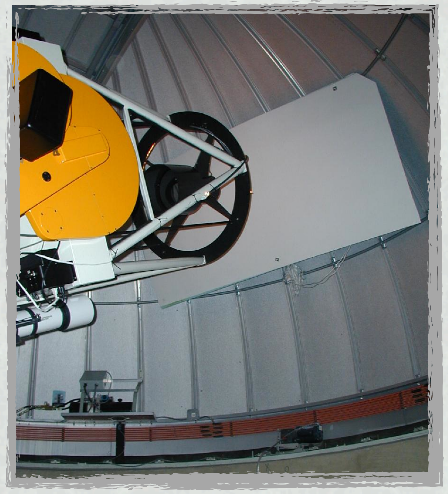
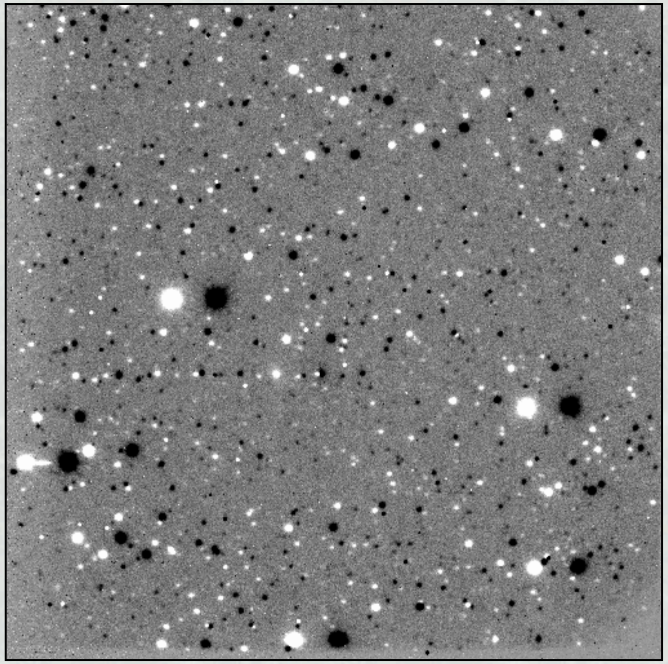
Observational Astronomy & Data Reduction

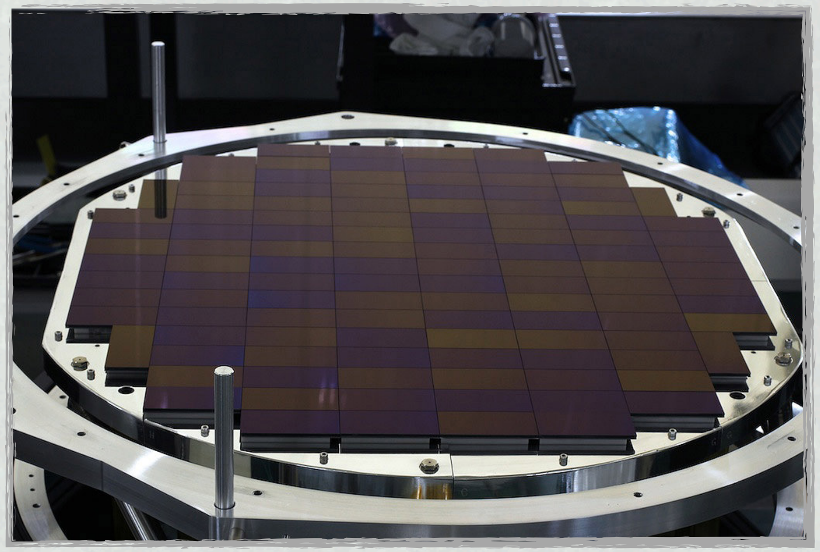


Lecture 2:

Detectors

Sources of Noise





Karín Menéndez-Delmestre

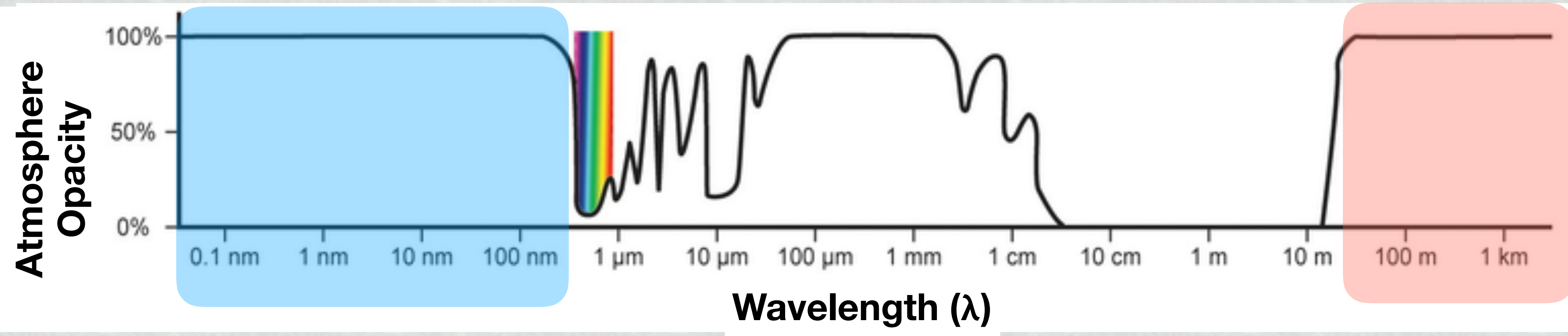
Observatório do Valongo

Earth's atmosphere — an opaque medium

- Opaque towards the bulk of the electromagnetic spectrum:
  - Blocks high-energy photons (UV, X-rays, γ-rays) and partially blocks infrared and mm.

  - **Reflection**: the highest layers in the atmosphere (ionosphere) reflect radio waves with $\lambda \geq 23.5$ m

  - **Continuum absorption** due to ionization or photo-dissociation
    - absorption of all energies higher than that necessary to ionize atoms and/or dissociate molecules
    - Oxygen and nitrogen absorb all photons with $\lambda \leq 290$ nm



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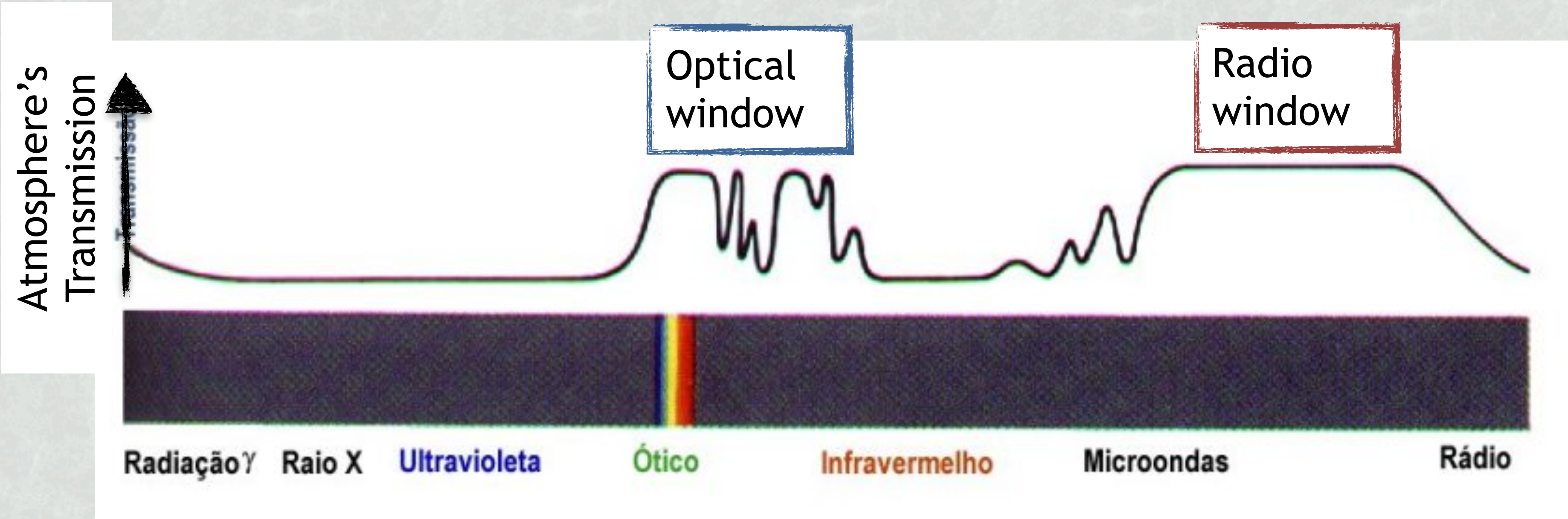
  - **Continuum absorption** due to ionization or photo-dissociation
    - absorption of all energies higher than that necessary to ionize atoms and/or dissociate molecules
    - Oxygen and nitrogen absorb all photons with $\lambda \leq 290$ nm
  - Absorption of particular frequencies - **lines** or bands - results from the **excitation of atoms and molecules**

Earth's atmosphere — optical & radio windows

- The atmosphere is transparent merely in a few wavelength ranges:
  - Radio window: radio/mm/submm
  - Optical window: including near-IR (J, H, K bands)



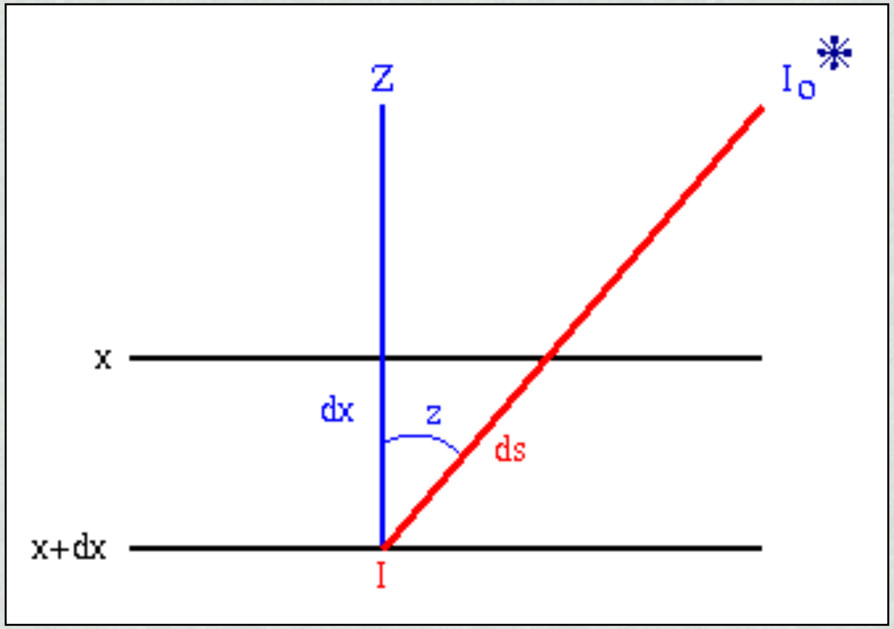
Airmass

- We can describe the flux received from a source, as it passes through an absorbing medium as:

$$I_{obs} = I_0 \, e^{-\tau}$$

  - τ: optical thickness of the intervening medium (how opaque, how transparent)
  - I_0: flux from source with no intervening medium

- Considering the atmosphere as such an intervening medium, we can express τ as a function of the angular distance from the zenith:



http://astro.if.ufrgs.br/rad/rad/

From figure:

cos (z) ds = dx
ds/dx = 1/cos (z)

airmass: sec (z)

$$\tau = \tau_0 \sec(z)$$

= a geometrical effect

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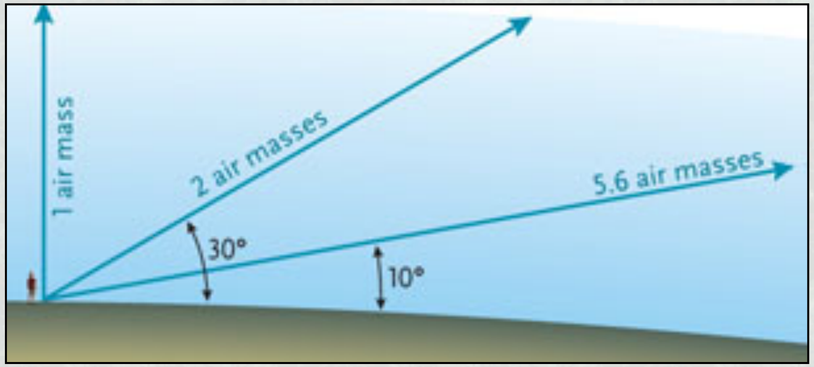
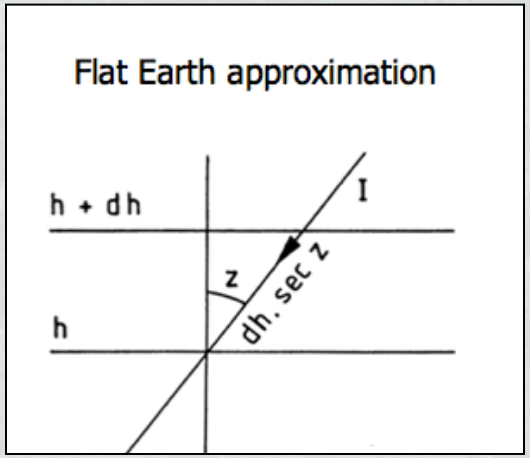
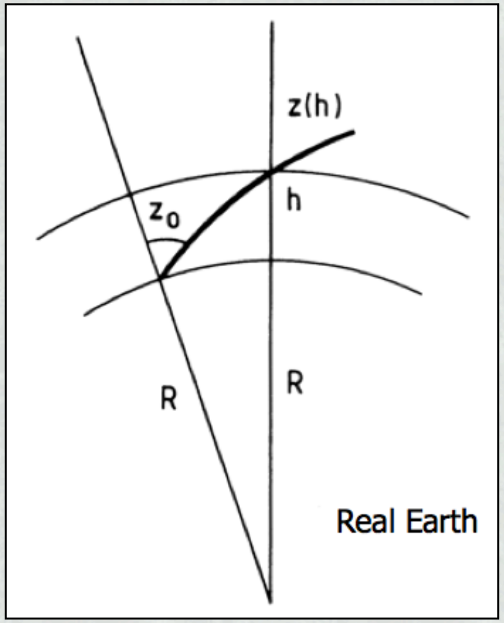
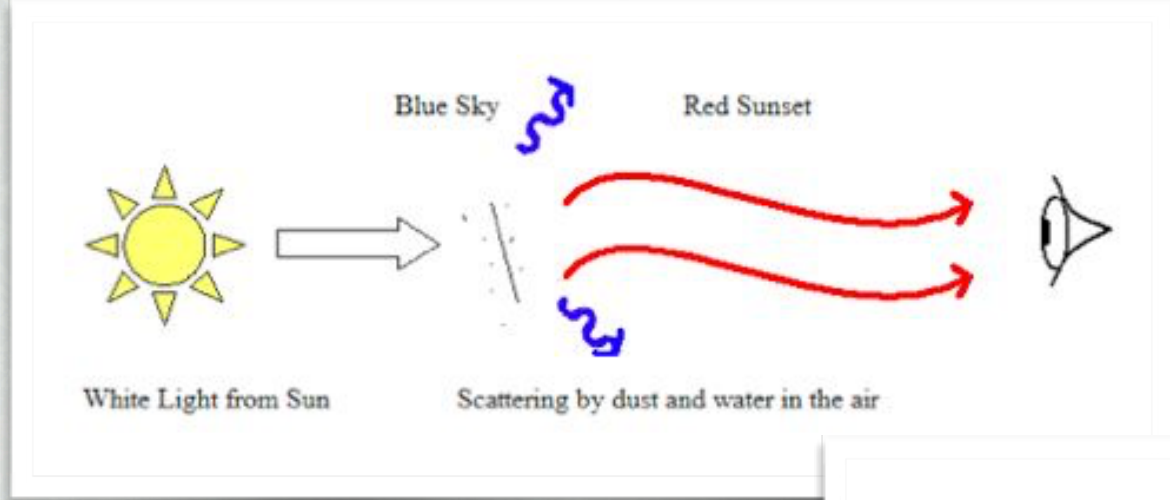






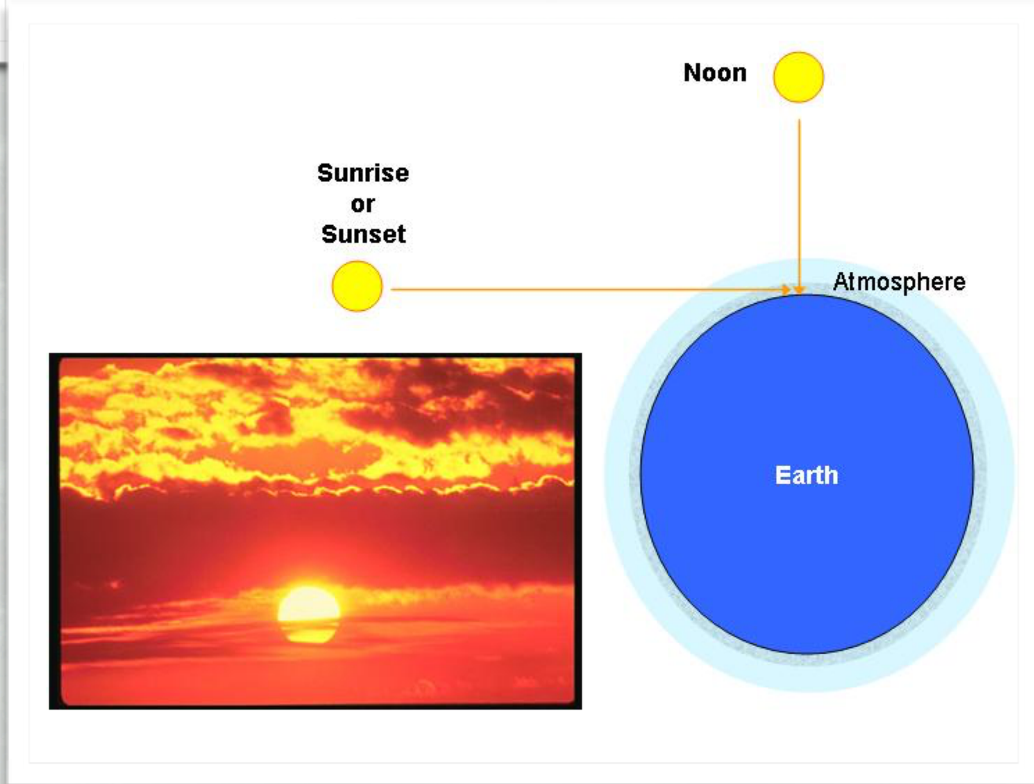
http://www.skyandtelescope.com/howto/visualobserving/19712459.html

Airmass — impact on measured magnitude



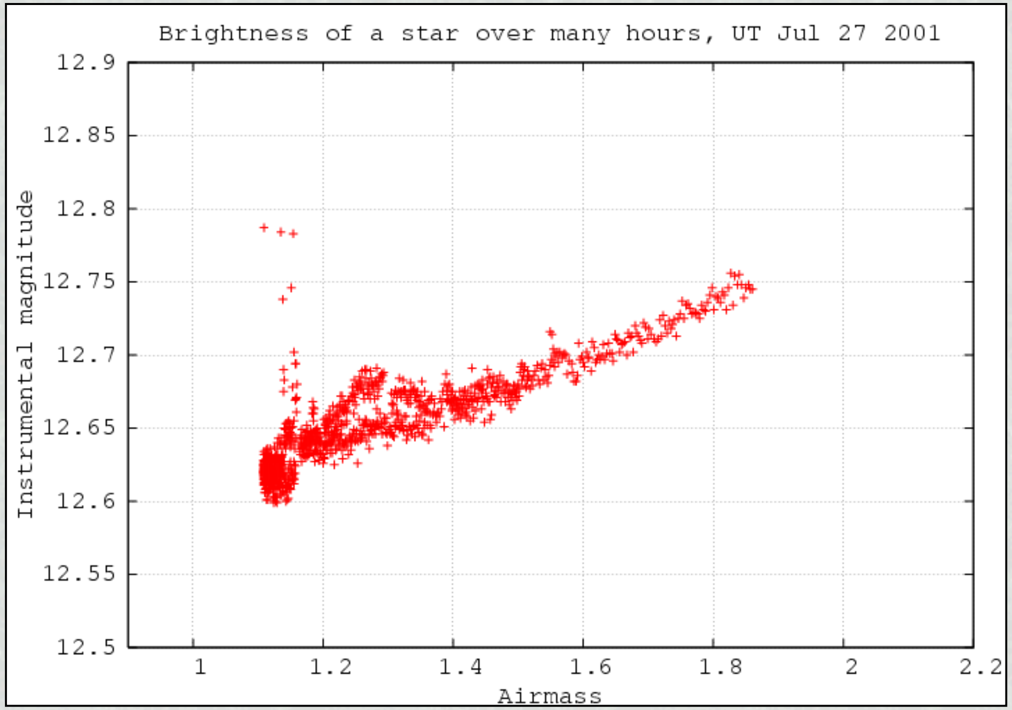
The closer to the horizon, the more the magnitude is affected. This is also why we can stare directly at the Sun when it is very close to the horizon!

Red sunsets!



Airmass — impact on measured magnitude

Observed magnitude in a period of a few hours as object sets (i.e., airmass varies)



http://spiff.rit.edu/classes/phys445/lectures/atmos/atmos.html

- The atmosphere affects observed magnitudes: $m(X) = m_0 + K X$

  K = extinction coefficient: $K = 1.086\,\tau_0$

  X = airmass (i.e, sec z)

  m_0: magnitude outside atmosphere

- *K* depends on λ:
  - Effect is smaller in redder bands

passband	k
U	0.6
B	0.4
V	0.2
R	0.1
I	0.08

http://spiff.rit.edu/classes/phys445/lectures/atmos/atmos.html

Airmass — what's ok and what's not

- The ideal moment to observe a celestial body is when it is the closest to the zenith —> lowest airmass
- In the **optical**, the (typical) accepted **airmass** is **< 1.5**

altitude~40°

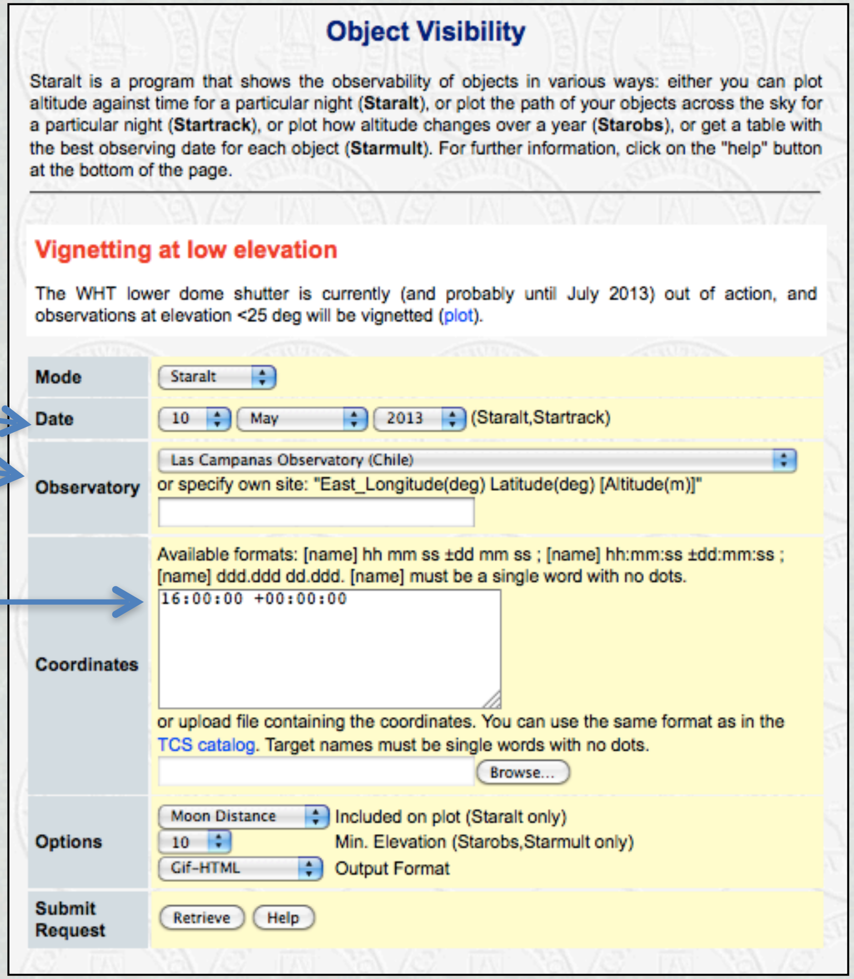
- **near-IR**: **airmass < 2.0** → Subjetive!

altitude~30°

—> bluer bands are more severely affected by higher values of airmass

Airmass — Prepare for your observing run!

- As part of the pre-observing preparation, need to consider at which times the airmass will be sufficiently low for effective observing of the science target.
- Airmass tables:
    - Visibility based on:
        - Date
        - Telescope location (longitute, latitude)
        - RA/DEC of target



StarAlt:
http://catserver.ing.iac.es/staralt/

Other options available:
http://www.briancasey.org/artifacts/astro/airmass.cgi

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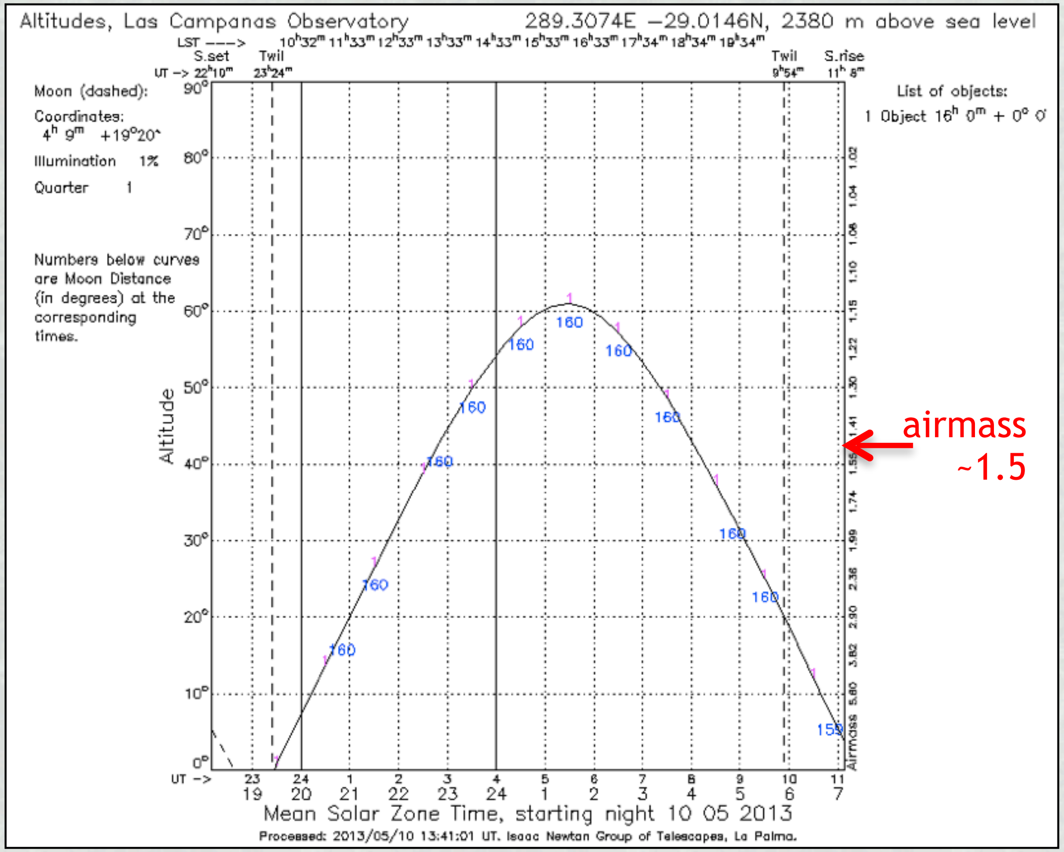

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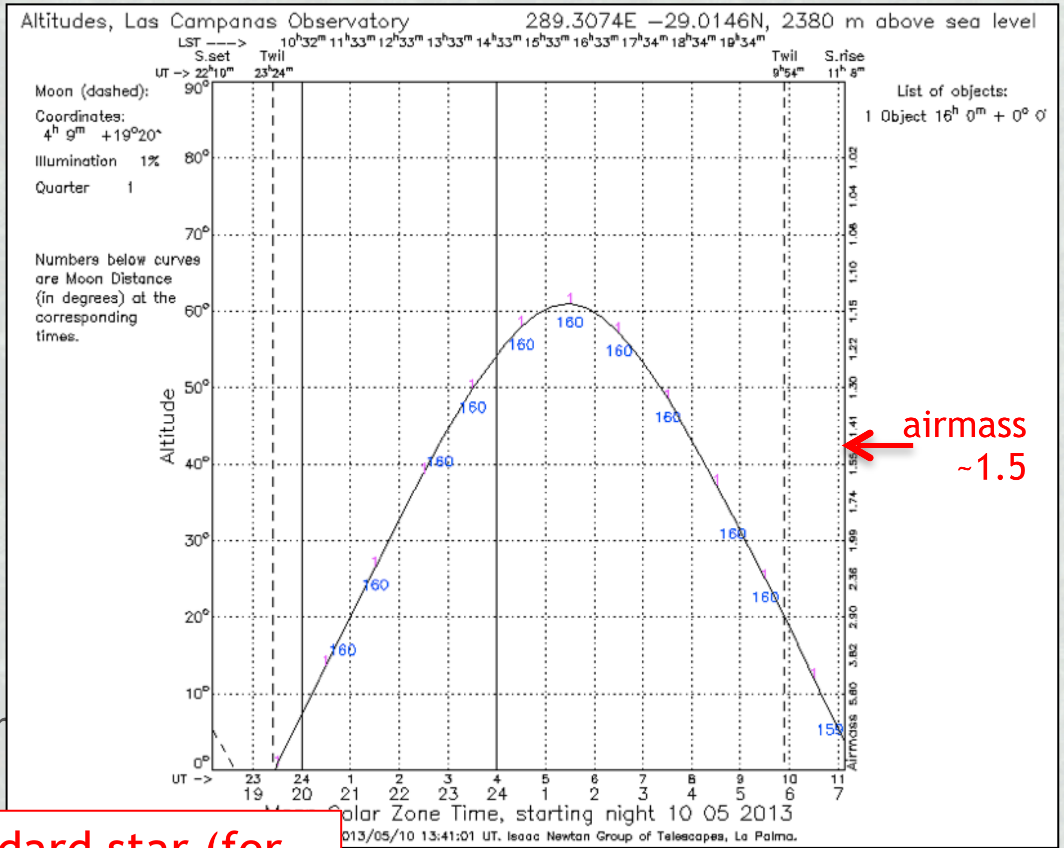
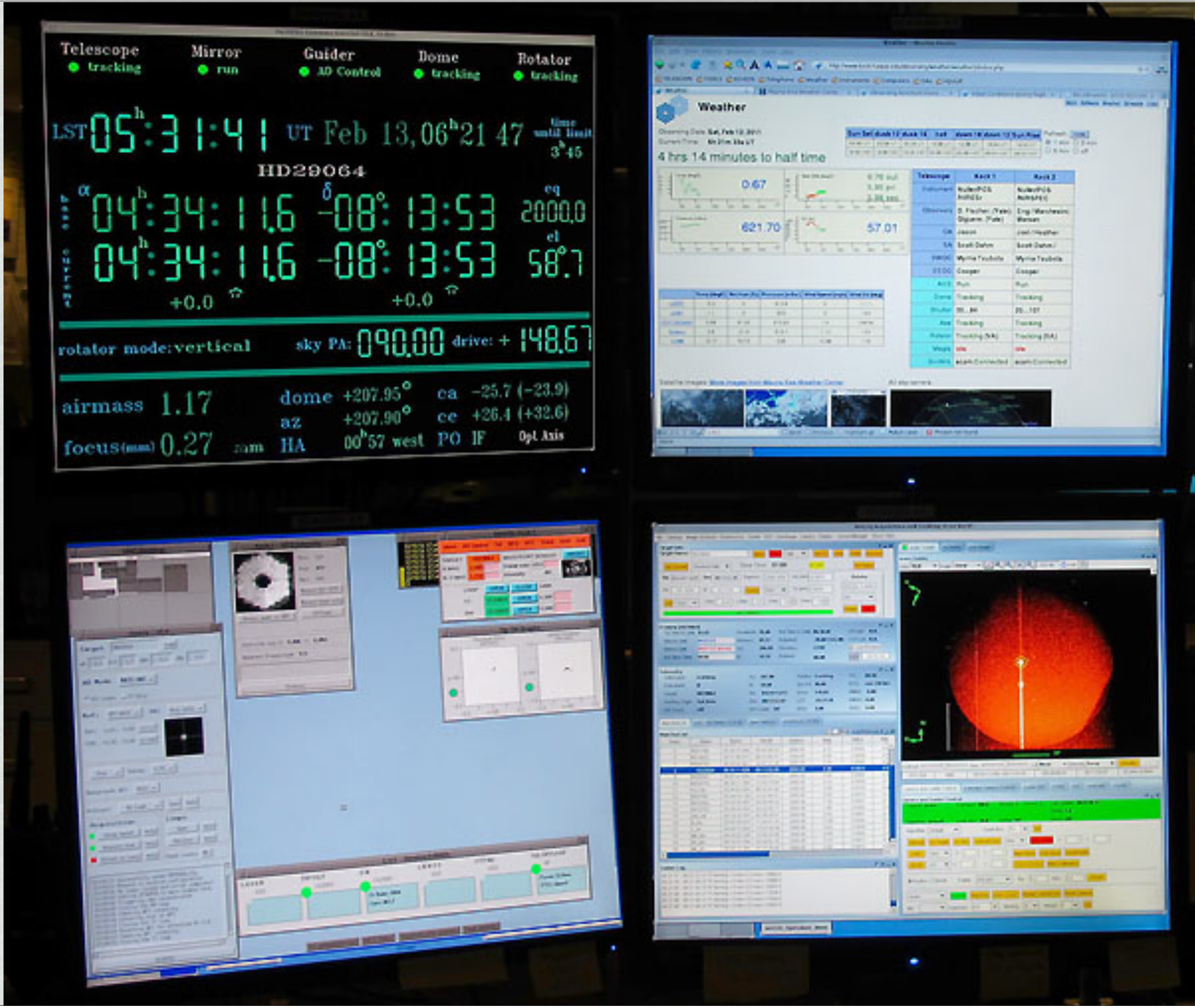


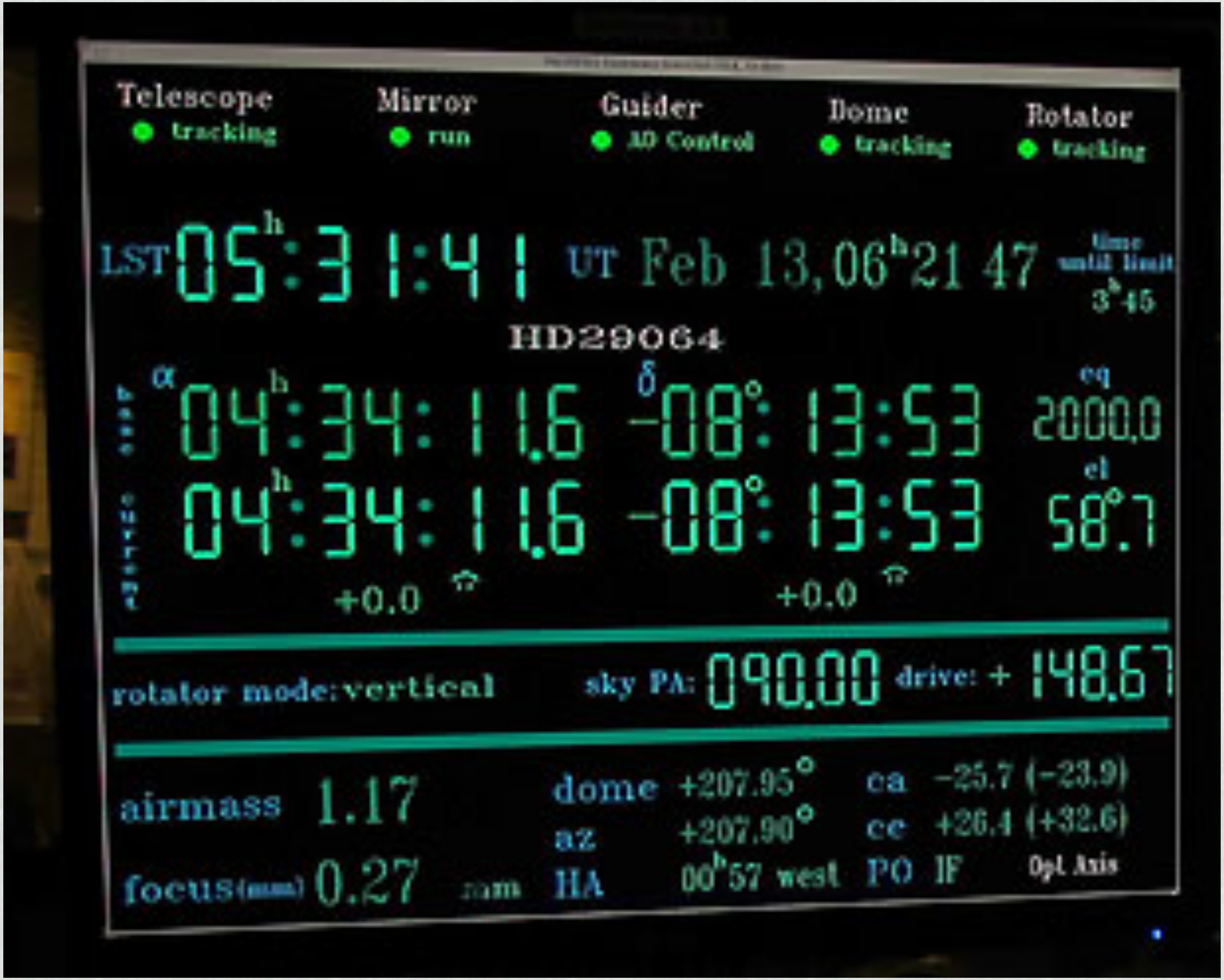
airmass ~1.5

StarAlt:
http://catserver.ing.iac.es/star

Note: Important to consider a standard star (for post-observing flux calibration) observed at a similar airmass as science target.

http://darkerview.com/darkview/index.php?/categories/34-Working-on-the-Mountain/P2.html


Telescope
tracking
Mirror
run
Guider
AO Control
Dome
tracking
Rotator
tracking
LST 05h:31:41 UT Feb 13, 06h21 47
time until limit 3h45
HD29064
α 04h:34:11.6 δ -08°:13:53 eq 2000.0
04h:34:11.6 -08°:13:53 el 58°7
+0.0
+0.0
rotator mode:vertical
sky PA: 090.00 drive: + 148.67
airmass 1.17
dome +207.95° ca -25.7 (-23.9)
az +207.90° ce +26.4 (+32.6)
focus(mm) 0.27
HA 00h57 west PO IF Opt Axis
Weather
4 hrs 14 minutes to half time
0.67
621.70
57.01



Telescope
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HA 00h57 west
PO IF
Opt Axis

Question #1

- What object is the telescope pointing to at the time when the image was taken? (i.e., what are the coordinates?)
  – At what airmass?
- What's the hour angle?
  - Has it gone past the local meridian?
- What are the right ascension (RA) coordinates that correspond to an object directly at the local zenith?

Detection

- Detectors do not generate a "real" image *per se*; they *sample* the image
- "Detection" means that the electromagnetic energy of the radiation is converted/transformed into a different form.
  - Typically electrons → photoelectric effect!

<u>Photoelectric effect</u>

- Most detectors used in astronomy rely on this effect.
- Photons with sufficiently energy will free electrons as they hit the surface of a material: photoelectrons.

Detectors — a bit of history

Human eye

- First and only detector until 19th century
- Low collecting capacity:
  - Aperture ~7mm
  - Compare to Keck telescope(10m), the human eye has very small collecting capacity!

$$A_{Keck} / A_{olho} / \sim [10 / (7 \times 10^{-3})]^2 \sim 10^6$$

- Does not allow for the storage of information
  - Drawings and hand-written annotations (e.g., Galileo)
- The eye does not allow for long integrations

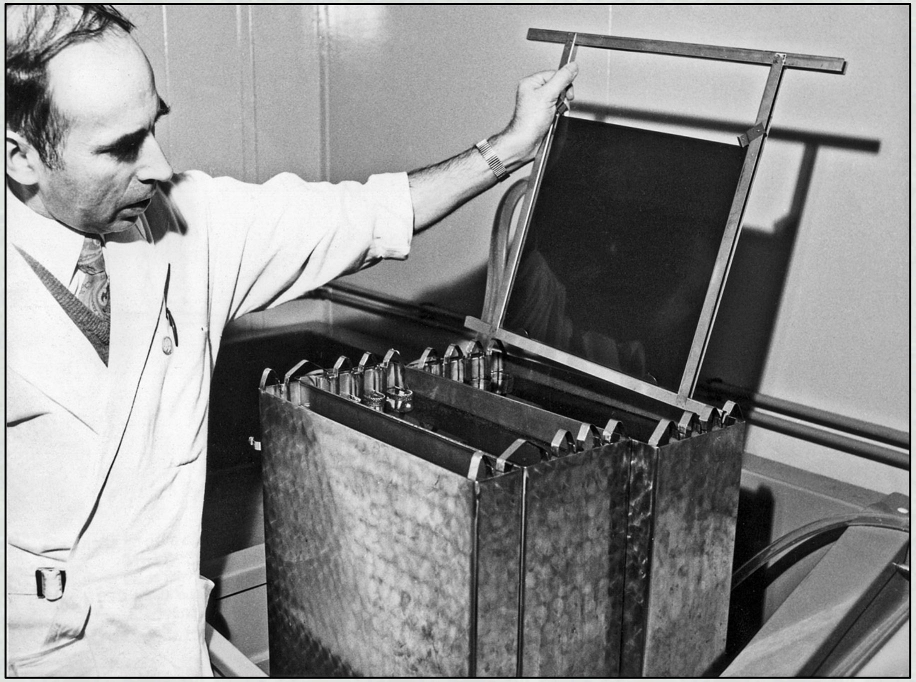
Detectors — a bit of history

Photographic plates

- They appear on 2nd half of 19th century
- Detection based on a photochemical process

Advantages:

- The density and quantity of information is very high in a photographic plates.
  - Pixels are very small (size of crystals ~0,5μm compared to 10μm in a CCD)
  - Large field of view (physical size of ~50cm compared to the few cm of a CCD



http://www.eso.org/public/images/ehpa-8-015/

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Disadvantages:

- sensitivity is limited and non-linear (depends on the exposure time)
- the chemical processing of the photographic plates is complex and with many possibilities of introducing errors.

Detectors — CCDs rule!

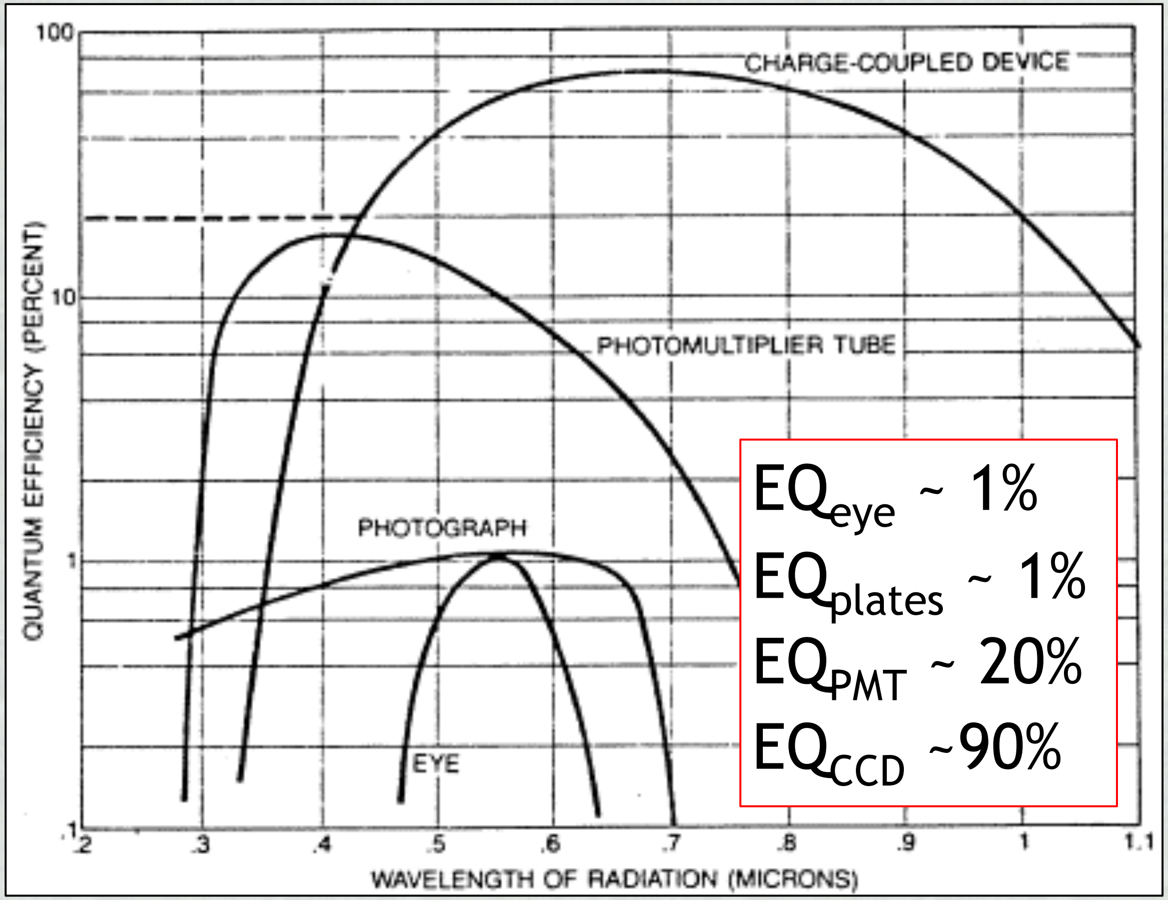
- In the last 20-30 years there has been a transformation in the technology of optical/near-IR astronomical detectors - the CCDs have become the main players

- <u>Sensitivity</u>

– *Quantum efficiency:* Ratio of (number of photons detected) to (number of incident photons)

– High sensitivity → high quantum efficiency

– Quantum efficiency is a function of wavelength



EQ_{eye} ~ 1%

EQ_{plates} ~ 1%

EQ_{PMT} ~ 20%

EQ_{CCD} ~90%

http://www.physics.uc.edu/~sitko/AdvancedAstro/3-Brightness/Brightness.

Coupled Charge Devices (CCD)

- CCDs are integrated circuits, based on silicon
- Physical principle of detection:
  - photoelectrons are freed in silicon semiconductors
  - This generates an electric current that can be quantified with an analog-digital converter (ADC)
    - Counts = ADU = DN

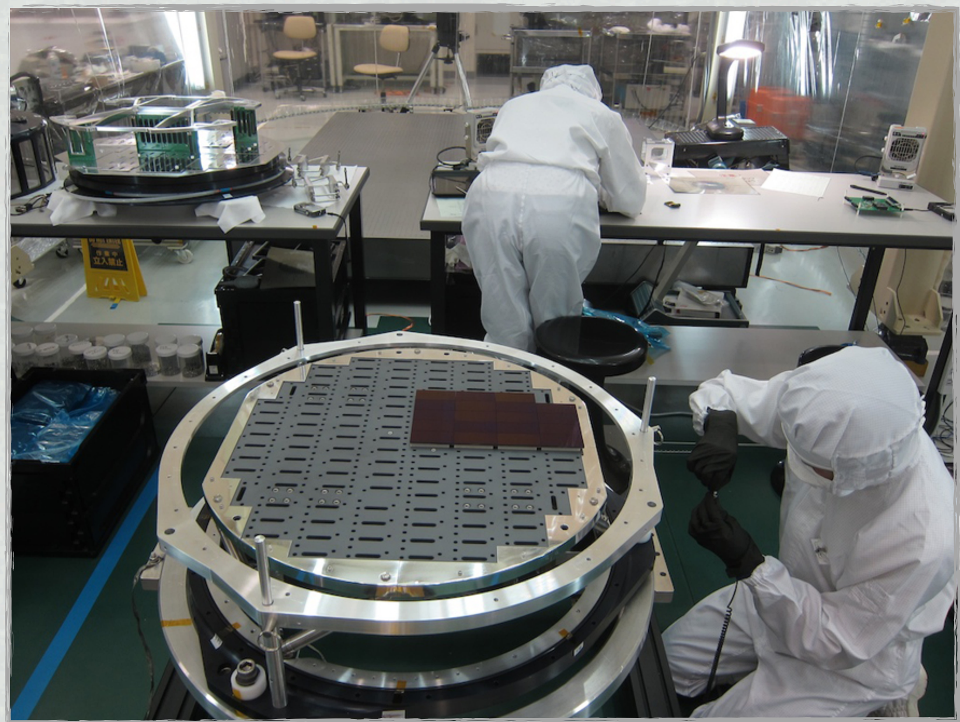
Analog-to-Digital Unit | Digital Number

- DN is not a fundamental unit, the # electrons is!
- the gain (e^-/DN) is defined by the electronics.

Coupled Charge Devices (CCD) — pros & cons

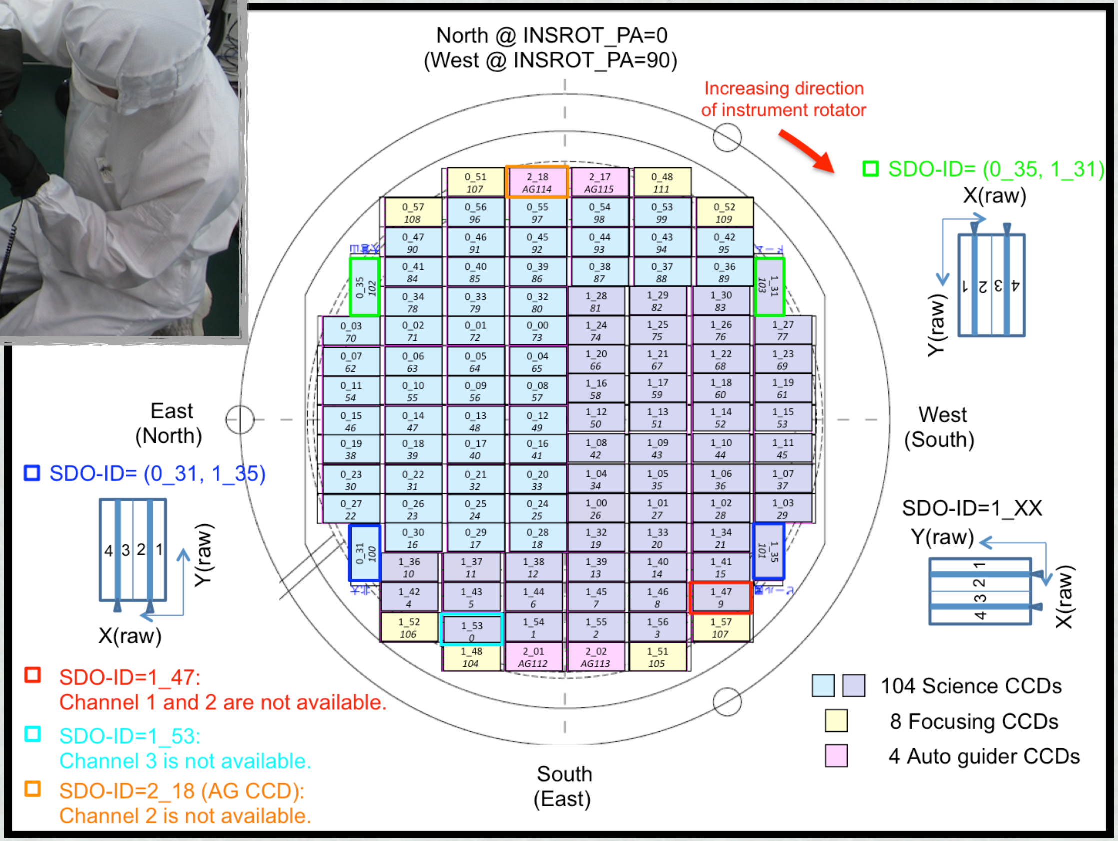
- Advantages:
  - High sensitivity (i.e., quantum efficiency)
  - Low noise
  - Linearity
  - Good dynamical range (storage capacity of 30k to 300k electrons/pixel)
  - Easy storage
  - Broad spectral coverage
- Disadvantages:
  - Expensive → hence, small!
  - Relatively small FOVs
    - Situation has greatly improved with recent development of large format CCDs.
    - State of the art sizes now surpass 4096^2 pixeis!

CCDs – large format CCDs



Subaru Telescope:
Hyper Suprime Cam

116 CCDs: 104 for science
– rest for focusing and auto guider



Sizes:

2048 × 4176 pix per one CCD
Full FOV: 90 arcmin (diameter)

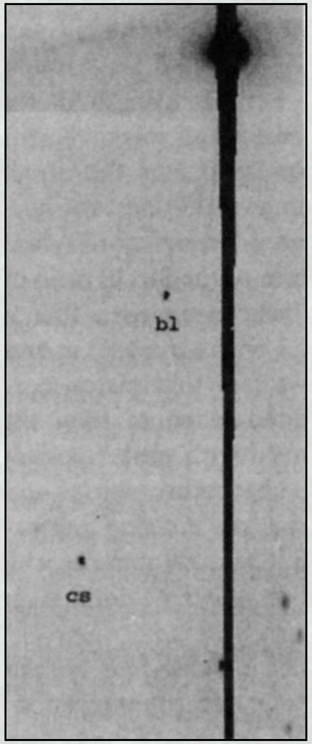
CCDs — how they work

- Charges produced in a given region of the semi-conductor stay confined through the integration
  - Lines on a CCD are separated by isolating material

    → Photons incident on a line will produce electrons that will stay “imprisoned” in this line.

“bleeding”:

- Saturation can affect pixels on the same column



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  - Lines on a CCD are separated by isolating material
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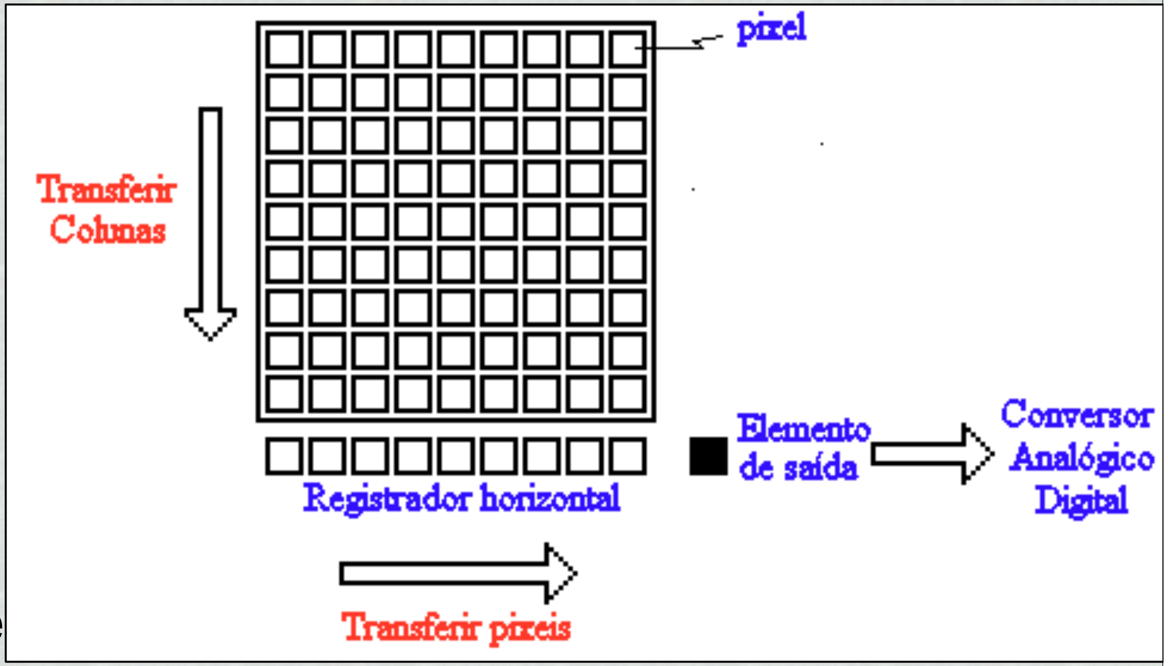
  - To restrict electrons along the column direction, potential differences are adjusted by adjacent electrodes.
    - → Photoelectrons are thus kept within their pixels and thus accumulate through the exposure
    - → Individual pixels represent potential wells were electrons are accumulated.

CCDs – reading out the image

- Reading out:
  - Once the integration is completed, charges are transported (via adjustments in the voltage):

(1) First transferred along each column to the horizontal register;
(2) Then transferred to the exit element, sequentially;
(3) Afterwards, the electric current passes through an analog-digital converter (ADC) and the image is digitalized.



http://astro.if.ufrgs.br/rad/ccd/

CCDs — reading out the image

- Reading out:
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Think of it as little buckets!

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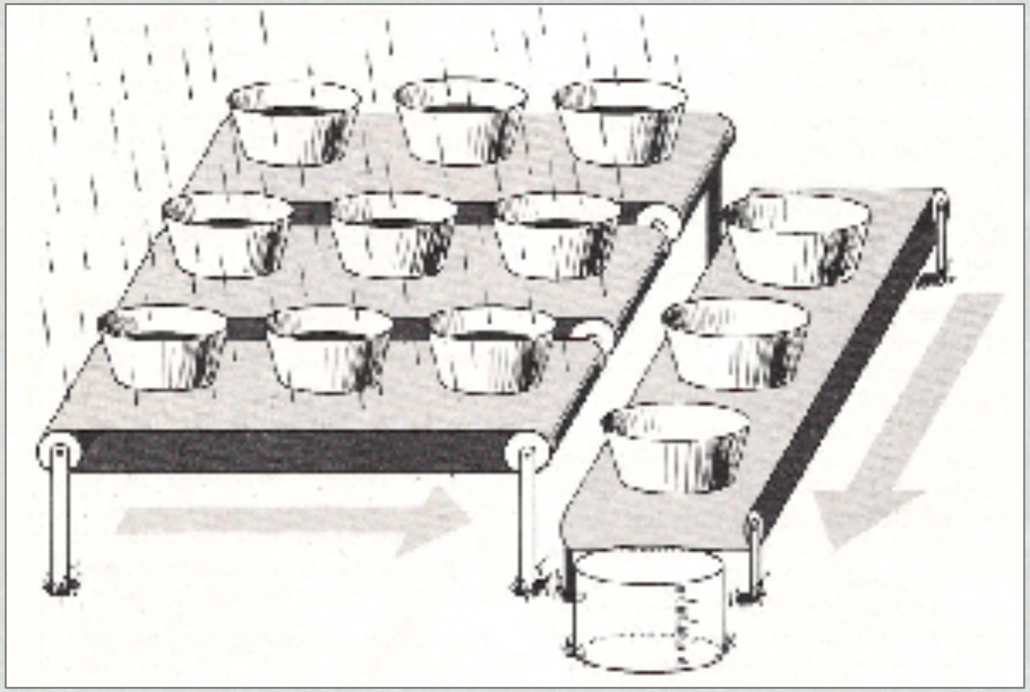

http://astro.if.ufrgs.br/telesc/fotografia.htm

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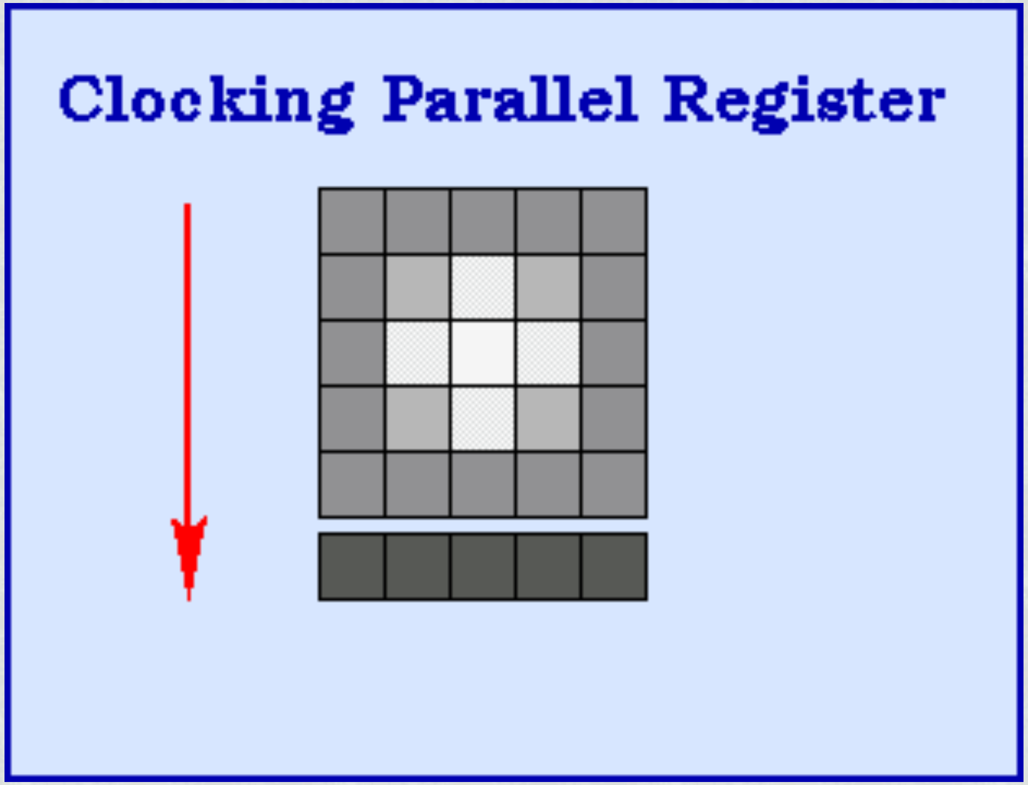


http://www.astro.virginia.edu/class/oconnell/astr511/lec11-f03.html

Signal

- When we observe, we seek to extract information carried by the electromagnetic output of our science target
  → **signal** (i.e., number de photons)
- Even without being exposed to an astronomical source, a detector provides a non-zero signal.
  - the atmosphere, the telescope and (non-cooled) optical components emit considerably.
  - These contribute to a non-zero signal on the detector.

Errors and Uncertainties

- There are a number of issues associated to the instrument that we need to correct for.

- Noises:
  - Are inherent to the processes involved in the measurement and need to be taken into account for the data analysis.

- Some of these can be eliminated (or at least minimized) with a series of steps that constitute the “calibration” of the data.
  - e.g., calibration images: *flat*, *bias*

Sources of noise

- Main sources of noise:
  - shot noise (associated to signal itself)
  - sky background noise
  - dark current noise
  - read-out noise

Due to the statistical nature of photon counting (Poisson statistics)

- To correct for these noises, astronomers need to take a set of calibration images before/during/after science observations

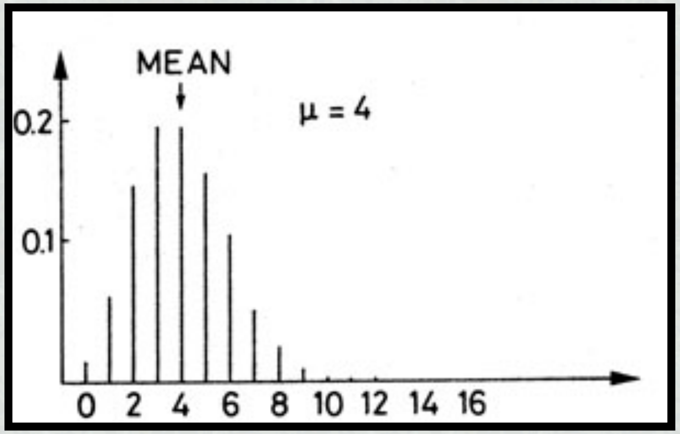
Shot noise – Poisson statistics in a nutshell

<u>Main idea:</u>

- Consider a source of photons that produces approximately 100 counts/s on the detector
  - – The time between each individual detection is not *exactly* 10ms
  - – The arrival of each photon is somewhat random —> we speak of the *probability* of detecting photons in a fixed interval of time
    - Each passing second, the exact amount of photons detected will vary: 105, 98, 97, 103, ...
    - Consider the # of detections in a time interval of 40ms
      - – Expected value: 100 counts/s * 40e-3s = 4 photons

→ Dispersion around the expected value of 100

- 20% probability of detecting 4 photons. Other values are also likely:
  - – 6 photons are detected with a ~10% probability



http://ned.ipac.caltech.edu/level5/Leo/Stats2_2.html

Shot noise – Poisson statistics in a nutshell

- Emission of light is a discrete process – photon counting

Poisson distribution

- Each photon is an independent event and the arrival of each one is not predicted with infinite precision

→ **The signal has an intrinsic noise due to its statistical nature**

- The Poisson distribution of probabilities gives the probability that a N events happen (in our case, the N photons detected) in a fixed amount of time –> this statistics rules the detection of photons.

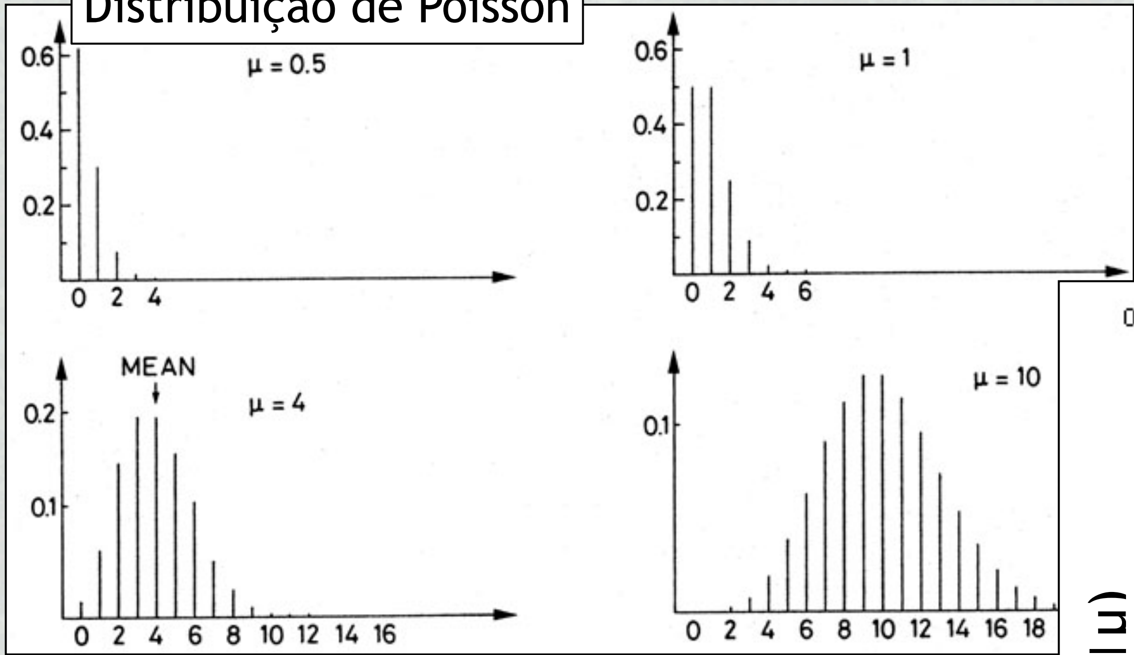
$$P(N) = \frac{(\mu)^N e^{-\mu}}{N!}$$

  - μ (= ρT) represents the average counts detected
    - ρ is the average flux (photons/second)
    - T is the time interval of observation

Shot noise — Poisson statistics in a nutshell

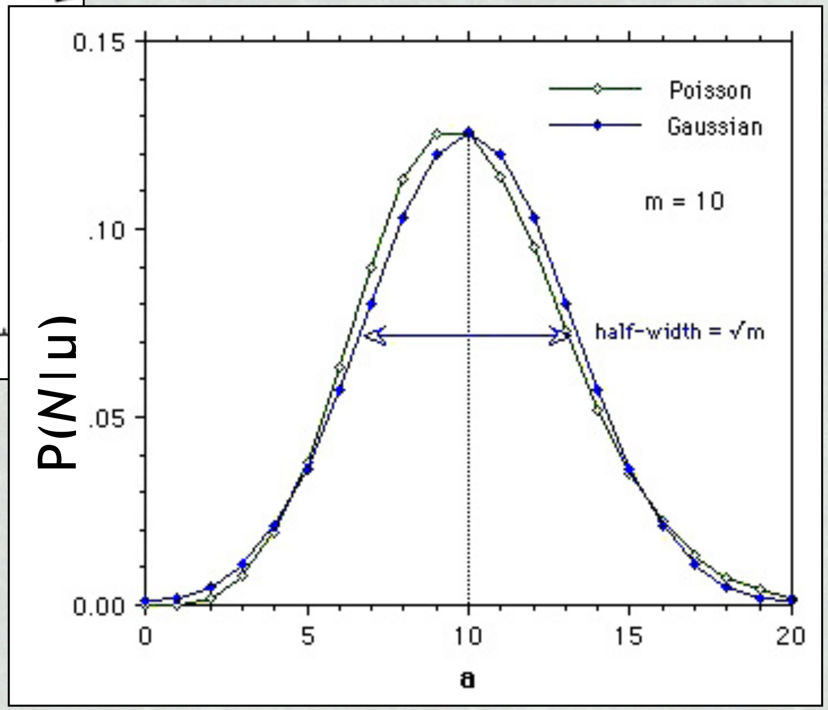
- As the number of events increase, the distribution becomes closer to that of a Gaussian

Distribuição de Poisson



http://ned.ipac.caltech.edu/level5/Leo/Stats2_2.html

μ = mean value



http://www4.nau.edu/microanalysis/Microprobe-SEM/Statistics.html

- The “shot noise” is associated to the standard deviation, given by:

$$\sigma = \sqrt{\rho T}$$

Shot noise – Poisson statistics in a nutshell

- In a fixed amount of time, the signal from a stable source (i.e., constant flux) is equal to the photons detected
  - The shot noise corresponds to: $\sigma = \sqrt{N}$

    → $$S/R \sim \frac{N}{\sqrt{N}} = \sqrt{N}$$

- The signal-to-noise is small when considering a small number of photons (i.e., very small exposure times).
  - It can be increased by:
    - Taking longer exposures, or
    - combining multiple images

Sky noise — the sky background

- The flux from an astronomical source (F_o) reaches us superposed onto the sky flux (F_S) → we need to subtract the sky from "under" the sky!

$$F_o = (F_o + F_S) - F_S$$

- A proper sky subtraction is particularly crucial to study low surface brightness regions
  - An incorrect determination of the sky may introduce large uncertainties —> particularly important when studying faint extended opjects (galaxies!)
- The sky noise also follows Poisson statistics:

$$\sigma_{sky} = \sqrt{R_{sky} \times t \times n_{\text{pix}}} = \sqrt{N_{sky}}$$

R_{sky} = photons/s; t = exposure time;

n_{pix}= number of pixels occupied by target

N_{sky}= number of photons from the sky within the region covered by target

Sky background — main sources

- Diffuse daylight → Sun

<u>Diffuse night light</u>:

- **Moon**
  - **Light reflected by the Moon, scattered by the atmosphere**
    - When the Moon is above the horizon, this will be the main contributor to the sky background
  - When observing, the night sky's brightness may depend on several factors:
    - Location (close to city?)
    - Elevation of telescope
    - Atmospheric conditions (humidity)
    - Phase of the moon
    - Distance of target from the moon
    - Observed band

Sky background — Moon vs. no-Moon

- If the sky is bright, it becomes quite challenging to study faint objects.
- The sky brightness poses a limit on how faint our targets can be.
- Moonless nights are critical for observations of faint objects in the optical.
  - Not so for near-IR!

Sky surface brightness

(mag/arcsec^2)

Band	Wavelength (λ)	New Moon	Full Moon
U	3700 Å	22,0	
B	4400 Å	22,7	19.4
V	5500 Å	21,8	19,7
R	6400 Å	20,9	19,9
I	8000 Å	19,9	19,2
J	1,2 μm	15,0	15,0
H	1,6 μm	13,7	13,7
K	2,2 μm	12,5	12,5

Sky background — main sources

- Diffuse daylight → Sun

<u>Diffuse night light</u>:

- **Moon**
- **human lights**

"When the eastern power grid failed, from Ontario to New York City, in August 2003, it revealed something many city dwellers had never seen: from horizon to horizon, a sky full of stars. Then the power came back on."

Credits: International Dark-Sky Association
http://www.planetary.org/multimedia/space-images/earth/light-pollution_ida_20030800.html

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- **Moon**
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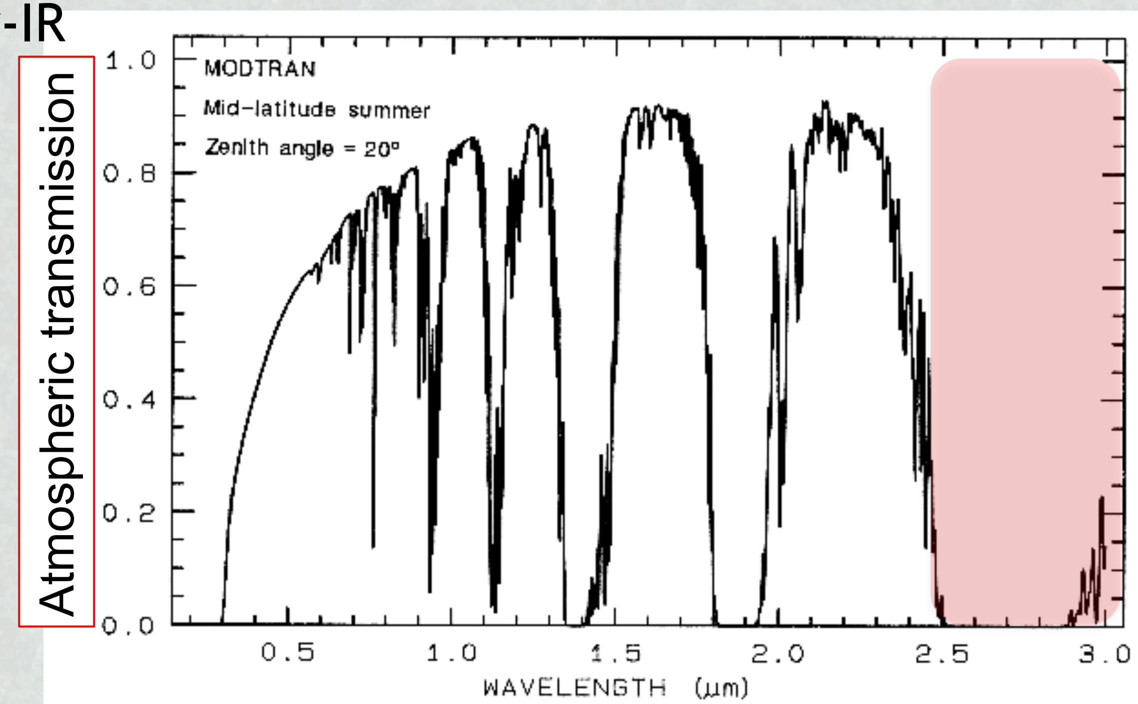
- **thermal emission from the atmosphere**
  - Water vapor and CO_2 within the atmosphere reduces the transparency, particularly in the near-IR
  - Sky is very bright at λ>2.4 μm → opaque atmosphere!



http://speclab.cr.usgs.gov/PAPERS.refl-mrs/refl4.html

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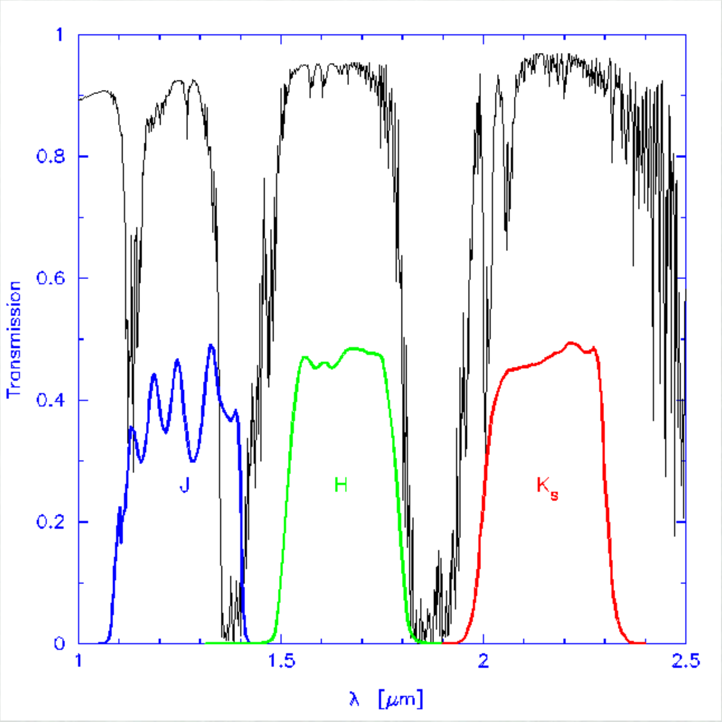
The near-IR bands J, H, Ks are specifically designed to catch these transparent windows in the near-IR!



http://www.astro.caltech.edu/~jmc/2mass/v3/transformations/

Sky background — main sources

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<u>Diffuse night light</u>:

- **Moon**
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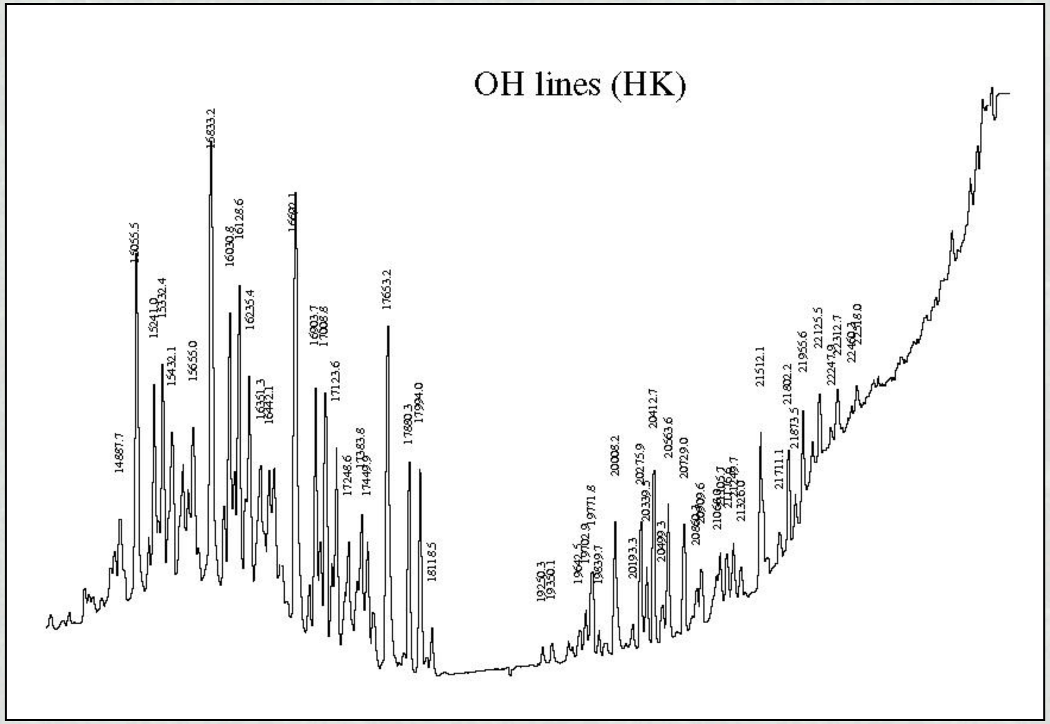
- **Diffuse night light: thermal emission from the atmosphere**
- **Airglow (atmosphere)**
  - OH Skylines



http://www.iac.es/proyecto/LIRIS/obsmodes/calib_lambda/lr_hk_oh_lines.jpg

See also NOAO's OH line Atlas

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Diffuse night light:

- **Moon**
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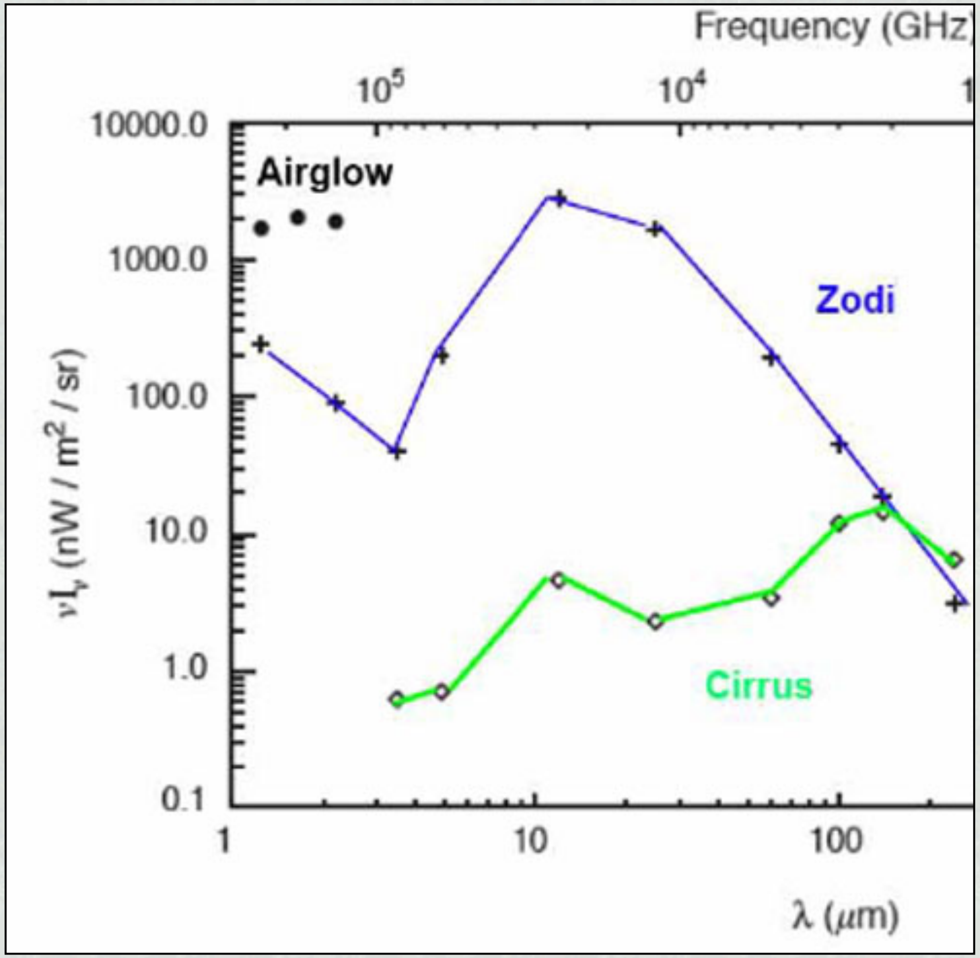
- **Diffuse night light: thermal emission from the atmosphere**
- **Airglow (atmosphere)**
  - OH Skylines
    - →The sky becomes too bright beyond K-band
    - →Need extremely low levels of humidity for infrared observations
  - *"Bright nights"* (bright time) → Full Moon ±5 days
  - *"dark nights"* (dark time) → New Moon ±5 days;
    - Usually reserved for observing programs targeting faint objects in optical bands

Sky background — main sources

- Diffuse daylight → Sun
- Diffuse night light*
- Airglow
- Zodiacal light: solar light scattered by interplanetary dust concentrated on the ecliptic
  - Does not vary with time
  - Has a solar spectrum
- Cirrus: stellar light scattered by interstellar dust

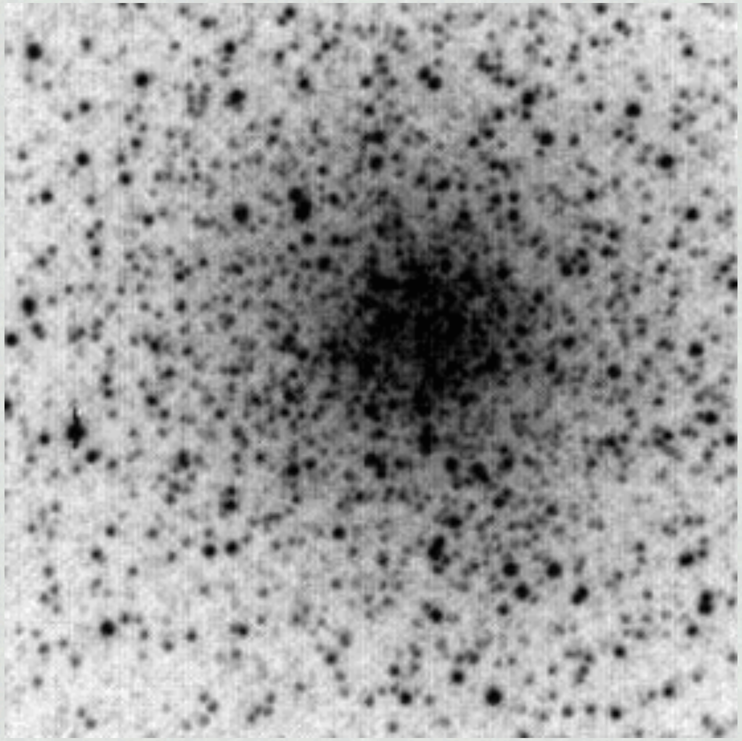


Ellis et al. 2007
http://ned.ipac.caltech.edu/level5/March07/Ellis/Ellis8.html

* when the Moon is up, it dominates in the optical

Sky background — getting rid of it!

- To effectively remove the sky background, need to:
  - Use a dedicated sky image (point the telescope away from science target) to subtract it from the science image.
    - This requires half of the observing time to be spent on the sky!



http://www.astro.washington.edu/courses/astro480/IRAF/iraf2_tutorial.html

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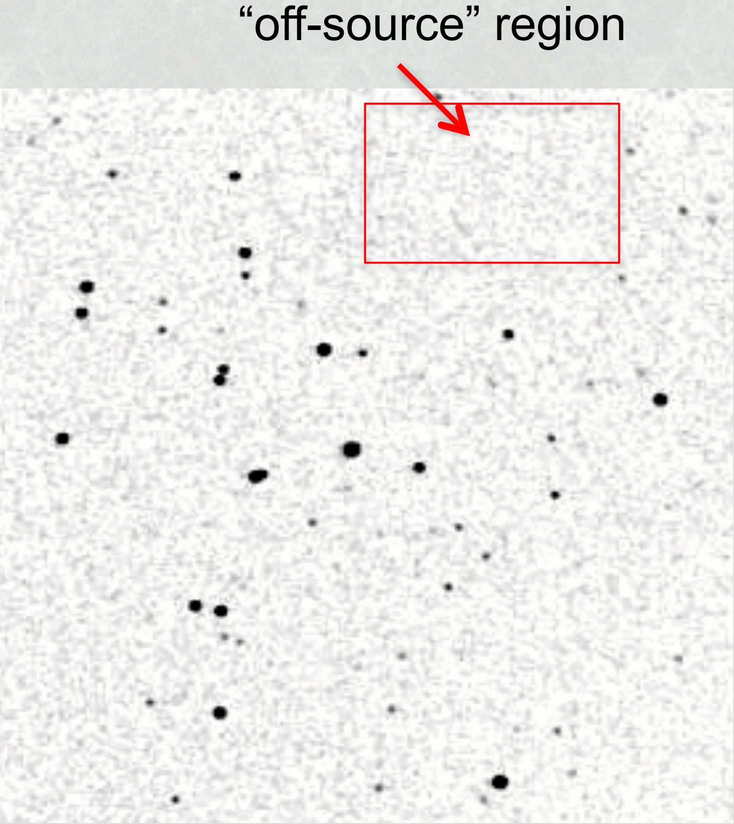
  - Use an off-source region within the science image to calculate the sky background.
    - A better approach when possible!



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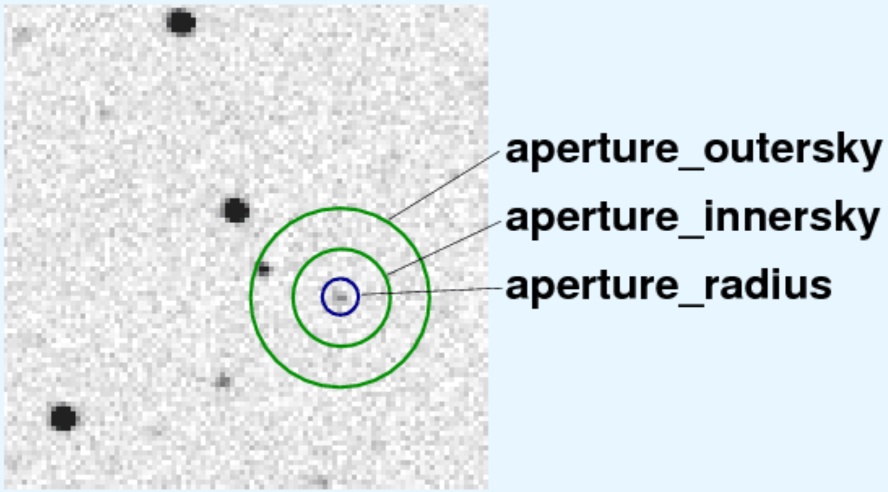


$$F_o = (F_o + F_S) - F_S$$

where F_S is given by:

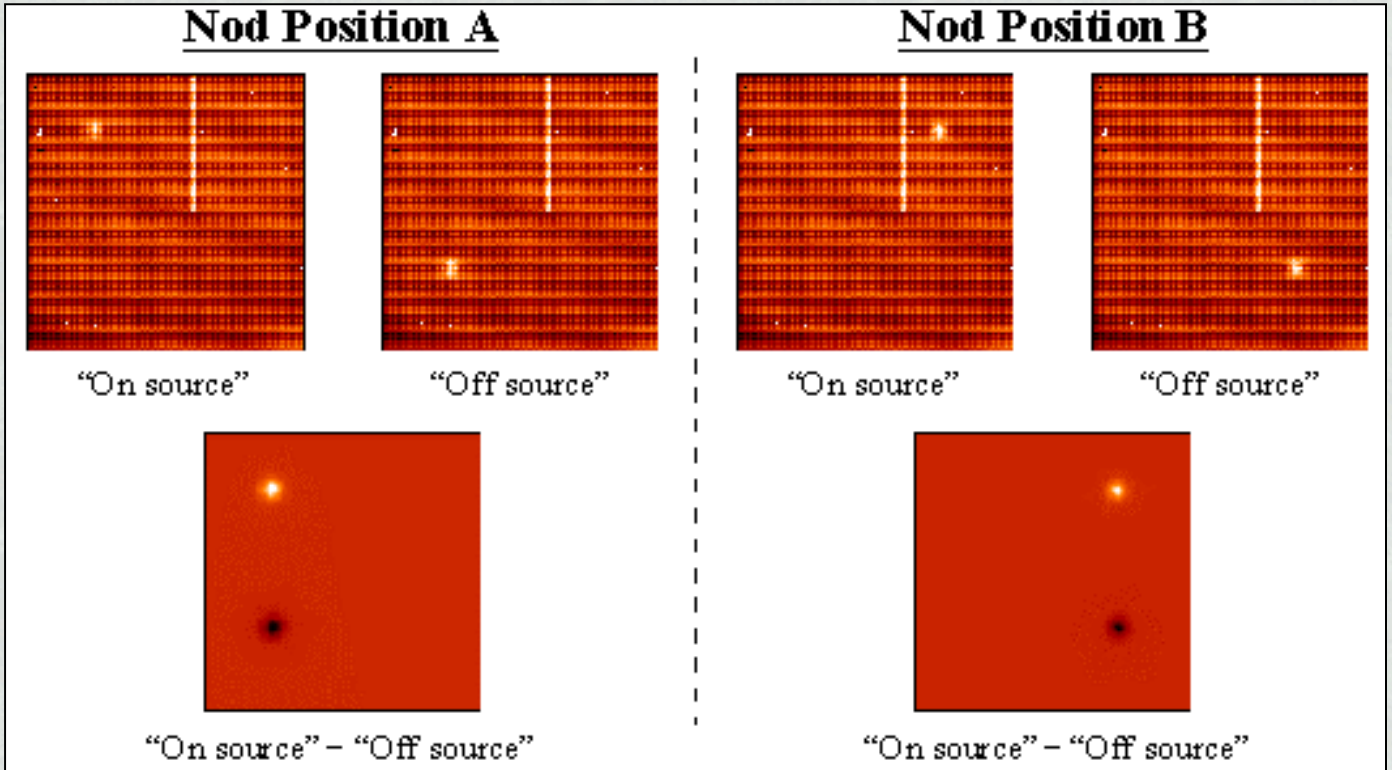
$$\langle sky \rangle / pixel \times n_{pix}$$

http://spiff.rit.edu/classes/phys445/lectures/signal/signal_illus.html

Sky background — getting rid of it!

<u>Imaging:</u>

- Multiple images where science target is placed in different parts of the FOV (*nod sequence*)



$(obj + sky)_{pos\ 1} - (obj + sky)_{pos\ 2}$

$= (obj)_{positive\ in\ pos\ 1} + (obj)_{negative\ in\ pos\ 2}$

Assuming that the sky has not varied much!

http://www.iac.es/proyecto/CCam/Atmosphere.htm

Sky background — getting rid of it!

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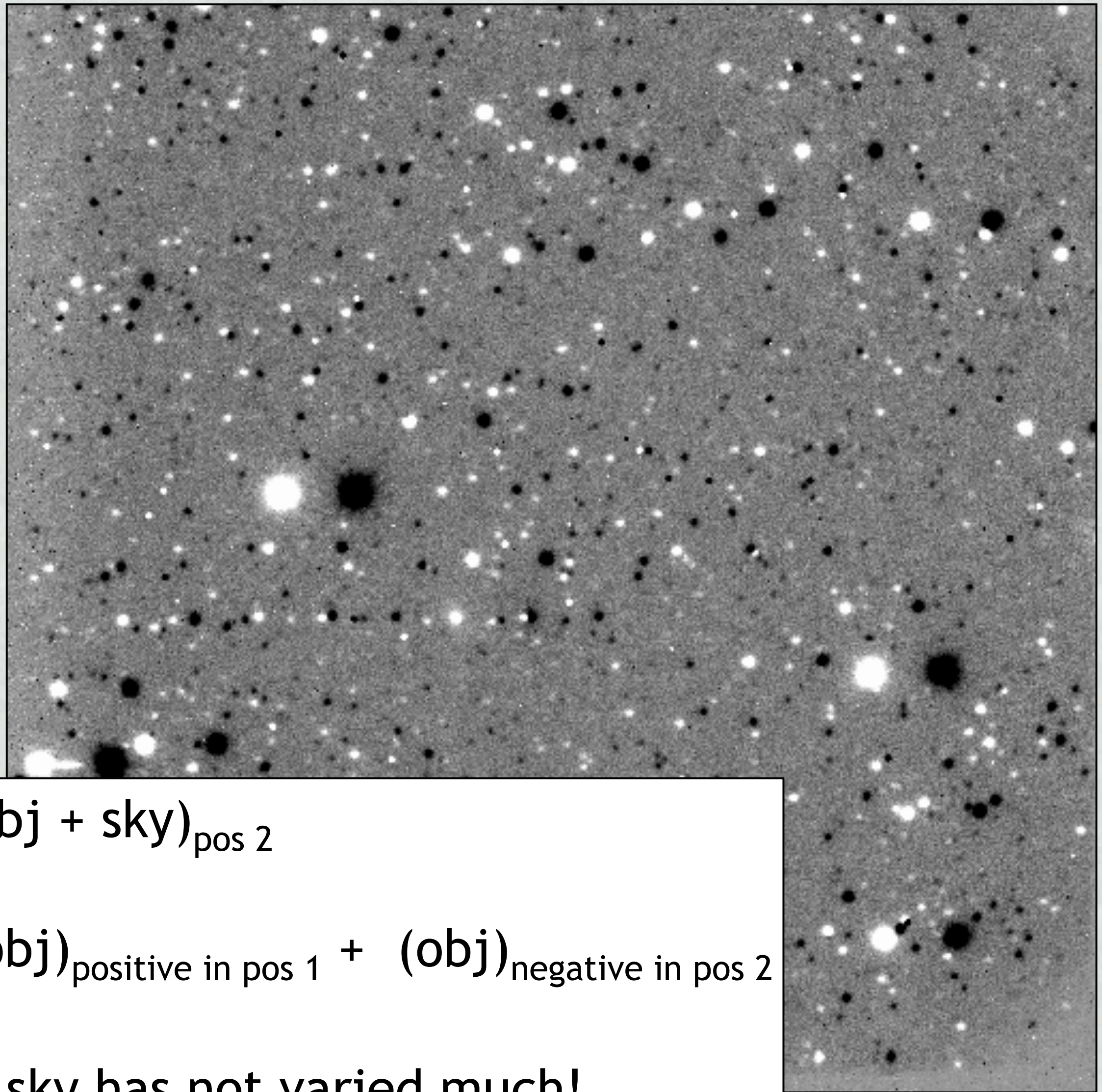
- Multiple images where science target is placed in different parts of the FOV (*nod sequence*)



$(\text{obj} + \text{sky})_{\text{pos 1}} - (\text{obj} + \text{sky})_{\text{pos 2}}$

$= (\text{obj})_{\text{positive in pos 1}} + (\text{obj})_{\text{negative in pos 2}}$

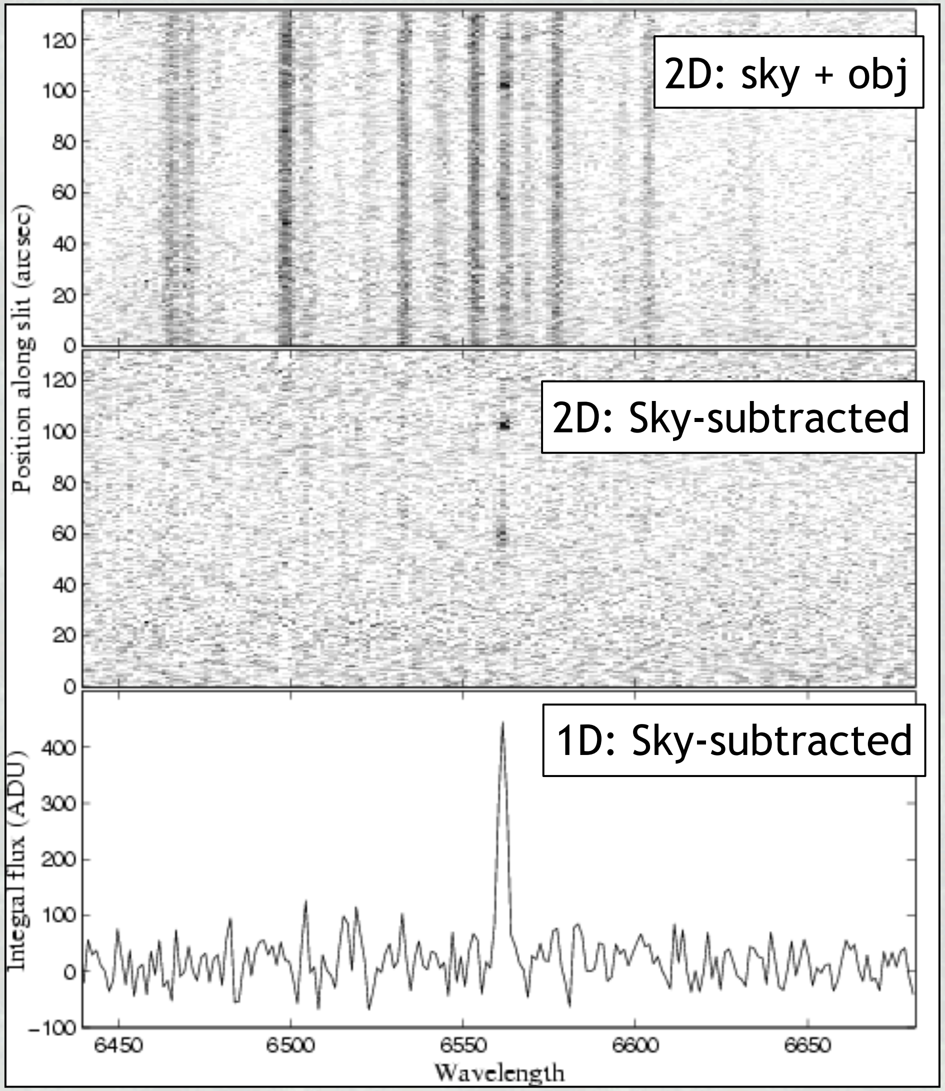
Assuming that the sky has not varied much!

http://astronomy.nmsu.edu/tharriso/ast536/ast536week02.html

Sky background — getting rid of it!

Spectroscopy

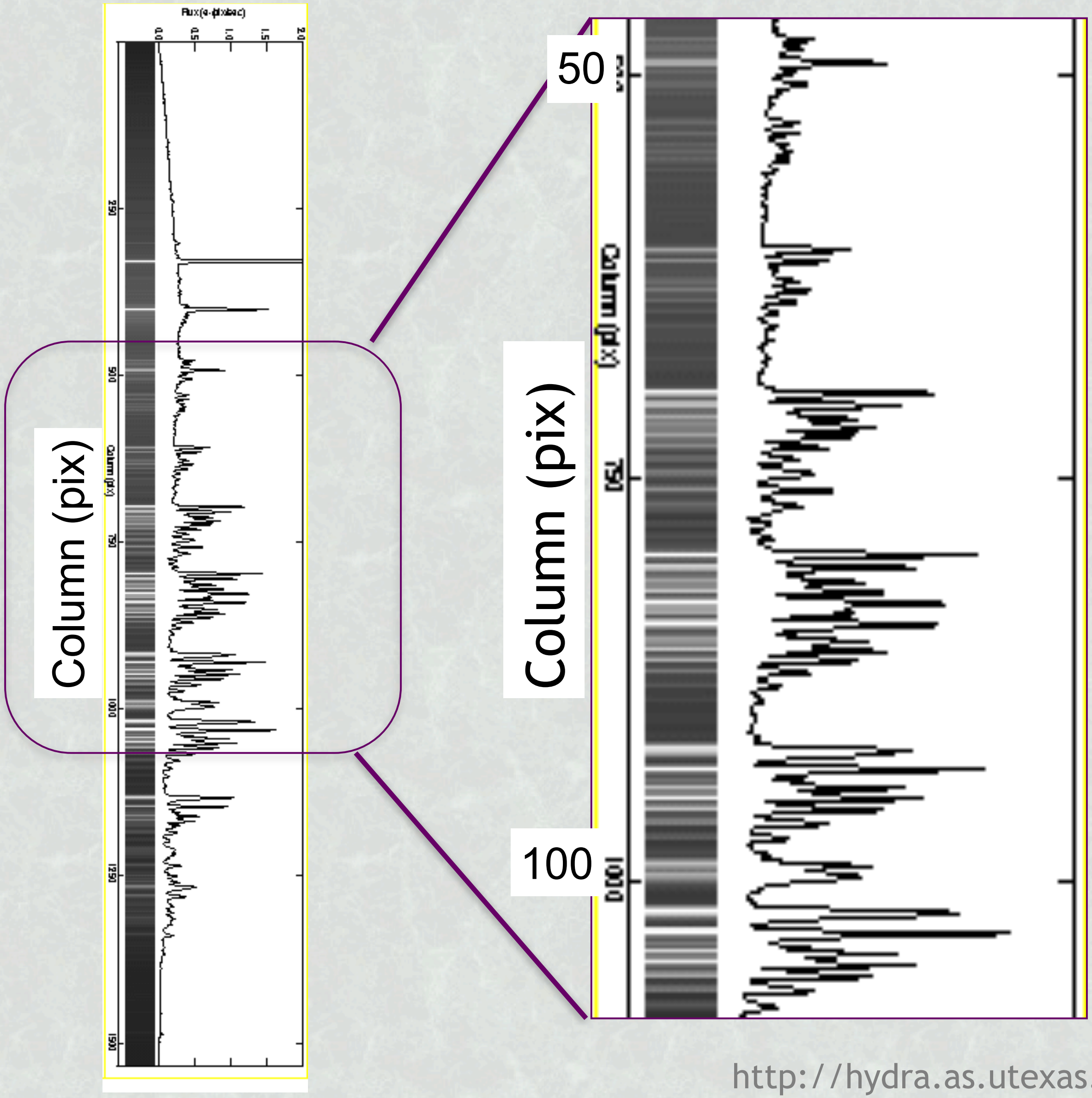
- Need to subtract sky lines



Makarov et al. 2003 (Hα in dwarf galaxies)
http://www.aanda.org/articles/aa/full/2003/27/aa3591/img157.gif

(a side note)

Sky lines: useful for wavelength calibration

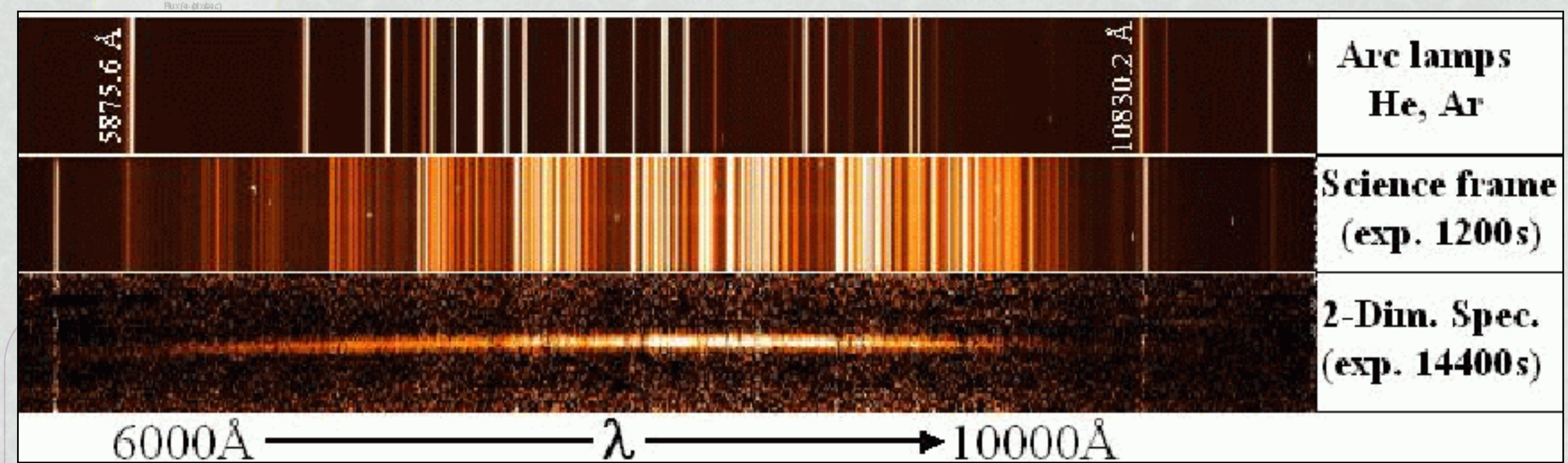


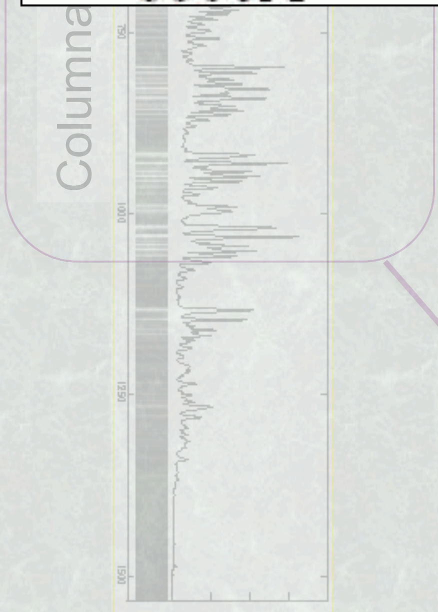
- We can use sky line catalogs to identify the emission lines in our raw spectra and this way determine which column corresponds to which wavelength.

http://hydra.as.utexas.edu/imgs/lcal-Sky-1.0.0.gif

(a side note)

Sky lines: useful for wavelength calibration





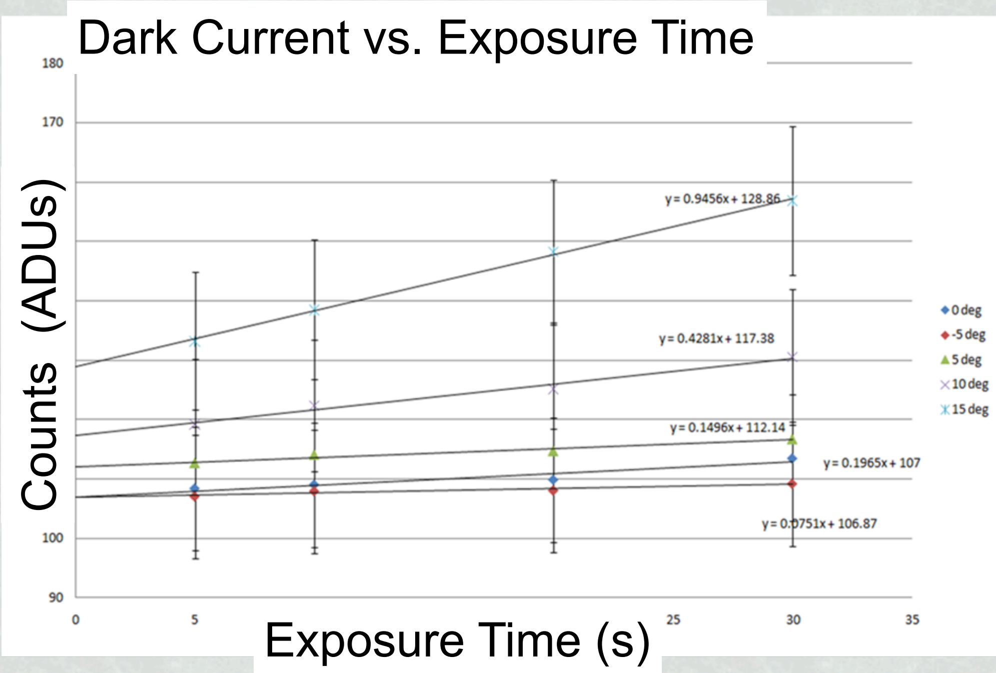
- Identifying the sky lines can sometimes be tricky (there are many!)
- Another option to calibrate λ: use arc-lamps Ne, Ar, He.

Vanzella+05
http://www.aanda.org/articles/aa/full/2005/16/aa1532/img28.gif

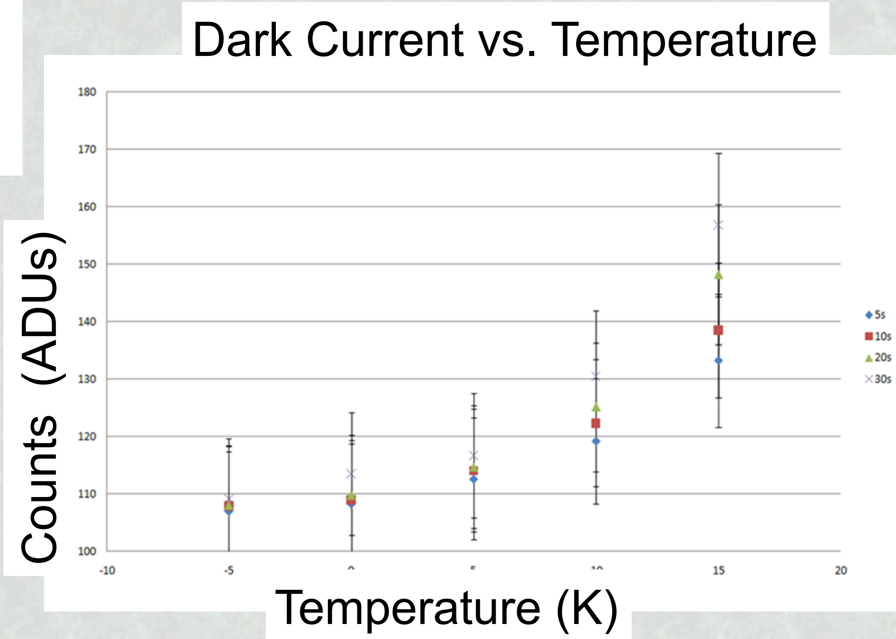
Dark Current — CCD sweating electrons!

- Thermal motion of atoms within the silicon substrate of the CCD can free electrons —> this generates what is knows as the "dark current"
- The accumulation of dark current happens independently of whether the CCD is exposed or not to any light.
  - Typically, this source of noise is not significant (depends on the CCD).
  - In the near-IR, this noise can be considerable!

Dark Current — CCD sweating electrons!



- The rate at which the dark current increases can be greatly reduced (factor of ~100 or more) by cooling the CCD.



- For this reason, cameras are generally immersed within liquid H to keep CCDs cool!

https://wikis.bris.ac.uk/display/astro/CCD+Linearity

Dark Current — time-dependent noise

- The dark current increases as a function of time —> can be significant for long exposures

- For a dark current D (in units of e^-/s/pixel), the noise within the area occupied by the science target (in pixels, n_{pix}) will be:

$$\sigma_{dark} = \sqrt{D\pi r^2 t} = \sqrt{D\, n_{pix}\, t}$$

- The pixels on a CCD can be “flushed” (i.e., cleared of charge) right before an exposure is taken. The accumulation of dark current starts immediately!

Dark Current – getting to a dark-subtracted image

- The dark current must be removed not only from science exposures, but from other images (e.g., standard star frames, flats)

- This requires the observer to take a set of dark exposures (camera closed!) with exposure times matching the different exposure times used through the night
  - this is usually done in the afternoon prior to the observations

- Generally multiple darks will be obtained at each exposure time to combine and create a "master dark frame" that will be representative of the dark current for such a time exposure.

(raw science frame) – ("master" dark) =
dark-subtracted science frame