Astro 210

Lecture 14

Feb 19, 2018

Announcements

- **HW4 due online in PDF, Friday 5:00 pm**
- Hour Exam grading underway
- **Night Observing begins this week**
  Campus Observatory. Mon, Tue, Wed, Thur. 7–9pm
  bring **report form** available on Moodle
  take and submit **selfie** while there
- extra **Planetarium show** this Thursday Feb 22

FYI: Interesting Upcoming Lectures

Not part of class, but great talks with amazing speakers

Probing Behind the Man in the Moon – Results from NASA's GRAIL Mission
Prof. Jay Melosh, Perdue
Astronomy Colloquium, Tomorrow Tues Feb. 20, 3:45-4:45pm, Astro Bldg 134

Mapping the Nearest Stars for Habitable Worlds
Iben Distinguished Lecturer: Prof. Sara Seager, MIT
Astronomy Colloquium, Tues Mar 6, 3:45-4:45pm, NCSA Auditorium

Telescopes: The Story Thus Far

Telescope jobs:

1. collect/concentrate photons
2. detect photons
3. create image and/or spectrum

Research telescopes today are all **reflectors**

Q: meaning?

Q: what's the alternative?

Q: why are reflectors preferable?

Q: which is your eye?

iClicker Poll: Telescope Properties

Which of these is the most important aspect of a telescope?

A Ability to magnify small angular regions

B Ability to detect faint objects (small flux)

C Ability to see fine detail (features on small angular scales)

Telescope Power

telescope priorities and dependence on
lens/mirror diameter D ("aperture")

☆ **Light Gathering Power**

astronomical objects are **dim** $\rightarrow$ need as much light as possible
$\rightarrow$ need "photon bucket"
light gathering power $\propto$ area of lens/mirror $\propto D^2$
bigger is better!

Hubble: $D = 2.4$ m

Keck (Hawaii): $D = 10$ m $\rightarrow$ 17$\times$ the light gathering power!

- so for a fixed exposure time,
  Keck can see objects 17$\times$ fainter flux
- or to see the same level of brightness
  Keck needs to expose 17$\times$ less time

⋆ Angular Resolution

ang res = smallest angular separation distinguishable

→ sets *angular size* of *finest detail* in image

wave nature of light:

passing through finite telescope aperture (non-infinite diameter)

light rays diffract: bent

→ pointlike source image smeared into blob (Airy disk)

point spread "blob" size: smallest angular size measurable

diffraction sets unavoidable limit:

$$\theta_{\rm obs} \geq \theta_{\rm min,obs} = \theta_{\rm diff} = 1.22\frac{\lambda}{D} \qquad (1)$$

objects separated by $\theta < \theta_{\rm obs}$ smeared into one blob

Keck: $\theta_{\rm diff} = 0.01$ arc sec at 500 nm diffraction limit sets optimal telescope resolution

but: Earth *atmosphere* is turbulent – fluctuating density
$\rightarrow$ light path distorted
and distortion rapidly fluctuates
$\rightarrow$ light path rapidly fluctuates
$\rightarrow$ point sources appear to jiggle: "twinkling"
`www: twinkle animation`

twinkling further smears out point source image
$\rightarrow \theta_{\text{obs,Keck}} = \theta_{\text{atm}} \geq 1 \text{ arc sec} \gg \theta_{\text{diffract}}$
- unavoidable in ground-based observations
- better with smoother airflow ("good seeing")

Q: so obviously, the solution is?

go to space! $\longrightarrow$ HST $\theta_{\rm diff} = 0.05$ arc sec at 500 nm
this is the main motivation for Hubble Telescope!
$\longrightarrow$ unprecedented angular resolution

⋆ Magnification

only worthwhile if enough light gathering power & resolution
$\longrightarrow$ need to have a sharp image to magnify!
magnification set by focal lengths of objective (i.e., main mirror)
and eyepiece: magnification $= f_{\rm obj}/f_{\rm eye}$

Telescopes: Detectors

Once light collected, focused, need to

- detect photons
- determine λ/colors

Historical choice:

- **naked eye** – just look!

Q: Problems? other means of detection?

naked eye as photodetector

benefits:

- readily available, and cheap!

problems:

- only $\sim$ 1% of photons detected!
- can't store image
- only sensitive to small portion of EM spectrum (visible λs)

photographic film

better!

- can collect light $\longrightarrow$ see much dimmer objects
- stores image

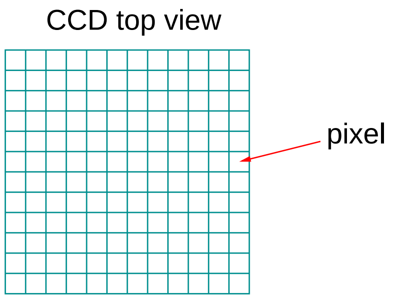
but: efficiency still small

only $\sim few$% of incoming γs registered on film

- **Charged-Coupled Device (CCD)**

same technology as digital camera, camcorder!

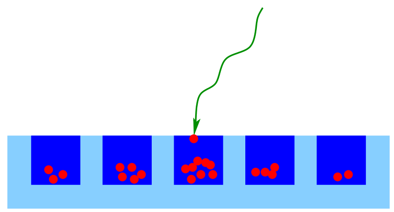
setup: silicon wafer = semiconductor
with a *grid/array* of capacitors
serve as picture elements–**pixels**



how it works:
photons → silicon → e knocked out (photoelectric effect)
charge accumulates in capacitors (e^- potential well = "bucket")
for each pixel:

$$\text{total charge} \propto \text{number of incident photons}$$

after exposure ("integration") time, read out array
charge pattern → image! and flux measurements!



CCD side view

Q: benefits of CCDs?

CCDs: The Good and the Bad

CCDs have many great features

⋆ efficiency: $> 80\%$ of incident photons detected

⋆ linearity: charge signal $\propto$ photon counts $\propto$ flux

⋆ digital data $\rightarrow$ good for computers

⋆ essentially all modern telescopes – HST, Keck – use CCDs

downside:

- expen$ive, hard to make large CCD's
- CCDs count photons but give no λ info

  Q: do we care? what's the fix?

Colors and Spectra

CCDs count photons, no λ info

but: spectral/color information is critical for astronomy
e.g., encodes temperature, composition, ...

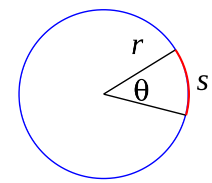
imaging
place different **filter** in front of CCD
each allowing only some wavelength range $\Delta\lambda$
can be relatively broad "passbands" or "color" `www: DECam filters`
or can focus on important lines, e.g., Balmer Hα

spectroscopy
use **grating or prism** to spread ("disperse") light by λ
then position on CCD $\leftrightarrow$ λ

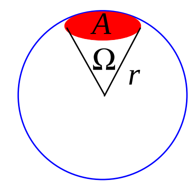
Field of View

key telescope property: *field of view*
area of sky visible in one image

Note: 2-D *areas* on sky, i.e., on celestial sphere
quantified using spherical angle technology
for sphere of radius r:



- in 1-D arc length s subtends ordinary angle $\theta = s/r$
  range $\theta \in [0, 2\pi]$ radians



- in 2-D, patch on sphere of area A subtends **solid angle**

$$\Omega = \frac{A}{r^2}$$

units: dimensionless, but 1 steradian = 1 sr = 1 radian^2
can convert to deg^2 using deg/rad ratio
range: $\Omega \in [0, 4\pi]$ sr

Q: estimate human eye field of view?

Fields of Dreams

Vote your conscience:

iClicker Poll: Rank these from *largest* to *smallest* field of view

A paper towel tube, drinking straw, Hubble telescope

B paper towel tube, Hubble telescope, drinking straw,

C Hubble telescope, paper towel tube, drinking straw

Fields of View

- naked eye: see almost a full hemisphere
  $\Omega_{\rm fov} \approx 2\pi$ steradian $= 2\pi$ rad^2

- typical modern telescopes, e.g., Hubble, Keck:
  $\Omega_{\rm fov} \approx 1$ arcmin $\times$ 1 arcmin $=$ 1 arcmin^2 much smaller than human eye

drinking straw: $\Omega_{\rm straw} \approx 1$ deg$^2 = 3600$ arcmin$^2 \approx 3600\, \Omega_{\rm scope}$!

Field of View and LSST

$\Rightarrow$ modern telescopes (so far!) have *tiny* fields of view! priority has been to deeply study small regions of sky

But a revolution is coming...

Large Synoptic Survey Telescope `www: LSST`

- site: Cerro Pachón ridge, Andes mountains, Chile
- primary mirror diameter $D = 8.4$ m: large but not unusual
- field of view $\Omega_{\rm fov} = 10 \ \rm deg^2$ **enormous!**
  requires 3.2 Gigapixel camera!
  first telescope to have such a large field of view
- Illinois is LSST member; Astronomy, Physics, NCSA involved
  computing challenge: 20 TB/night, 60 Petabytes in 10 years

Q: why is such a large field of view useful? what does this allow?

Coming Soon–Cosmic Movie & Wallpaper

thanks to large field of view
LSST can **scan entire night sky** in a few days!
and then **repeat** this scan for ≈ 10 years

result: ≈ 1000 deep digital images of *every point* on the southern celestial sphere, spanning 10 years!

Strategy: *compare* images of *same* region

- some things won't show any change *Q: like?*
  add exposures to get *very* deep images
  "The Sky: The Wallpaper"
- other things *will* show change! *Q: like?*
  subtract exposures to find & monitor changes
  $\rightarrow$ reveal celestial variability over timescales $\sim$hours to years
  "The Sky: The Movie"
  $\Rightarrow$ this has never been done on such a huge scale!