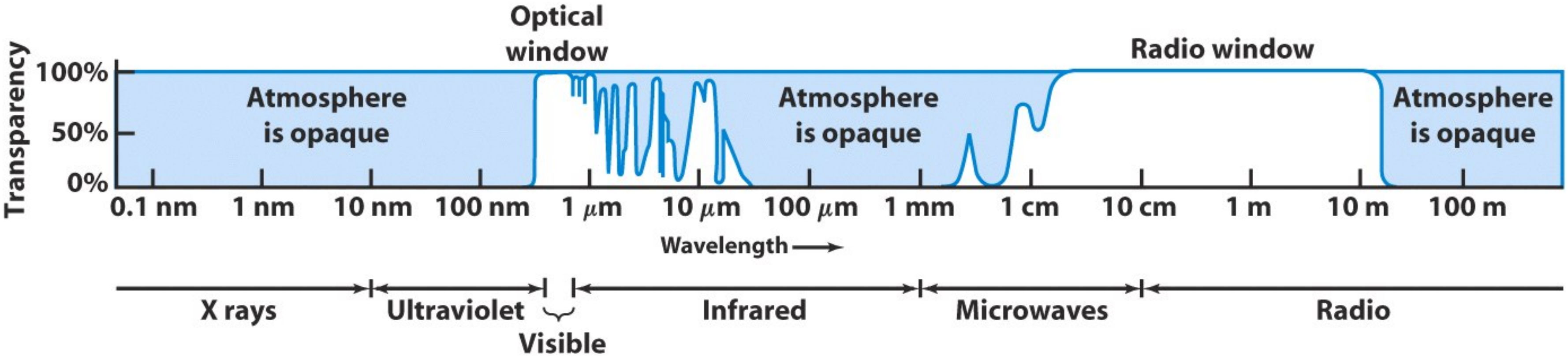


Radio Jupiter

Credit: I. de Pater (UC Berkeley) NRAO, AUI, NSF

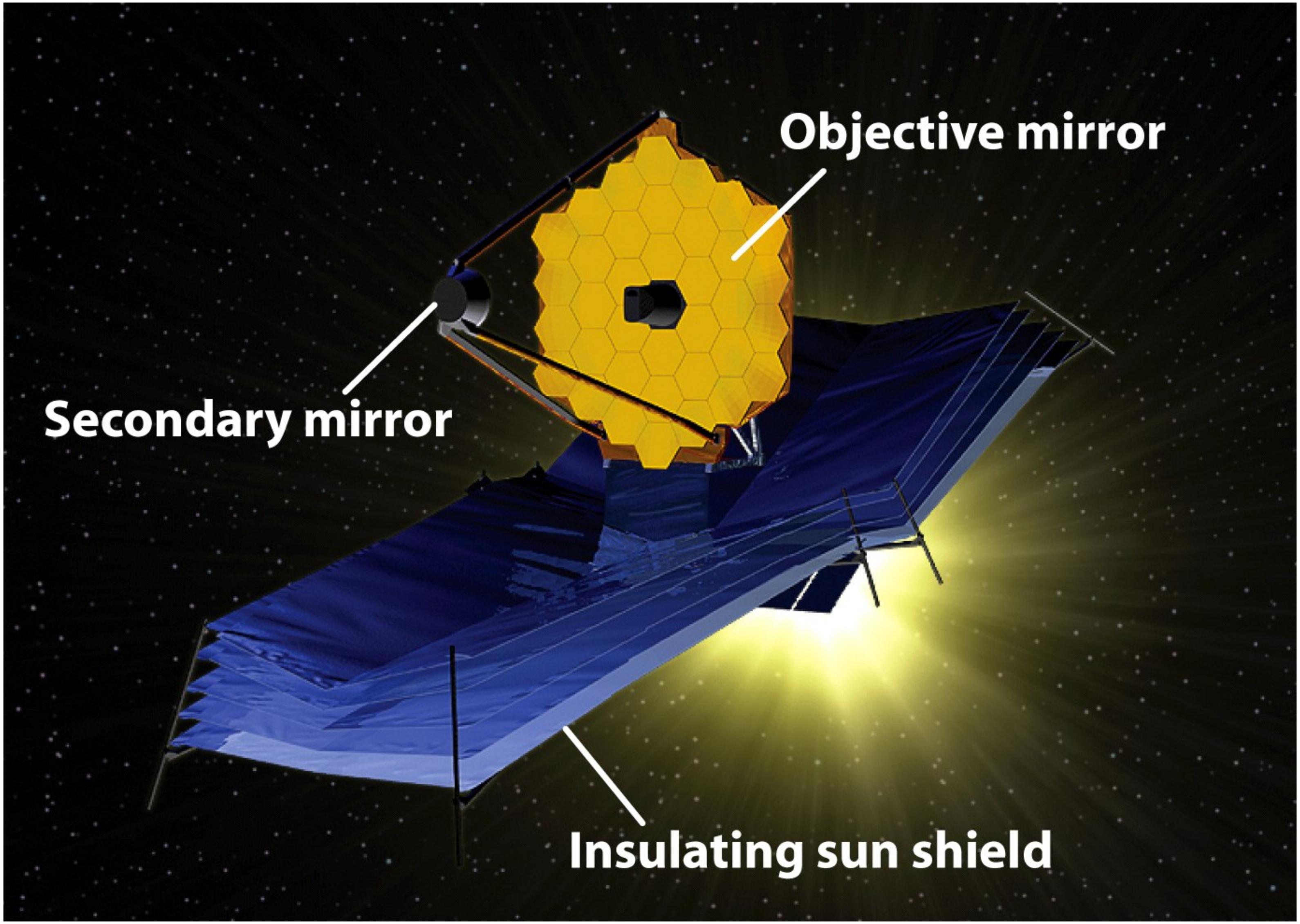
7.7 Space telescopes

Telescopes in orbit are free of atmosphere turbulence and can observe at wavelengths to which the Earth's atmosphere is opaque.

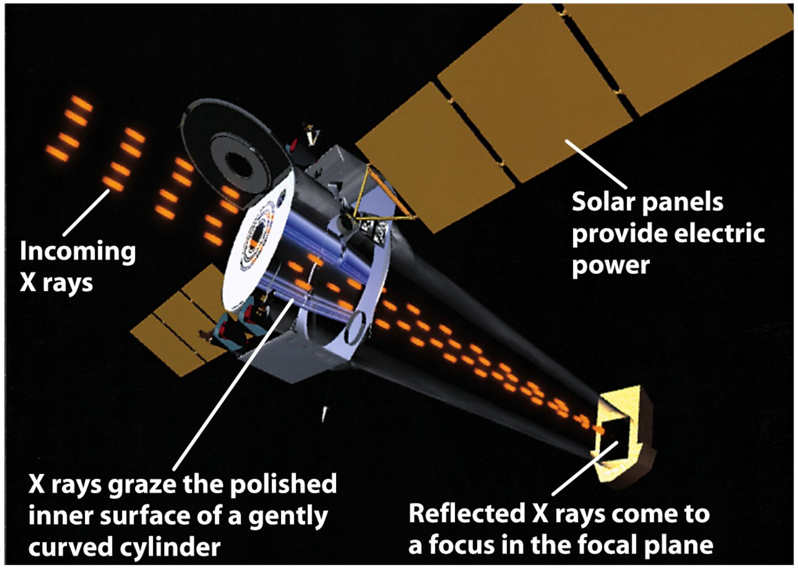


- The atmosphere is transparent in three wavelength regions, optical window, radio window, and some parts of near infrared.
- Telescopes in the space can observe dusts around stars and galaxies in infrared, hot stars and gas, the Sun's corona, and planets atmosphere in ultraviolet and X-rays, and some very energetic phenomena in γ-rays.

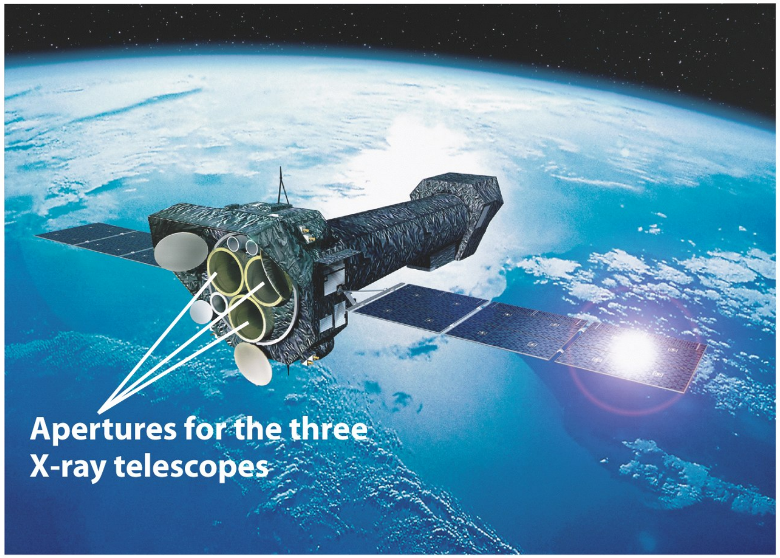
The Hubble Space Telescope (HST) launched in 1990 had a 2.4-meter objective mirror and was designed to observe at wavelengths from 115 nm (ultraviolet) to 1μm (infrared). HST uses a CCD to record images. HST has made numerous discoveries.



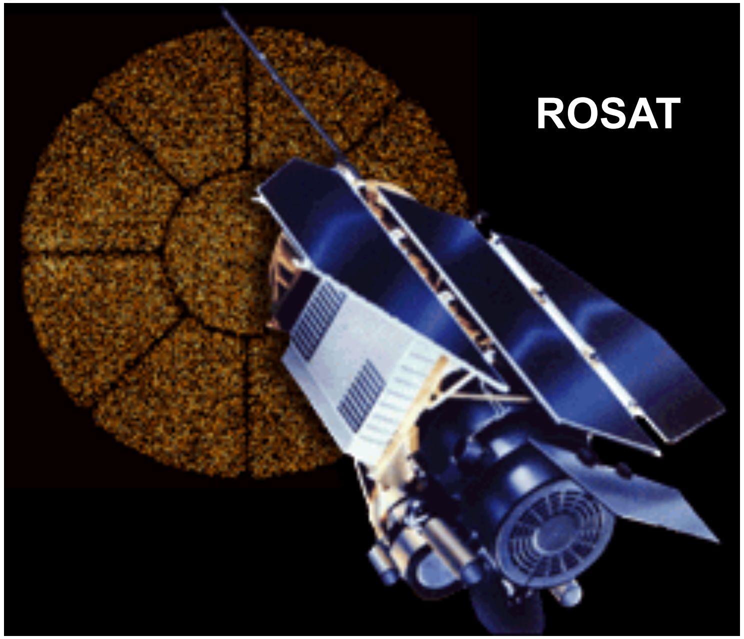
The James Webb Space Telescope (JWST) to be launched soon will have a 6.5-m diameter objective mirror, and observe from 600 nm to 28 μm.

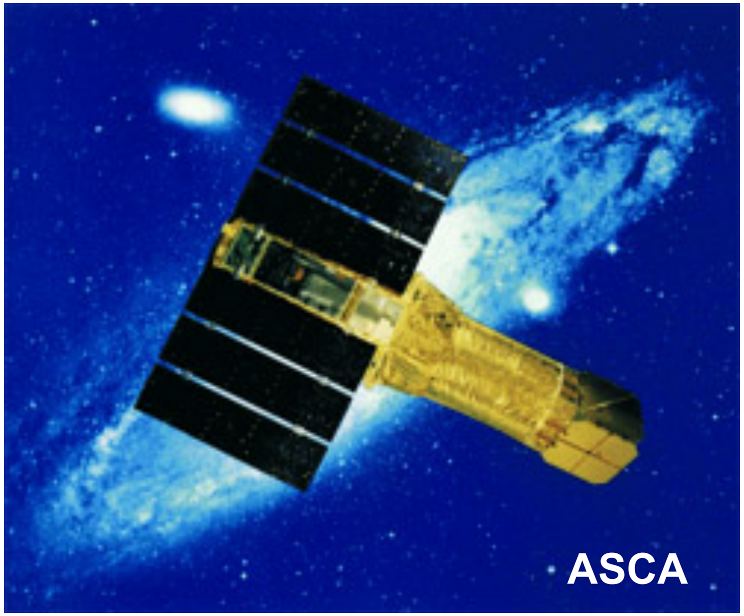


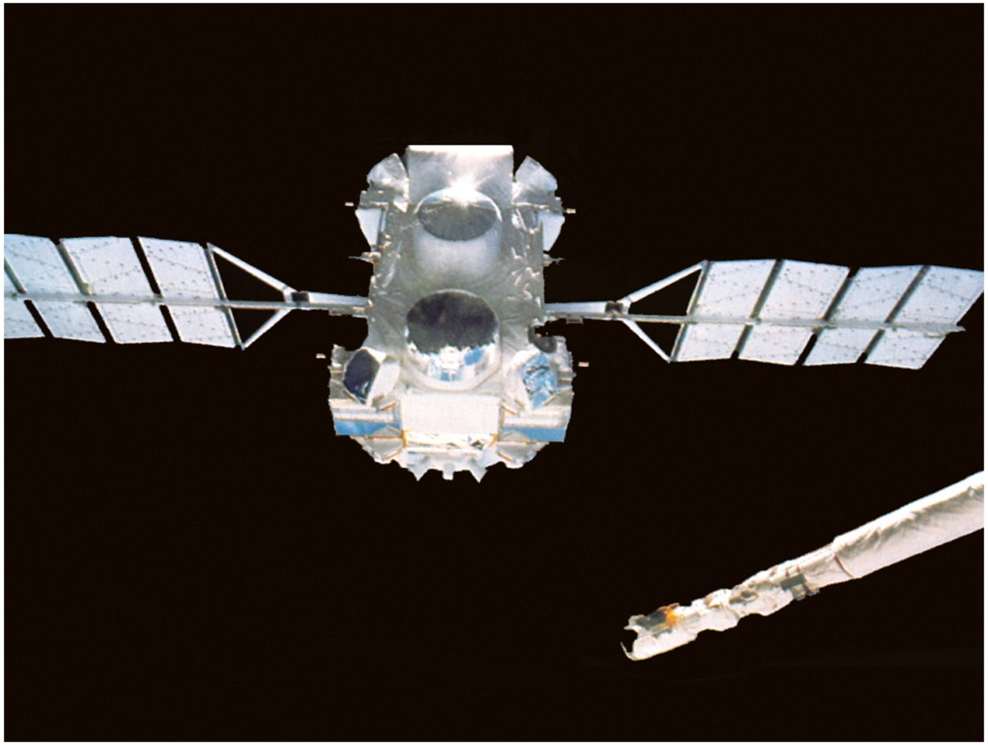
(a) Chandra X-ray Observatory



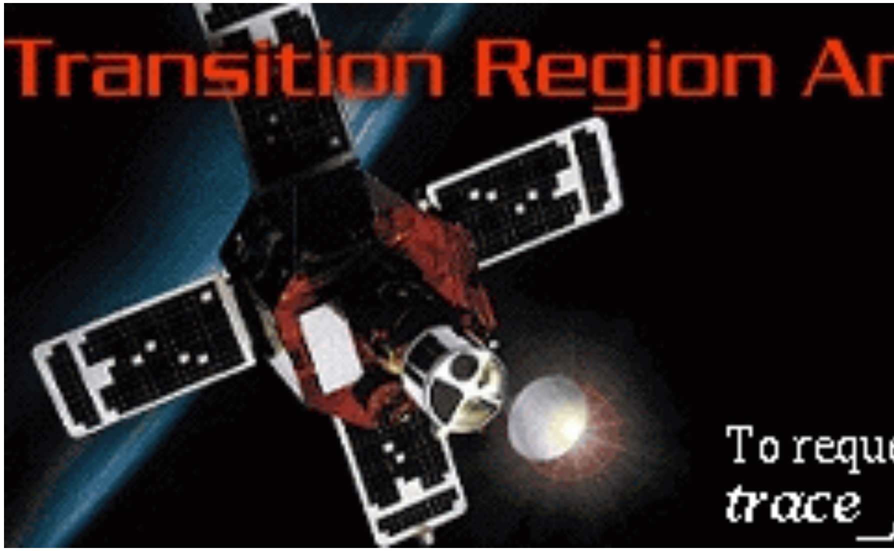
(b) XMM-Newton

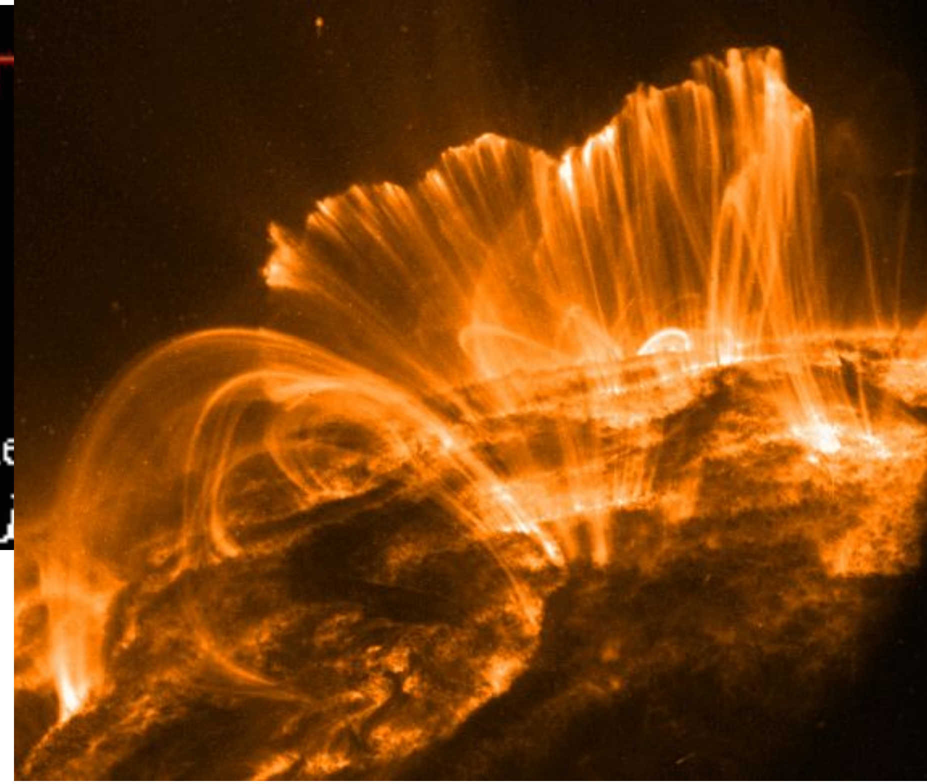






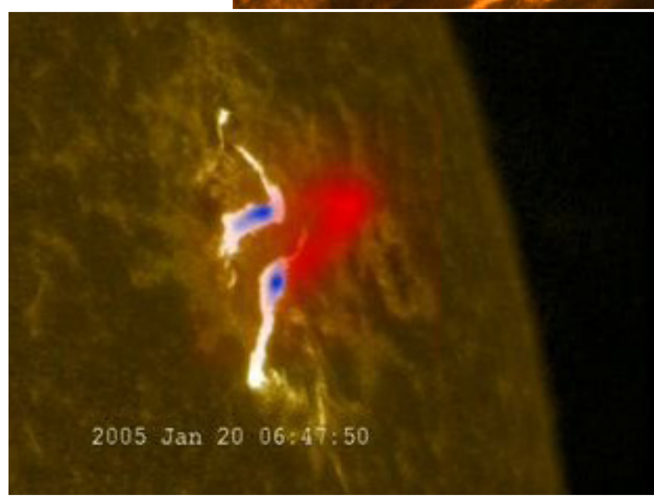
The Compton Gamma Ray Observatory (CGRO) detect Gamma ray and hard X-ray bursts.



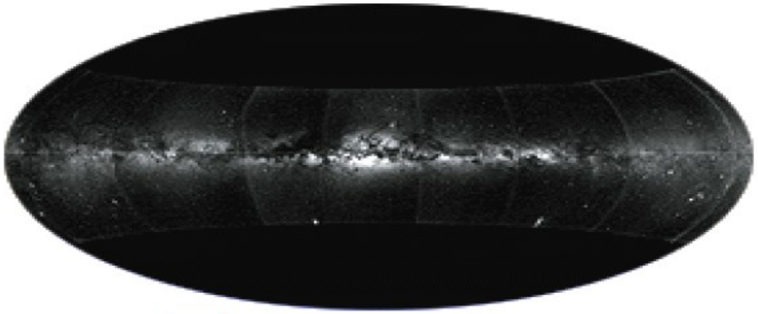


TRACE

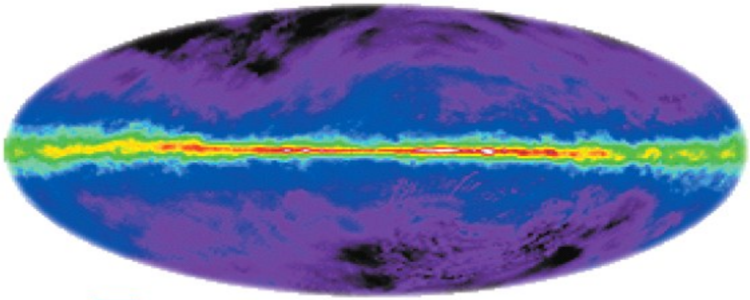
RHESSI



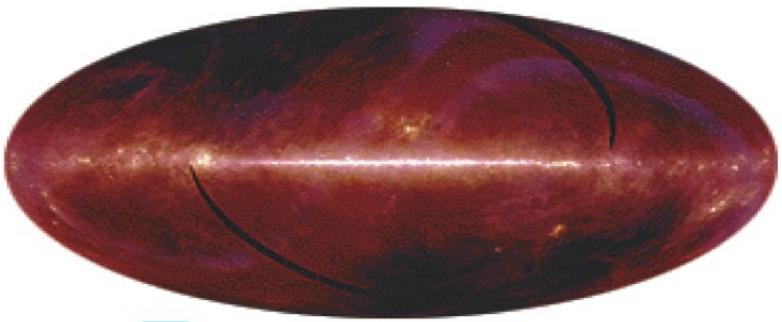
Ultraviolet, X-ray, and Gamma ray space telescopes observing the Sun.



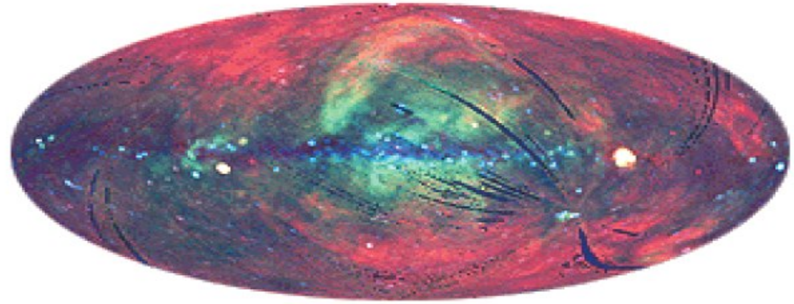
(a) R I V U X G



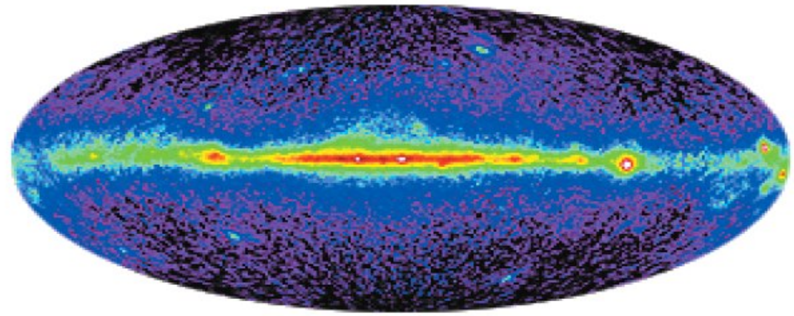
(b) R I V U X G



(c) R I V U X G



(d) R I V U X G



(e) R I V U X G

The entire sky at five wavelength ranges: visible, radio, infrared (IRAS), X-ray (ROSAT), and gamma-ray (CGRO) showing different structures of the Milky Way and beyond.

Key Words

- adaptive optics
- angular resolution
- baseline
- chromatic aberration
- chemical composition
- diffraction
- focal length
- focal plane
- interferometry
- magnification
- objective lens
- objective mirror
- optical telescope
- radio telescope
- reflecting telescope (reflector)
- refracting telescope (refractor)
- Seeing
- CCD
- spectrograph
- spherical aberration

Summary

- Atmosphere turbulence and light pollution blur telescope images. Adaptive optics can be applied to ground-based telescopes to correct the atmospheric distortion.

- Radio telescopes use interferometry techniques to achieve high resolution images.

- Telescopes in space are free from the Earth's atmosphere turbulence and are able to observe light at wavelengths - infrared, ultraviolet, X-ray, and gamma-ray - blocked by the atmosphere.

Star trails above Mauna Kea

(Peter Michaud, Gemini Observatory)