Physics 134

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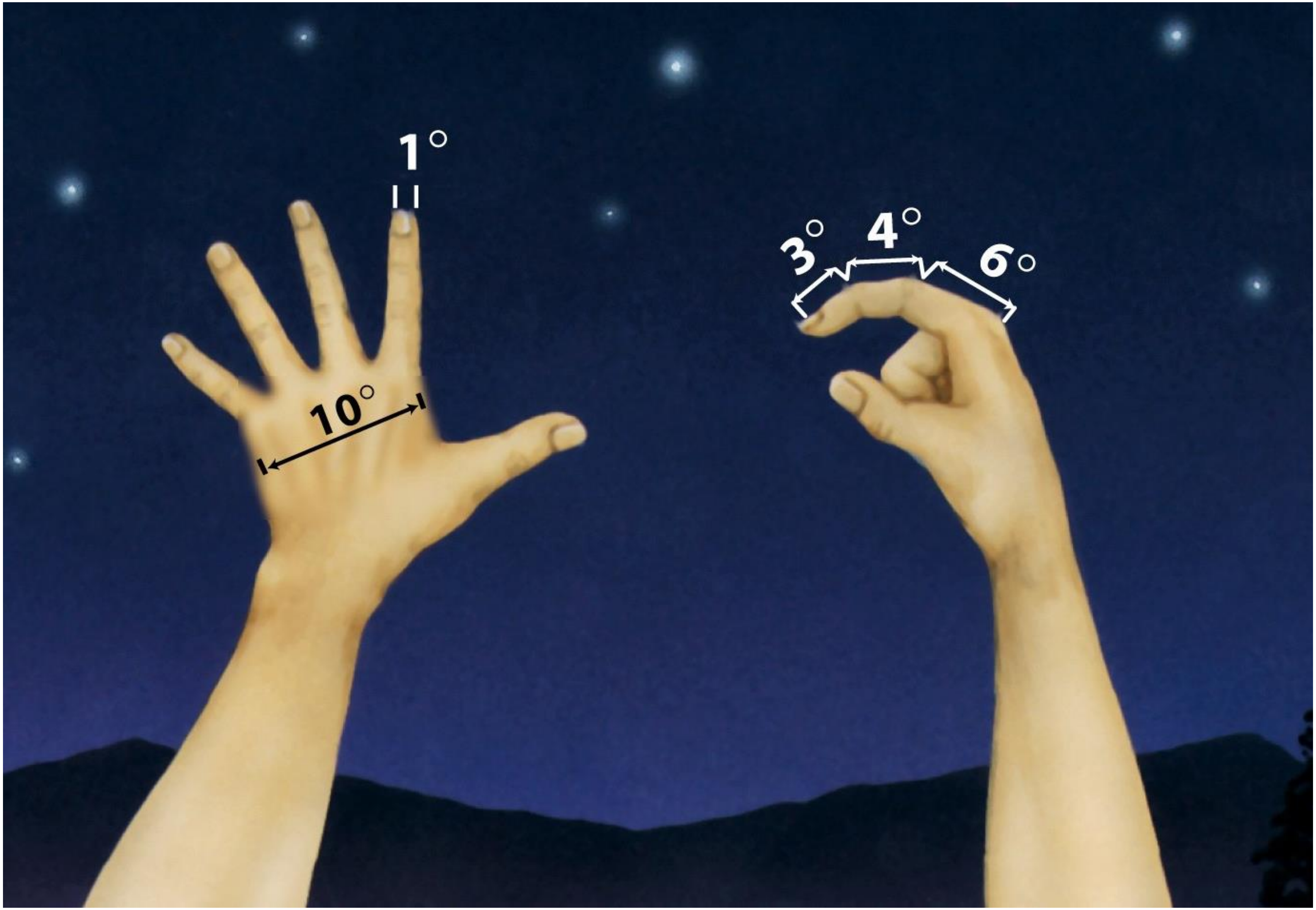
Introduction Lecture 2

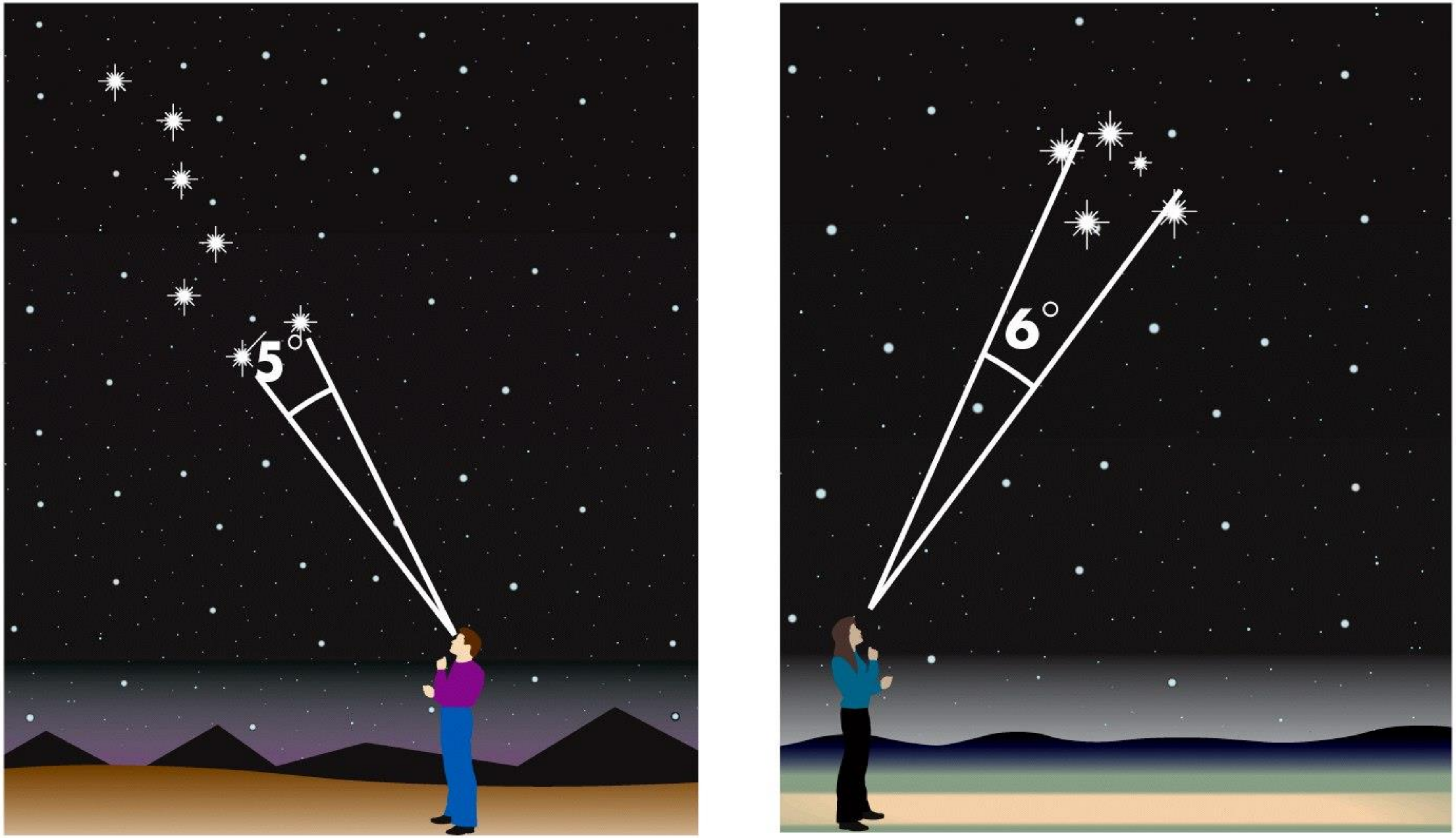
Angular Measurements

- 360 degrees (360^o) in full circle
- 2π radians = 360 degrees
- 1 degree = $2\pi/360=0.01745$ radians (rad)
- 1 rad = $360/ 2\pi=57.296$ degrees
- 1 rad = 206,265 arc sec
- Subdivide one degree into 60 **arcminutes**
  - minutes of arc
  - abbreviated as 60 arcmin or 60´ ***<u>(NOT feet)</u>***
- Subdivide one arcminute into 60 **arcseconds (arc sec)**
- **1 degree = 60*60=3600 arc sec**
  - seconds of arc
  - abbreviated 60 arcsec or 60” ***<u>(NOT inches)</u>***

1° = 60 arcmin = 60´

1´ = 60 arcsec = 60”

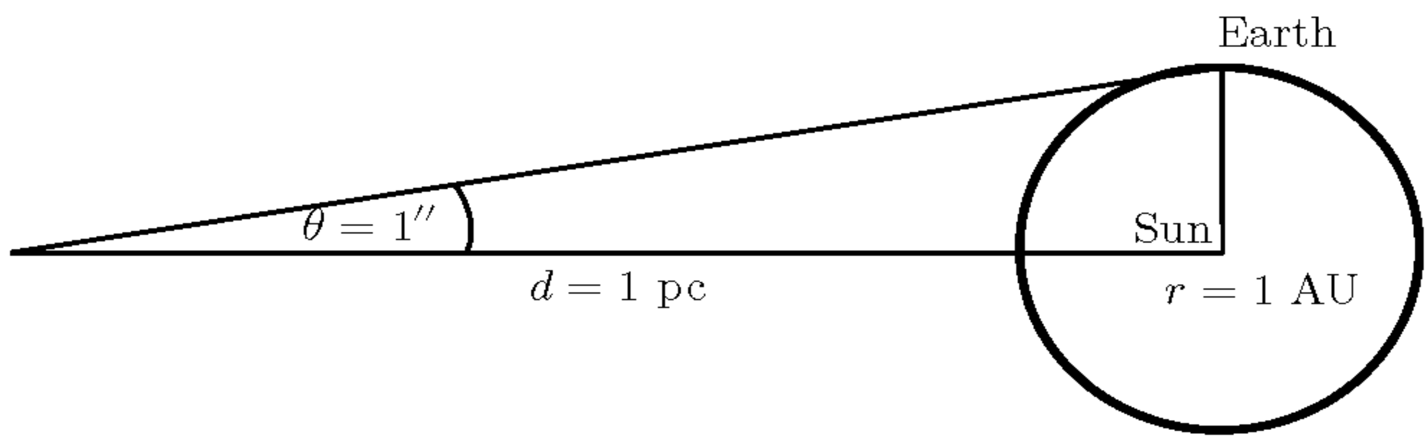

1°
10°
3°
4°
6°


5°
6°

Astronomical distances are often measured in astronomical units, parsecs, or light-years

- **Astronomical Unit (AU)**
  - One AU is the average distance between Earth and the Sun
  - 1.496×10^8 km or 92.96 million miles
- **Light Year (ly)**
  - One ly is the distance light can travel in one year at a speed of about 3×10^5 km/s or 186,000 miles/s
  - 9.46×10^{12} km or 63,240 AU
- **Parsec (pc)**
  - the distance at which 1 AU subtends an angle of 1 arcsec or the distance from which Earth would appear to be one arcsecond from the Sun
  - 1 pc = 3.09×10^{13} km = 3.26 ly

How a Parsec (pc) is Defined
1 pc ~ 3.26 ly



Distances to Objects

Distance	Comments
1.3 pc	Closest Star (α Centauri – Proxima is closest)
1.3 light seconds	Earth to Moon
8 light minutes	Earth to Sun
5 light hours	Pluto
4.2 ly	Closest Star
2.5×10^{4} ly	To Galactic Center
10^{5} ly	Galactic Diameter
2×10^{6} ly	Andromeda (M31)
10^{10} ly	Most distant observed galaxy
2×10^{10} ly	Size of Universe

LCO World Wide Sites

https://lco.global/observatory/sites/

LCO sites

	Elevation (m)	Code	Timezone	Status
Siding Spring Observatory 31° 16′ 23.88″S 149° 4′ 15.6″E	1,116	COJ	UTC+10	1 x 2-meter (#02) 2 x 1-meter (#11,#03) 2 x 0.4-meter (#03,#05)
South African Astronomical Observatory 32° 22′ 48″S 20° 48′ 36″E	1,460	CPT	UTC+2	3 x 1-meter (#10,#13,#12) 1 x 0.4-meter (#07)
Teide Observatory 28° 18′ 00″N 16° 30′ 35″W	2,330	TFN	UTC	2 x 0.4-meter (#14,#10) 2 x 1-meter (coming online 2021)
Cerro Tololo Interamerican Observatory 30° 10′ 2.64″S 70° 48′ 17.28″W	2,198	LSC	UTC-3	3 x 1-meter (#05,#09,#04) 2 x 0.4-meter (#09,#12)
McDonald Observatory 30° 40′ 12″N 104° 1′ 12″W	2,070	ELP	UTC-6	2 x 1-meter (#08,#06) 1 x 0.4-meter (#11)
Haleakala Observatory 20° 42′ 27″N 156° 15′ 21.6″W	3,055	OGG	UTC-10	1 x 2-meter (#01) 2 x 0.4-meter (#06,#04)
Wise Observatory 30° 35′ 45″ N 34° 45′ 48″E	875	TLV	UTC+2	1 x 1-meter
Ali Observatory 32° 19′ N 80° 1′E	5,100	NGQ	UTC+8	Under construction

LCO 0.4m Telescopes

In “dome” and in Chile

https://lco.global/observatory/telescopes/04m/

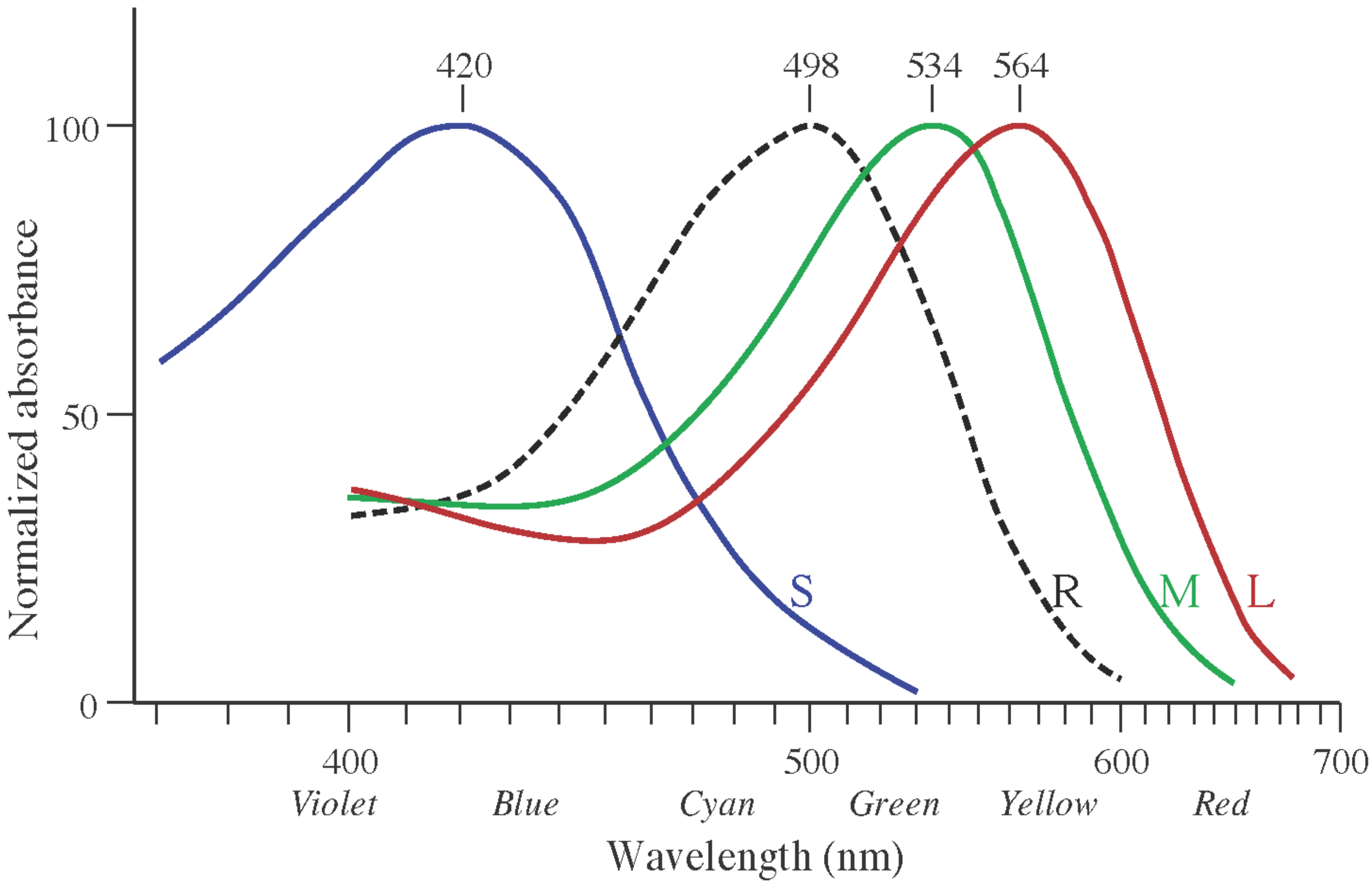
Some LCO Telescope Sites

UL: 2m Haleakala HI, UR: 2m Siding Springs AU LL: Siding Springs complex LR: Sedgwick CA

LCO Resources
lco.global

- Instruments
  - lco.global/observatory/instruments/
- Exposure and SNR Calculator
  - exposure-time-calculator.lco.global/
- Filters
  - lco.global/observatory/instruments/filters/
- BANZAI - Data Processing Pipeline
  - lco.global/documentation/data/BANZAIpipeline/
- Recent Science and Educational Research
  - //lco.global/highlights/
- Spacebook – Learn Astronomy
  - https://lco.global/spacebook/

Human Eye Response



Magnitudes – to describe "brightness"

- Magnitudes need to be specified at a wavelength
- m_v is "visible" band - eye peak about 550nm)
- m=Apparent magnitude (as we measure)
- M=Absolute magnitude (as though obect were a point source at d=10 pc
- Defined based on historical human perception
  - Larger m is dimmer
  - Log scale – 5 mag =100x brightness
  - m=15 is 100x dimmer than m=10)

$$m_2 - m_1 = 2.5\log\frac{b_1}{b_2}$$

$$M - m = 2.5\log\left(\frac{10\text{ pc}}{d}\right)^2 = 5\log\frac{10\text{ pc}}{d} = 5\log 10 - 5\log d = 5 - 5\log d$$

Magnitudes and Flux

Brightest Star (Sirius A ~ m_V=-1.46)
Unaided human eye can see down to about m=6
Assuming a clear dark sky (not SB)

Magnitude	Flux (photons $\text{cm}^{-2}\ \text{s}^{-1}$)	Eye (photons/s)	Palomar (photons/s)
0	3×10^{6}	10^{6}	6×10^{11}
5	3×10^{4}	10^{4}	6×10^{9}
10	300	100	6×10^{7}
15	3	1	6×10^{5}
20	0.03	10^{-2}	6×10^{3}
25	3×10^{-4}	10^{-4}	60
30	3×10^{-6}	10^{-6}	0.6

$$F(m=0) = 1\times10^{-5}\ \text{erg cm}^{-2}\ \text{s}^{-1} \times \frac{1\text{photon}}{3.6\times10^{-12}\ \text{erg}} \approx 3\times10^{6}\ \text{photons cm}^{-2}\ \text{s}^{-1}$$

$$m_2 - m_1 = 2.5\log\frac{b_1}{b_2}$$

Imaging Sensor Parameters & SNR

Typical device is cooled CCD or CMOS – LCO uses CCD's

Symbol	Quantity (units)
N_R	Readout Noise (e^-)
i_{DC}	Dark Current (e^- / s)
Q_e	Quantum efficiency (dimensionless)
F	Point Source Signal Flux on Telescope (photon $\mathrm{s}^{-1}\ \mathrm{cm}^{-2}$)
F_β	Background Flux from Sky (photons $\mathrm{s}^{-1}\mathrm{cm}^{-2}\ \mathrm{arcsec}^{-2}$)
Ω	Pixel Size (arcsec) (assuming greater than seeing)
ε	Telescope Efficiency (dimensionless)
τ	Integration Time (s)
A	Telescope Area (cm^2)

- Signal from Source $S = F\tau A\varepsilon Q_e$
- Dark current in detector $S_{DC} = i_{DC}\tau$
- Background signal $S_\beta = F_\beta A\varepsilon Q_e \Omega\tau$

Noise and Signal

- Time dependent signal term $S_{\text{time}} = S + S_{DC} + S_\beta$
- Assume all of these terms are uncorrelated
- Error in terms $N_S = \sqrt{S}$ $N_{DC} = \sqrt{S_{DC}}$ $N_\beta = \sqrt{S_\beta}$
- Uncorrelated errors add in quadrature

$$N_{\text{time}} = \sqrt{N_S^2 + N_{DC}^2 + N_\beta^2} = \sqrt{S + S_{DC} + S_\beta} = \sqrt{F\tau A\varepsilon Q_e + i_{DC}\tau + F_\beta A\varepsilon Q_e \Omega\tau}$$

- Detector Read noise NOT integration dependent

$$N_{\text{tot}} = \sqrt{N_R^2 + N_{\text{time}}^2} = \left(N_R^2 + \tau(i_{DC} + F_\beta A\varepsilon Q_e \Omega)\right)^{1/2}$$

- Define "effective area" $A_\varepsilon = A\varepsilon Q_e$
- Total noise per unit time $N_T = FA_\varepsilon + i_{DC} + F_\beta A_\varepsilon \Omega$

Signal to Noise Ratio (SNR)

$$\frac{S}{N} = \frac{FA_{\varepsilon}\sqrt{\tau}}{\left[\frac{N_R^2}{\tau} + FA_{\varepsilon} + i_{DC} + F_{\beta}A_{\varepsilon}\Omega\right]^{1/2}} = \frac{FA_{\varepsilon}\sqrt{\tau}}{\left[\frac{N_R^2}{\tau} + N_T\right]^{1/2}} = \frac{FA_{\varepsilon}\tau}{\left[N_R^2 + \tau N_T\right]^{1/2}}.$$

$$N_T = FA_{\varepsilon} + i_{DC} + F_{\beta}A_{\varepsilon}\Omega \qquad A_{\varepsilon} = A\varepsilon Q_e$$

Integration Time to Obtain Desired SNR (S_N)

$$S_N \equiv S / N = F A_\varepsilon \tau / \left[N_R^2 + \tau N_T \right]^{1/2}$$

$$\tau = \frac{S_N^2 N_T \pm \sqrt{S_N^4 N_T^2 + F^2 A_\varepsilon^2 S_N^2 N_R^2}}{2F^2 A_\varepsilon^2}$$

$$= \frac{S_N^2 N_T}{2F^2 A_\varepsilon}\left[1 + \sqrt{1 + \frac{4F^2 A_\varepsilon^2 N_R^2}{S_N^2 N_T^2}} \right]$$

Example (20 magnitude object)

$N_R = 12$

$i_{DC} = 1\, e^- \ \mathrm{s}^{-1}\ \mathrm{pixel}^{-1}$ at $35^\circ \mathrm{C}$

$Q_e = 0.3$

$A = 10^3$

$\varepsilon = 0.5$

$F_\beta = 10^{-2}$ photons s^{-1} cm^{-2} arcsec^{-2} (ideal sky)

$\Omega = 4\ \mathrm{arcsec}^2$

$F = 0.03$ photons s^{-1} cm^{-2} (20th magnitude)

Integration Time (sec)	SNR ($F_\beta = 10^{-2}$)	SNR ($F_\beta = 0.1$)
1	0.4	0.3
10	2.8	1.6
100	13	5.5
1000	42	18

Aperture Photometry

Removing sky from source

Symbol	Meaning
N_{IA}	Number of pixels in inner aperture
N_{OA}	Number of pixels in outer aperture
$G(j,k)$	Pre-flat-fielded image array
R	A/D counts per e^-
$N(j,k)$	$G(j,k)/R$, the pixel value in e^-