

# Astronomical Image Calibration

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# The C.E.K. Mees Observatory

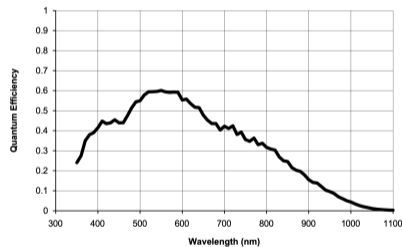
- ▶ Boller & Chivens 24-inch Cassegrain telescope
- ▶ SBIG STX 16803 CCD camera
- ▶ SBIG FW-7 filter wheel
  - ▶ 4 broadband filters (LRGB)
  - ▶ 4 narrowband filters ( $H\alpha$ ,  $H\beta$ , [OIII], [SII])
- ▶ External offset autoguider



# Our imaging system

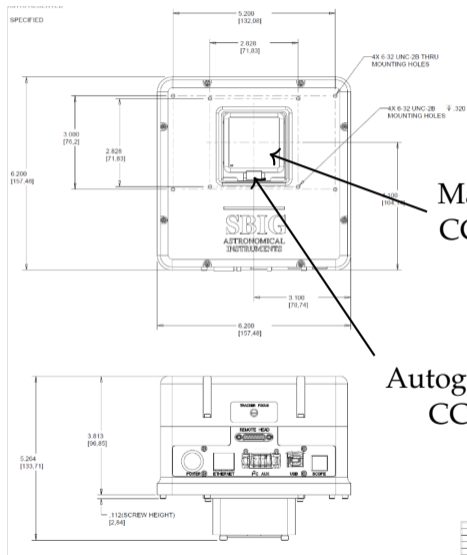
## Santa Barbara Instrument Group (SBIG) STX 16803 CCD cameras.

- ▶ Frame-transfer CCD,  $4096 \times 4096$ ,  $9 \mu\text{m}$  pixels, plus a separate interline CCD,  $657 \times 495$ ,  $7.4 \mu\text{m}$  pixels for autoguiding, next to the big imaging CCD. The latter is blocked by Filter Wheel #2.
- ▶ Quantum efficiency  $\eta = 0.45 - 0.6$  across the visible band.
- ▶ 16-bit output; 1.27 electrons per **data number** (DN) for Camera #1, 1.35 electrons per DN for Camera #2. (Pixel readouts are recorded in DN.)
- ▶ Dark current  $I_D/q_e = 0.009$  electrons per second per pixel at  $T = -20^\circ\text{C}$ .
- ▶ Read noise  $N_R = 9$  electrons (rms) per pixel at  $T = -20^\circ\text{C}$ . Half that, if the image is binned into  $2 \times 2$  pixel blocks, as we usually do except with our L filter.



*ON Semiconductor*

# Our imaging system



Main  
CCD

Autoguider  
CCD



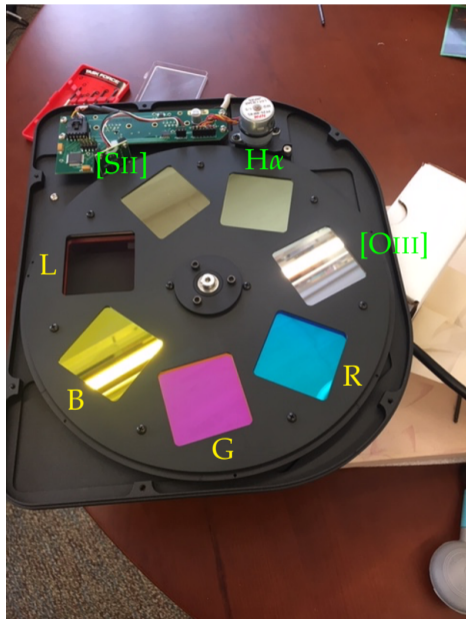
Shutter open



# Our filter wheels

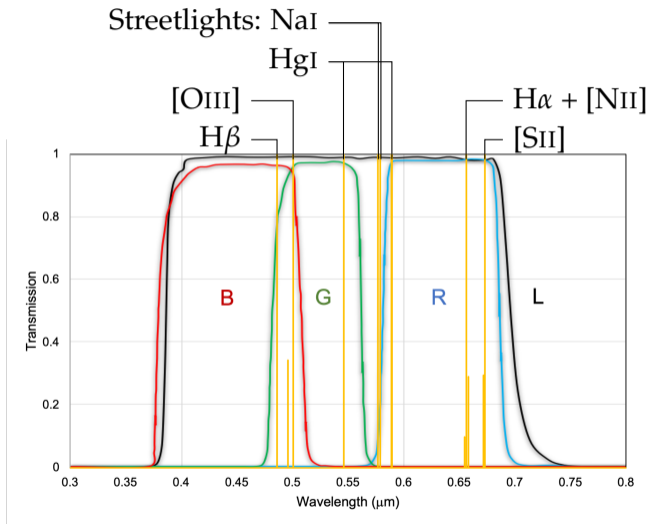
**SBIG FW-5 or FW-7 filter wheels.** They are enclosed and mount to the front of the cameras. Ours (#1, #2) are each devoted to the camera of the same number.

- ▶ Filter wheel #2, an FW-7, is shown on the right, open and viewed from the telescope side.
- ▶ All filters except L are **dielectric multilayer interference filters**, so in reflected light they do not look like the color that they transmit.



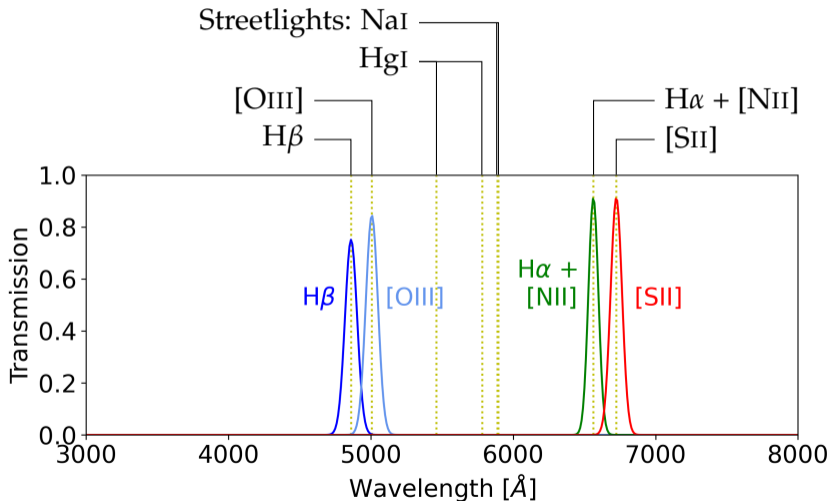
# Our broadband filters

For stellar magnitudes and colors: L, R, G, and B, all of which have peak  $\tau \gtrsim 0.95$ .



## Our narrowband filters

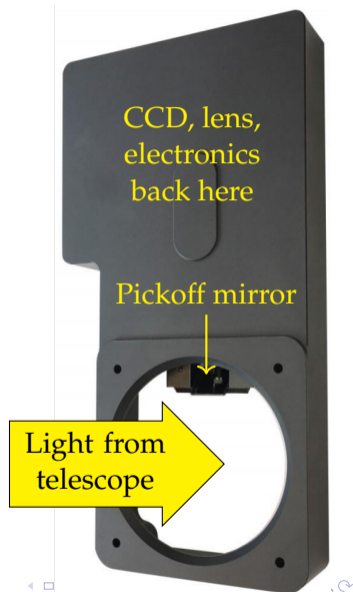
For spectral lines:  $H\beta$ ,  $[OIII]$ ,  $H\alpha$ , and  $[SII]$ , all of which have peak  $\tau = 0.75 - 0.9$ . FWHM widths are  $\Delta\lambda = 85, 85, 70,$  and  $80 \text{ \AA}$ , respectively.



## SBIG STX external offset guider

This contains a separate interline CCD,  $640 \times 480$ , with  $7.4 \mu\text{m}$  pixels, preceded by a lens that increases its field of view relative to the cameras' internal guider CCDs.

- ▶ Its light comes from a small pickoff mirror that protrudes from the edge of the telescope field of view toward the imaging CCD.
- ▶ Since it receives its light without having that light go through the filters first, and since its field of view is larger, it is considerably better for autoguiding than the cameras' internal guider CCDs.

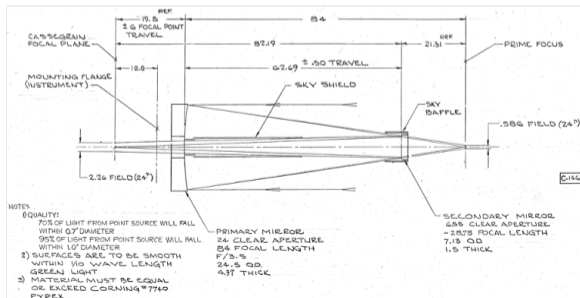




# Boller & Chivens/DFM Engineering 24-inch Cassegrain telescope

Installed 1965

- ▶ Primary mirror by Perkin-Elmer, originally for the [Stratoscope](#) program
- ▶  $f/13.5$ , **plate scale** 25.1 arcsec per mm in the Cassegrain focal plane
  - ▶ The large CCD covers 0.224 arcsec/pixel in  $1 \times 1$  binning, 15.4 arcmin on a side, 21.7 arcmin diagonal
  - ▶ The autoguider CCD: 0.259 arcsec/pixel,  $2.8 \times 2.1$  arcmin
- ▶ Unvignetted field of view 24 arcmin in diameter
- ▶ Collecting area:  $2700 \text{ cm}^2 = 0.27 \text{ m}^2$



# Making astronomical images, simplified

Much more complicated than most picture-taking.

- ▶ Identify a date range and a favorite object which is high in the sky at night for at least 3–4 hours on those dates.
- ▶ Compile, or plan to take, the calibration data.
  - ▶ Dark-current and bias frames, 32–256 frame sequences each, with the CCD operating at the temperature you intend to use ( $T = -35^{\circ}\text{C}$  to  $-20^{\circ}\text{C}$ ).
  - ▶ Flat field frames, 32–64 frame sequences in each filter.
  - ▶ A few 8–10 mag A stars near your target.
- ▶ Plan to autoguide on all deep-sky targets.

## At the telescope

For scientifically-useful images, take

- ▶ Frames in R, G, B, and/or narrowband spectral-line filters, all binned  $2 \times 2$  pixels. Relative numbers depend on desired sensitivity.
- ▶ Shorter-exposure sequences on the calibration standards, every so often.
- ▶ As many frame sequences as you have time for.
- ▶ 5 minute exposures in moonlight; 8–10 minute exposures in dark skies. All will be averaged together in the end.

For pretty pictures: as above, but

- ▶ 3–4 times as many frames in L as any of the other filters, in  $1 \times 1$  binning.
- ▶ Again, as many frames as you have time for in  $> 4$  hours.

Note that most deep-sky **APOD** images involve  $\gg 4$  hours.

# How long of an exposure is needed?

Before observations start, the first thing to figure out is how long it will take. For astronomical images, the instrument sensitivity and the target flux both need to be known to estimate the necessary exposure time.

- ▶ Individual **frames** should be exposed long enough that the sky background is larger than the dark current, but not so long that there are many cosmic-ray hits in the frame.
  - ▶ Usually 5–12 minutes per frame, depending on whether or not the moon is up.
- ▶ As many frames as it takes to fill the available time.
  - ▶ 4–5 hours is a good target for a high-quality color image of relatively large objects.
- ▶ More is always better.

## Sensitivity and signal-to-noise ratio

To astronomers, “sensitive” means a large ratio of signal to noise. Signal = current produced by the CCD’s absorption of light from the celestial object, which we will call  $I_S$ . Because of the finite, quantized electron charge and random arrival time of electrons at given points in a circuit, there are three statistically-independent noise sources in the CCD current. The general term for this effect is **shot noise**. In terms of the current drawn,

$$I^2 = \frac{q_e}{\Delta t} (I_S + I_B + I_D + I_R)$$

where

- $I_S$  Current produced by the photons from the object incident on the pixel
- $I_B$  Incident background current (e.g. moonlight, city lights)
- $I_D$  Dark current: Current drawn by the pixel even when no light shines; can be made negligible at sufficiently low CCD operating temperature
- $I_R$  Read noise: Additional current resulting from the readout circuitry
- $\Delta t$  Exposure time: time over which the current is averaged
- $q_e$  Charge of an electron

# Sensitivity and signal-to-noise

The **signal-to-noise ratio** is

$$\frac{S}{N} \equiv \frac{I_S}{I} \propto \sqrt{\Delta t}$$

**To increase the S/N by a factor of 2, then, the exposure time must increase by a factor of 4.** We strive to have sensitivity limited by natural sources of the background. Thus, we

- ▶ Operate the CCD at low enough temperatures so that  $I_D \ll I_B$
- ▶ Take long enough exposures so that  $I \gg I_N$

# Process the images

For each object and filter,

1. **Calibrate** each image: subtract dark and bias charge, divide by flat field.
2. **Remove** images in which something bad happened (clouds, tracking failure, dome lights inadvertently turned on, etc.)
3. **Align** the images so that the stars are all in the same pixels.
4. **Normalize** the images so that stars and blank sky are the same (corresponding) brightness in each.
5. Remove cosmic rays
6. Remove satellite trails
7. **Average** all of the images in the same filter; convert to physical units.
8. Extract the quantities that you need (e.g. fluxes for each star) and proceed to scientific analysis.

## For pretty pictures

After steps 1–7,

8. Make a composite RGB or false-color image out of the images taken with different filters, with brightness scales (usually) chosen so that A0 stars look white.
9. **Deconvolve** (sharpen) your averaged L image.
10. Process your deconvolved L image and composite RGB or false-color image with photo-editing software, making a composite LRGB image with
  - ▶ High contrast and dynamic range (black blank sky, vibrant colors, reduced noise)
  - ▶ No flaws such as “dust donuts,” etc.
  - ▶ Cropping to the desired size and aspect ratio.



## Dark current and bias correction

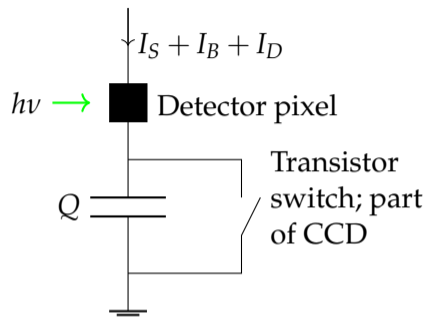
Dark current varies from pixel to pixel, and decreases exponentially with decreasing temperature for good detectors.

- ▶ All intrinsic semiconductor photodetectors are like this: for a bandgap  $\Delta E$ , carriers can be thermally produced at rates proportional to  $\exp(-\Delta E/kT)$ .

The semiconductor-transistor switches in CCD circuitry always inject charge abruptly when opened at the beginning of exposures. This is temperature dependent, too.

These effects lead to offsets in the charge,  $Q$ , that must be subtracted to leave the signal.

Dark current has shot noise, too. Subtraction gets rid of the average value, but not the shot noise.



## Dark current and bias correction

Bias current is a low-level current always present in the CCD to ensure that any random charge fluctuations do not result in a negative current.

Also, the difference between (or sum of) two statistically independent images has noise no larger than either one.

Therefore, detector arrays are operated at a low enough temperature to make both the offset and shot noise small. . .

And the dark current and bias correction are measured with averaging times long enough that the noise in these two corrections contribute insignificantly to the system sensitivity.

## Dark current and bias correction

In practice, **for each temperature and binning in use**, we usually

- ▶ Take 44 dark frames, each with 30-minute exposure time
- ▶ Take 280 bias frames, each with the minimum possible exposure time ( $\sim 50$  ms)
- ▶ Generate master dark and bias frames by averaging corresponding pixels, after discarding the smallest 4 (10) and largest 8 (14) values for each pixel in the stack of dark (bias) frames to reject cosmic ray hits on pixels.
- ▶ Dark frames can be taken during the day if the camera surroundings are truly dark.

The resulting corrected frame has, to good approximation, **no noise added by the master**.

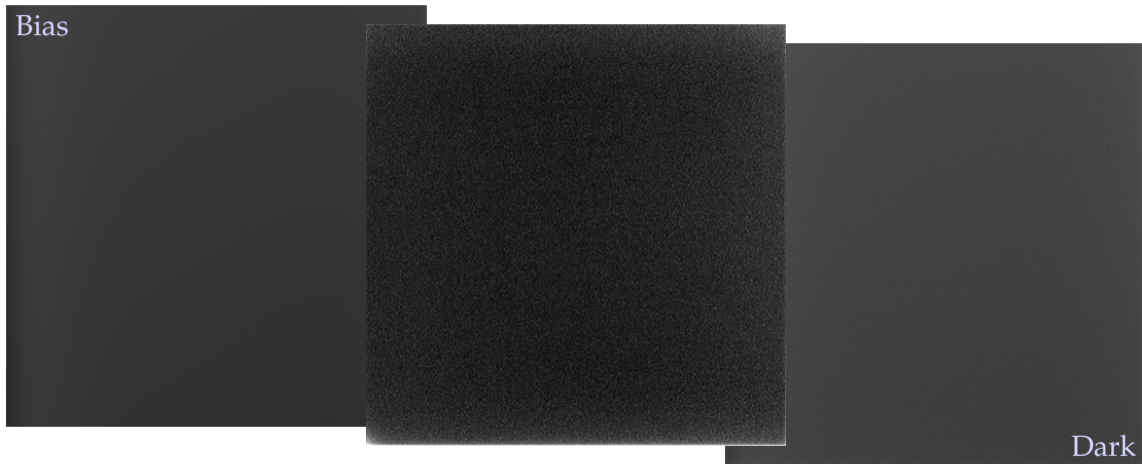
# Master dark and bias frames

-20°C, linear scale



# Master dark and bias frames

-20°C, linear scale



Dark - Bias, Linear scale, 0.01-0.02  $e^-$  /s.

## Flat field correction

- ▶ Good CCD detector arrays have small pixel-to-pixel variation in response, meaning that the responsive quantum efficiency is nearly uniform across the array.
- ▶ But the variation is not zero, and it would look like noise or systematic error in long enough exposures.
- ▶ Any optical surface close to the focal plane — e.g. windows and filters — can also contribute small variations in transmission among different areas of detector pixels.
- ▶ Ideally, an image of a uniformly-bright object would be perfectly uniform.
- ▶ So take a high signal-to-noise, dark and bias corrected, image of a uniform-brightness object, normalize it, and divide each target-exposure frame by that image.
- ▶ This restores uniformity to the focal-plane response, and it is called **flat-fielding**.

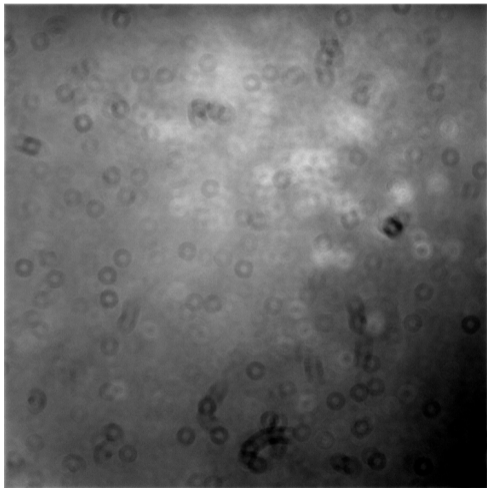
## Taking flat field frames

The hard part about flat-field correction turns out to be getting a uniformly bright object, with light taking the same optical path as that from celestial objects.

- ▶ Good: twilight-sky flats (professional-observatory standard)
  - ▶ Point at zenith, take many frames with large DN per pixel in each filter after sunset and before the sky gets dark enough to see stars. (Reverse for morning.)
  - ▶ Disadvantages: Has to be done at twilight; usually not enough time to take data for all of the filters; sky emission is scattered sunlight and therefore polarized.
- ▶ Better: electroluminescent-panel flats (Mees Observatory standard)
  - ▶ Completely cover the top of the telescope with seamless EL panel, take many frames with a large DN per pixel in each filter. Can be taken any time you want, even during the day.
  - ▶ At Mees: as good as the best twilight flats, and unpolarized as well.

# Master L flats

October 28, 2019

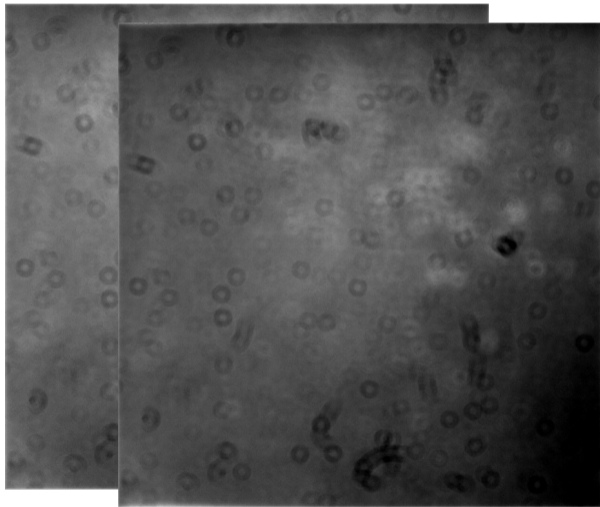


Electroluminescent panel.  
Linear scale



# Master L flats

October 28, 2019

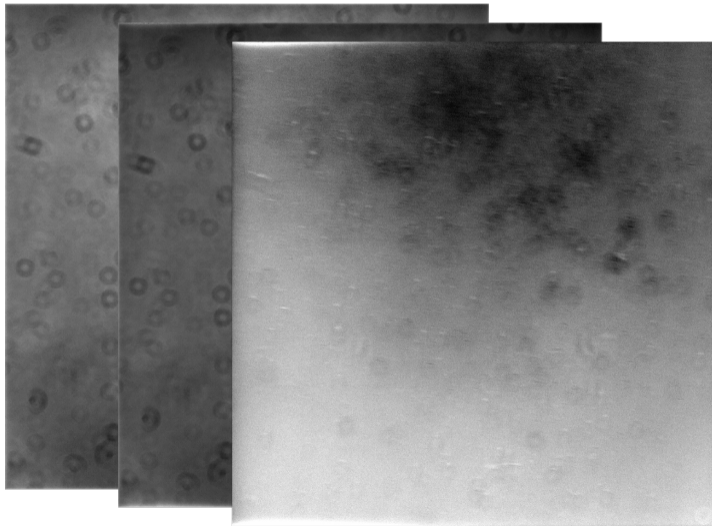


Electroluminescent panel.  
Linear scale

Twilight sky. Linear scale

# Master L flats

October 28, 2019



Electroluminescent panel.  
Linear scale

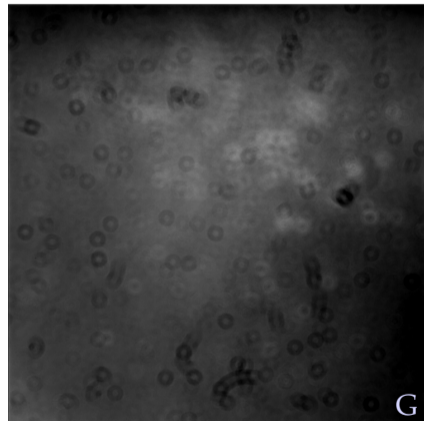
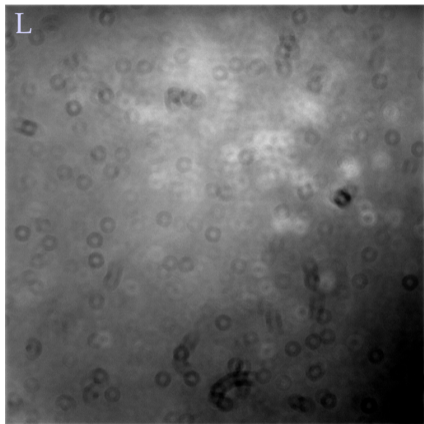
Twilight sky. Linear scale

Sky/EL. Linear scale

Most of the dust is on  
CCD cover window and is  
illuminated very slightly  
differently by the EL panel  
and the sky.

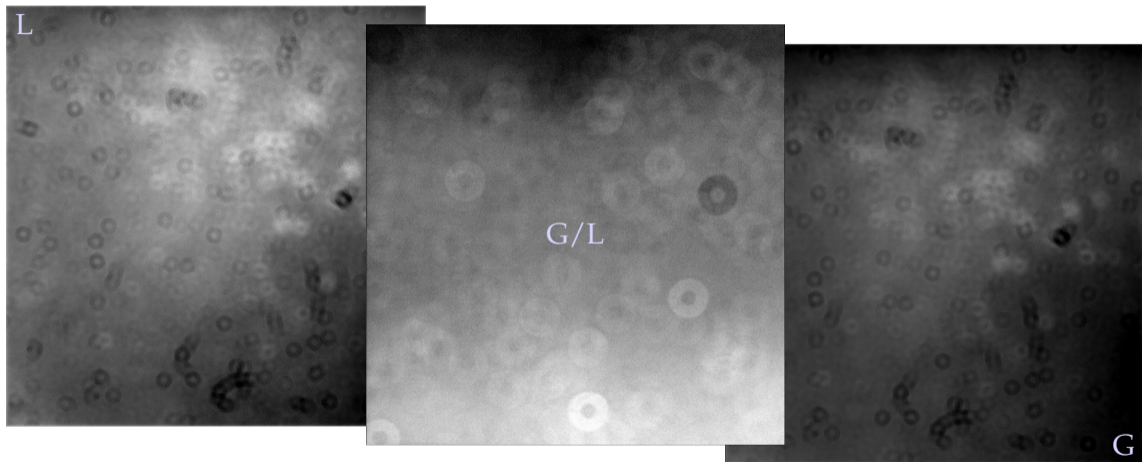
# Master EL-panel flats

October 28, 2019



# Master EL-panel flats

October 28, 2019



Linear scale,  $1.00 \pm 0.03$ . The CCD cover window was so dusty that the dust on the filters only shows up well in the quotients.

# Atmospheric absorption

Presuming that atmospheric conditions are the same throughout the observations:

- ▶ Because of atmospheric scattering and absorption, the signal from each star is largest when observed at its highest elevation / smallest zenith angle  $z$ .
- ▶ To a good approximation, the atmosphere is plane-parallel, and the path that light takes through it varies according to

$$\ell = \frac{\ell_0}{\cos z} = \ell_0 \sec z$$

where  $\ell_0$  is the vertical thickness of the atmosphere.

- ▶ If atmospheric opacity and scattering is small, light is attenuated according to

$$\begin{aligned} f &= f_0 \exp(-\sigma_0 \ell_0 \sec z) = f_0 \exp(-\tau_0 \sec z) \\ &\cong f_0 - f_0 \tau_0 \sec z \end{aligned}$$

where  $f_0$  is the **unattenuated** stellar flux in DN,  $\tau_0$  is the **zenith optical depth** of the atmosphere, and  $(1 - \tau_0)f_0$  is the signal in DN that would be received at zenith.

## Correcting atmospheric absorption

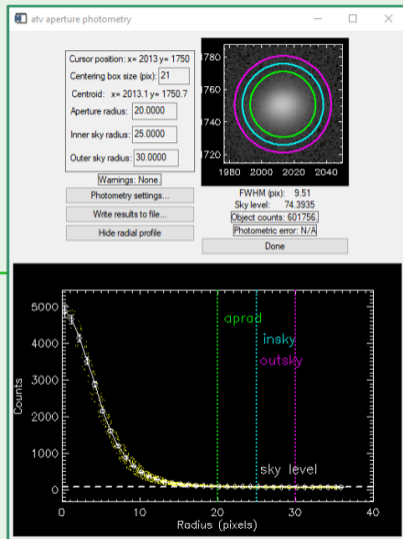
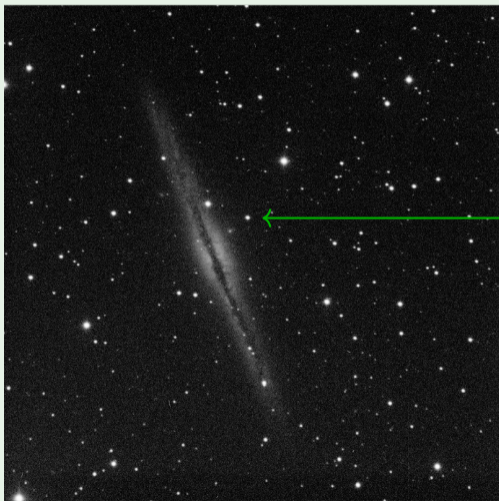
During observations of NGC 891 on October 28, 2019, a certain relatively isolated 13.3-magnitude star appeared in every frame. In the L frames, photometric measurements of this star, listed to the right, were made for each frame. Find the L-band zenith optical depth,  $\tau_0$ , and the absorption-corrected flux density,  $f_0$ , for this star.

First, note that conditions were deteriorating as time went on, as is evident here in the seeing. So we may not want to use all of the data.

After editing the data, though, it is just plot-and-fit.

Time	Altitude [deg]	sec z	Signal [ $\times 10^5$ DN]	Noise, rms [DN]	Seeing [arcsec]
19:45	34.399	1.7701	5.90	921	2.2
19:56	36.136	1.6958	5.86	909	2.4
20:01	36.933	1.6642	5.80	912	2.4
20:07	37.894	1.6281	5.99	932	2.2
20:12	38.699	1.5994	6.01	915	2.0
20:17	39.508	1.5719	5.98	911	2.2
20:22	40.321	1.5454	6.10	924	2.3
20:28	41.301	1.5151	6.17	895	2.1
20:33	42.121	1.4910	6.03	895	2.4
20:38	42.945	1.4678	6.04	937	2.5
20:43	43.772	1.4455	6.16	909	2.2
20:49	44.769	1.4199	6.22	923	2.2
20:54	45.603	1.3996	6.19	906	2.3
22:09	58.438	1.1736	6.31	901	2.4
22:15	59.486	1.1608	6.35	923	2.4
22:20	60.361	1.1505	6.39	947	2.4
22:25	61.238	1.1407	6.40	936	2.4
22:30	62.117	1.1313	6.39	940	2.4
22:36	63.174	1.1206	6.32	981	2.6
22:41	64.056	1.1121	6.28	968	2.8
22:46	64.939	1.1039	6.37	953	2.6
22:51	65.824	1.0961	6.38	950	2.6
22:57	66.887	1.0873	6.36	977	2.5
23:02	67.774	1.0803	6.34	979	2.6
23:07	68.662	1.0736	6.41	1000	2.6
00:15	80.744	1.0132	6.19	1130	3.1
00:20	81.619	1.0108	6.18	1170	3.0
00:26	82.661	1.0083	6.04	1200	3.5
00:31	83.517	1.0064	6.14	1090	3.3

# Correcting atmospheric absorption



## Correcting atmospheric absorption

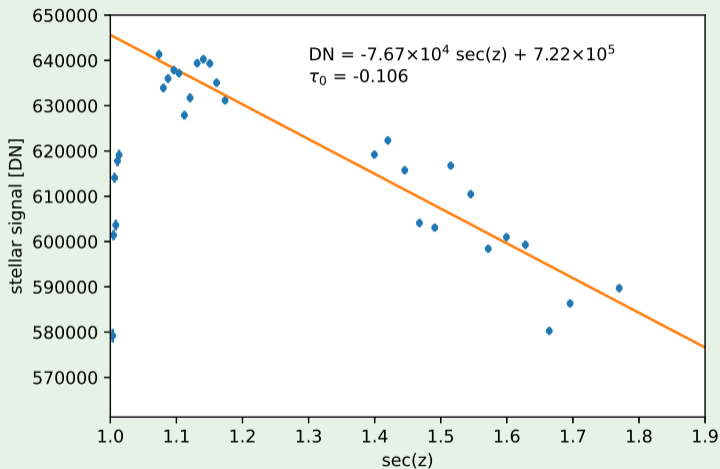
Here is the plot and fit, omitting the last six frames (points scattered well below the line on the y-axis) from the fit.

Note that the scatter is much larger than the noise: conditions were “not photometric.”

From the fit:

$$\tau_0 = \frac{7.67 \times 10^4}{7.22 \times 10^5} = 0.106$$

$$f_0 = 7.22 \times 10^5 \text{ DN}$$





## Transient removal

Let's imagine that we determine that we need six 10-minute frames to achieve the minimum S/N that we require for our analysis.

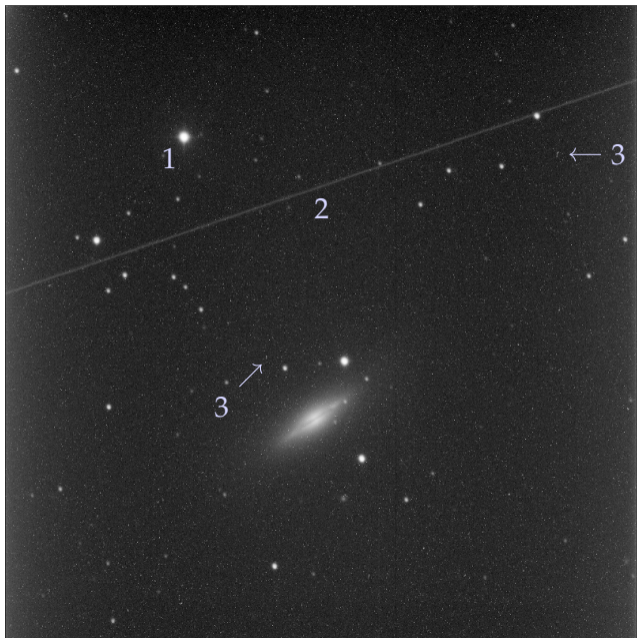
Why not take just one 60-minute frame?

- ▶ The **average of six 10-minute background-limited frames has precisely the same sensitivity as one 60-minute background-limited frame.**
- ▶ Multiple frames allow other problems to be easily avoided, such as
  - Overexposed bright stars** Sometimes, this cannot be helped, but it should be avoided whenever possible.
  - Cosmic ray hits** They occur in random locations and are easy to identify and correct in a stack of images.
  - Satellite trails** 1–2 per hour, especially at high declination.

# Transients

Five-minute G frame on NGC 5866,  
with

1. an overexposed star
2. a satellite trail
3. many cosmic-ray hits, of which only a couple of oblique-incidence ones are labeled



## Transient removal

There is not much that you can do about overexposed stars, unless they were your main target.

To get rid of transients,

- ▶ Align the stack of frames so that every star occupies the same pixels in each frame.
- ▶ Compute the median and the standard deviation,  $\sigma$ , for each pixel from the stack.
- ▶ Reject each pixel that deviates by more than  $2.2\sigma$  from the median, replacing its value with that interpolated from its un-rejected nearest neighbors. This procedure is one form of **median filtering**.
  - ▶ It can take a few iterations to remove satellite trails and occasional clusters of cosmic-ray hits, for lack of enough un-rejected neighboring pixels.

# Flux calibration

Finally, the images need to be multiplied by the factor that converts DNs to physical units.

- ▶ The basis for this conversion: observations, interleaved with the target-object observations, of at least one **standard star**: one set of stars
  - ▶ which cover the sky and a useful range of magnitudes
  - ▶ which are monitored to ensure that they are not variable
  - ▶ whose flux density is traceable to laboratory standards with high precision and accuracy, and thus **for which  $f_0(\lambda)$ , in physical units, is known.**
- ▶ A good choice are the Vega-like A0V standards for almost all observations.
  - ▶ Same magnitude at all visible wavelengths
  - ▶ Essentially no absorption lines except for the hydrogen recombination spectrum

# Flux calibration

1. Select and observe standards near your target, or at least covering a similar range of zenith angle on the same night (in every filter that you are using, of course)
2. Correct them for atmospheric attenuation
3. Measure their DNs — mean and standard deviation — in each filter
4. Scalar-multiply all target frames by the appropriate  $f_0/\text{DN}$  ratio

## Where do the zero-points come from?

The flux or flux density for zero magnitude,

$$f_0 = \int_{\text{filter}} \tau(\lambda) F_{\lambda}(\lambda) d\lambda \quad \text{or} \quad F_{\lambda 0} = \frac{\int_{\text{filter}} \tau(\lambda) F_{\lambda}(\lambda) d\lambda}{\int_{\text{filter}} \tau(\lambda) d\lambda}$$

of a standard star like Vega (flux density  $F_{\lambda}$  in a given filter, is one form of the **zero point** for a photometric system.

Zero points are, in turn, built from a network of calibrations that took decades to get extremely precise and accurate.

- ▶ Observation of laboratory light sources and bright standard stars with the same telescope and instruments.
- ▶ Detailed spectra of the bright standards.
- ▶ Fits of detailed stellar-absorption models to the spectra.

## Flux calibration

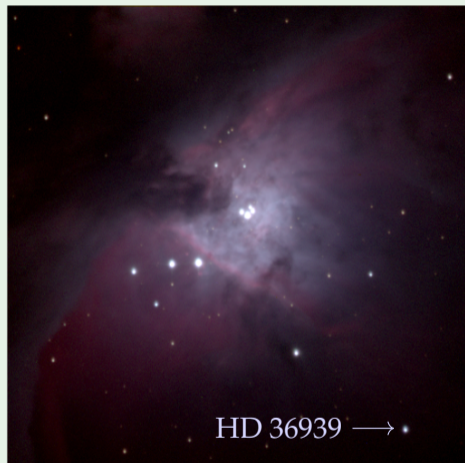
Conveniently placed in M 42 is HD 36939, a 9.01 magnitude A0V star. One night, we measured

$$B = 7.28 \times 10^4 \text{ DN/s}$$

$$G = 7.89 \times 10^4 \text{ DN/s}$$

$$R = 7.12 \times 10^4 \text{ DN/s}$$

for HD 36939. What flux conversion factors should we use for that night's RGB frames of M 42?



This is a special circumstance: we do not need to measure atmospheric absorption because HD 36939 and M 42 are always observed in the same frame, **and there is negligible difference in sec z and absorption within each frame.**

## Flux calibration

If the signal (current DN values) is actually in original DNs divided by exposure time, scalar multiply the B, G, and R frames by the factors

$$f = \frac{F_{\lambda_0}(\lambda_0)\Delta\lambda}{\text{signal}}$$

$$f_B = \frac{(6.18 \times 10^{-8})(128)(10)^{-9.01/2.5}}{7.28 \times 10^4} \text{ erg/s/cm}^2/\text{DN} = 2.70 \times 10^{-14} \text{ erg/s/cm}^2/\text{DN}$$

$$f_G = \frac{(4.10 \times 10^{-8})(80.5)(10)^{-9.01/2.5}}{7.89 \times 10^4} \text{ erg/s/cm}^2/\text{DN} = 1.04 \times 10^{-14} \text{ erg/s/cm}^2/\text{DN}$$

$$f_R = \frac{(2.32 \times 10^{-8})(101)(10)^{-9.01/2.5}}{7.12 \times 10^4} \text{ erg/s/cm}^2/\text{DN} = 0.819 \times 10^{-14} \text{ erg/s/cm}^2/\text{DN}$$

Since M 42 is an HII region, every pixel without a star has a flux equal to the sum of the spectral line fluxes spanned by the broadband filters.