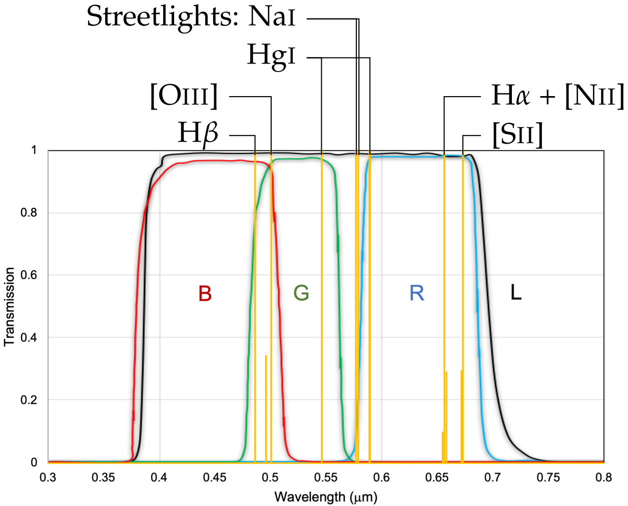
Instrumental Sensitivity

January 23, 2024

University of Rochester

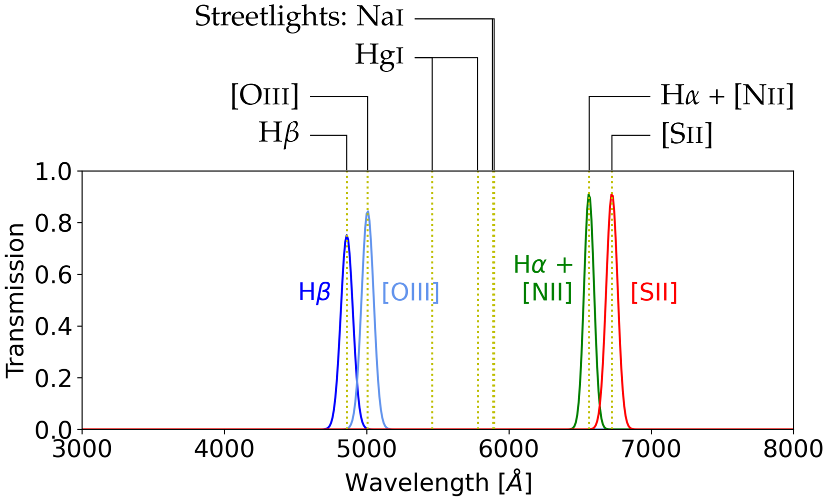
Our broadband filters

For stellar magnitudes and colors: L, R, G, and B, all of which have peak $\tau \gtrsim 0.95$. They come from Diffraction Limited (plotted below) or Baader Planetarium.



Our narrowband filters

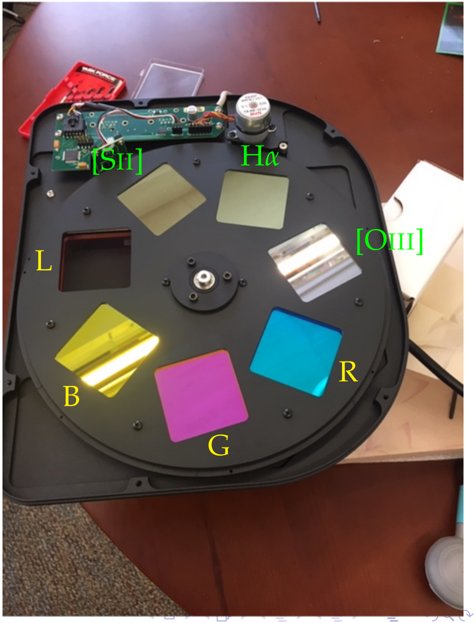
For spectral lines: Hβ, [OIII], Hα, and [SII], all of which have peak $\tau = 0.75 - 0.9$. FWHM widths are $\Delta\lambda = 85$, 85, 70, and 80 Å, respectively. Same vendors.



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.

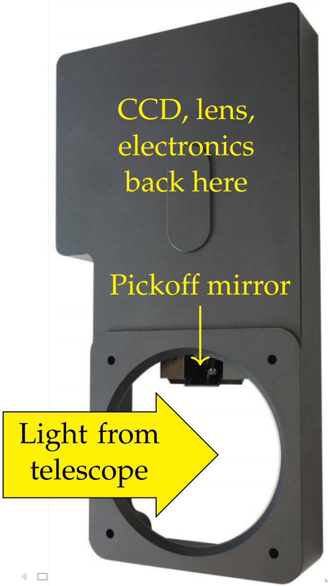
- Filter wheel #2, an FW-7, is shown on the right, open and viewed from the telescope side, and loaded up with the Diffraction Limited filter set.
  - Note that for the first part of the semester, the Hβ filter is occupying the L-filter's spot.
- All filters except L are dielectric multilayer interference filters, so in reflected light they do not look like the color that they transmit.



SBIG STX external offset autoguider

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

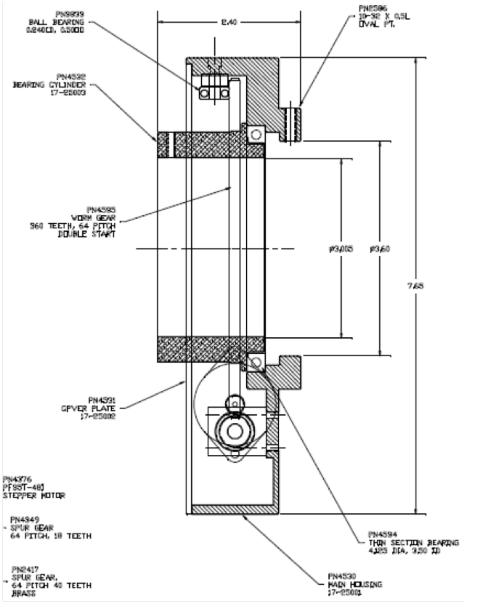
- Its light comes from a small pickoff mirror that protrudes from the edge of the telescope field of view toward the imaging CCD.
- Since it receives its light without having that light go through the filters first, and since its field of view is larger, it is considerably better for autoguiding than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



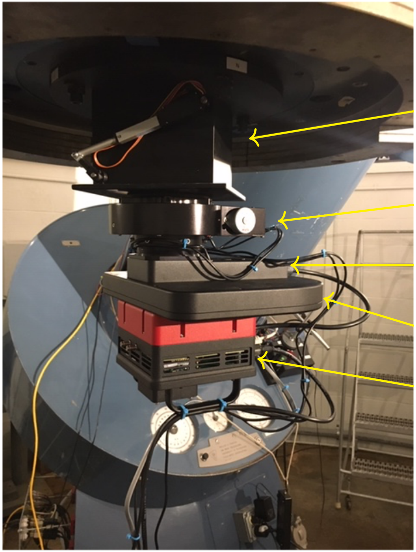
Optec Pyxis instrument rotator

A schematic of its cross-section is visible to the right.

- It can rotate the camera, filter wheel, and external autoguider precisely and reproducibly about the telescope's optical axis. Based on ball bearings and a worm/wheel mechanism.
- The external offset autoguider and the rotator make it possible to find a suitable star for autoguiding anywhere in the sky.



The back of the telescope



Photometer box, including remote-control camera cover

Rotator

Offset autoguider

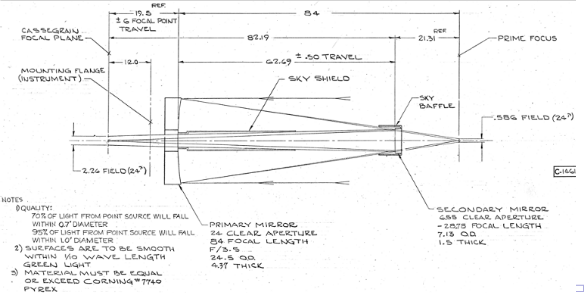
Filter wheel #2

Camera #2

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 1×1 binning, 15.4 arcmin on a side, 21.7 arcmin diagonal
  - The autoguider CCD: 0.259 arcsec/pixel, 2.8×2.1 arcmin
- Unvignetted field of view 24 arcmin in diameter
- Collecting area: $2700\ \mathrm{cm}^2 = 0.27\ \mathrm{m}^2$



Dome & TCS

Ash Dome. Installed in 2014 to replace the original Astro Dome.

DFM Engineering TCSGalil telescope control system (TCS). Third major upgrade in 2019.

The TCS enables all the components previously discussed to be operated remotely *via* a wireless but fast network connection and Windows Remote Desktop.

Brightness of celestial objects

Recall the magnitude:

- For two objects A and B, their fluxes F_A and F_B (power per unit area, in real physics units) and magnitudes are related by

$$m_A - m_B = 2.5 \log\left(\frac{F_B}{F_A}\right)$$

- From here, we just need to convert to/from physical units for a zero-magnitude star, usually Vega. Here is Vega, for the Johnson filters:

Band	λ_0 μm	$\Delta\lambda$ μm	ν_0 10^{14} Hz	F_λ W cm^{-2} μm^{-1}	F_ν W m^{-2} Hz^{-1}	$\log F_\nu$ F_ν in W m^{-2} Hz^{-1}
U	0.36	0.07	8.3	4.35×10^{-12}	1.88×10^{-23}	-22.73
B	0.43	0.10	7.0	7.20×10^{-12}	4.44×10^{-23}	-22.36
V	0.54	0.09	5.6	3.92×10^{-12}	3.81×10^{-23}	-22.42
R	0.70	0.22	4.3	1.76×10^{-12}	2.88×10^{-23}	-22.54
I_S	0.80	0.24	3.7	1.20×10^{-12}	2.50×10^{-23}	-22.60

Examples

We do not know what the signal power would be from an arbitrary object in the sky at an arbitrary wavelength, but we do know the magnitudes of many stars.

What is the power that the Mees telescope collects from a 12.5 magnitude A0V star within the bandwidth of the G filter?

From the spectrum above, we see that the G filter covers wavelengths $\lambda = 5010 - 5900$ Å. Thus, its center wavelength is $\lambda_0 = 5460$ Å and its bandwidth is $\Delta\lambda = 890$ Å.

This is very much like the Johnson V filter in the table above, so we will assume the same F_λ in G for the zero magnitude star:

$$\begin{aligned} F_0 &= F_\lambda \Delta\lambda = (3.92 \times 10^{-12}\ \mathrm{W\ cm^{-2}} \mu\mathrm{m}^{-1})(0.089 \mu\mathrm{m}) \\ &= 3.5 \times 10^{-13}\ \mathrm{W\ cm^{-2}} \end{aligned}$$

Examples

Then the 12.5-magnitude flux $F_{12.5}$ is given by

$$12.5 - 0 = 2.5 \log\left(\frac{F_0}{F_{12.5}}\right)$$
$$F_{12.5} = 10^{-5}F_0 = 3.5 \times 10^{-18}\ \mathrm{W\ cm^{-2}}$$

The telescope's collecting area is $a = 2700\ \mathrm{cm}^2$, so

$$P_S = F_{12.5}a = \boxed{9.4 \times 10^{-15}\ \mathrm{W}}$$

Examples

Atmospheric turbulence (seeing) blurs the images of stars taken with uncorrected ground-based telescopes, typically to a diameter of 2 arcsec at Mees. For simplicity, suppose that this image is uniform in brightness. How many pixels of the array does it cover?

The solid angle of this 2 arcsec uniform blur is

$$\Omega_{\text{seeing}} = \pi \left(\frac{2 \text{ arcsec}}{2} \right)^2 = \pi \text{ arcsec}^2$$

The number of pixels is then

$$N = \frac{\Omega_{\text{seeing}}}{\Omega_{\text{pixel}}} \approx \boxed{63}$$

In reality, the seeing-broadened stellar image would be gaussian, with a typical full width to half-maximum (FWHM) around 2 arcsec.

Examples

Suppose the star in the first example produces the image in the second example. How many electrons are collected in each pixel of the star's image in a $\Delta t = 300$ s exposure? By how many data numbers (DN) does the star's image exceed the background sky level in the displayed image?

The total charge in the star's image, collected within Δt, is $Q_S = I_S \Delta t$. Ignoring atmospheric transmission (for now), the number n of electrons in each of the $N = 63$ pixels is

$$n = \frac{Q_S}{N q_e} = \frac{I_S \Delta t}{N q_e} = \frac{\tau\eta}{N}\frac{\lambda_0 P_S}{hc}\Delta t = \frac{(0.96)(0.6)}{63}\frac{(5460\text{Å})(9.4\times 10^{-15}\text{ W})}{hc}(300\text{ s})$$

$$= \boxed{71,000\text{ electrons}} = (71,000)e^{-}\left(\frac{DN}{1.35e^{-}}\right) = \boxed{53,000\text{ DN}}$$

This stellar image would be close to saturation; the maximum output of a camera pixel is 65,536 DN ($= 2^{16}$ DN).

Examples

On a moonless night, in a 300 s exposure in G, the background is measured — in blank, star-free sky — to be 70 DN per pixel. Is this observation background-limited?

We know from the CCD camera specs that read noise is

$$\Delta Q_{R,\mathrm{rms}} = 9q_e$$

For background and dark current, we get

$$\overline{Q_B} = q_e \left(\frac{1.35}{\mathrm{DN}}\right)(70\ \mathrm{DN}) = 105q_e \qquad \overline{Q_D} = q_e(0.009e^-\ \mathrm{s}^{-1})(300\ \mathrm{s}) = 2.7q_e$$

$$\Delta Q_{B,\mathrm{rms}} = \sqrt{105q_e^2} = 10.2q_e \qquad \Delta Q_{D,\mathrm{rms}} = \sqrt{2.7q_e^2} = 1.6q_e$$

No, it is not; background shot noise and read noise contribute just about equally.

Examples

- Sure enough, well-behaved parts of the same image have $\Delta Q_{\text{rms}} = 11q_e$, not too far from the $13.7q_e$ expected from the three contributions above.
- For broadband observations on moonless nights, 8–10 minutes frames should be taken instead of 5 minute frames like this one.

Suppose that we had a moonless night and were taking $\Delta t = 600$ s exposures. How many of them would we have to take to barely detect (S/N = 5) 24$^{\text{th}}$ magnitude stars within the size of the stellar image as in the second example?

Suppose that gives a background of $n = 140$ DN = 189 electrons per pixel on average, and that the observation is background-limited. In $N = 63$ pixels, the noise current is therefore

$$I_{B,\text{rms}} = \sqrt{\frac{q_e \overline{I_B}}{\Delta t}} = \sqrt{\frac{q_e}{\Delta t}\frac{Nnq_e}{\Delta t}} = \frac{q_e}{\Delta t}\sqrt{Nn}$$

$$\frac{I_{B,\text{rms}}}{q_e} = 0.18\ \text{s}^{-1}$$

Examples

Find the signal power — call it P_{S5} — that is five times noise:

$$\frac{S}{N} = \frac{I_S}{I_N} = \frac{\tau\eta q_e \lambda_0 P_{S5}}{hcI_{B,\mathrm{rms}}} = 5$$

$$P_{S5} = \frac{5hcI_{B,\mathrm{rms}}}{\tau\eta q_e \lambda_0} = 5.7 \times 10^{-19}\ \mathrm{W}$$

According to the chart of flux density for zero magnitude, the power for a 24$^{\mathrm{th}}$ magnitude star in the G filter is

$$P_{G=24} = F_\lambda(V) a \Delta\lambda (10)^{-24/2.5} = 2.37 \times 10^{-19}\ \mathrm{W}$$

So the noise current needs to be smaller by a factor of

$$f = \frac{P_{S5}}{P_{G=24}} = 2.4$$

Examples

This, in turn, requires an increase in the exposure time by a factor of $f^2 \approx 5.8$, since

$$\left(\frac{S}{N}\right)_{BL} = P_S\sqrt{\frac{\lambda\tau\eta}{hcP_B}\Delta t}$$

Since other problems would set in were we to try and take a single 3480 s exposure, this result suggests taking a total of six 600 s exposures.

Examples

Repeat the last example under the assumption that the seeing is 1 arcsec instead of 2 arcsec.

The background, which is spread uniformly over the image, stays the same, independent of seeing.

But now, the stars are concentrated in $N = 63/4 \approx 16$ pixels, and only 16 pixels worth of background provide noise that may obscure the signal:

$$I_{B,\mathrm{rms}} = \frac{q_e}{\Delta t}\sqrt{Nn}$$

$$\frac{I_{B,\mathrm{rms}}}{q_e} = 0.092\ \mathrm{s}^{-1}$$

$$\frac{S}{N} = \frac{I_S}{I_N} = \frac{\tau\eta q_e \lambda_0 P_{S5}}{hcI_{B,\mathrm{rms}}} = 5$$

$$P_{S5} = \frac{5hcI_{B,\mathrm{rms}}}{\tau\eta q_e\lambda_0} = 2.9 \times 10^{-19}\ \mathrm{W}$$

Examples

Since, as we have seen, the power from a 24^{th} magnitude star is

$$P_{G=24} = F_\lambda(V) a \Delta\lambda (10)^{-24/2.5} = 2.37 \times 10^{-19}\ \text{W}$$

we almost get S/N = 5 on such stars in a single 600 s frame. So, two frames, even through it is a little overkill.

Better/worse seeing improves/degrades sensitivity **substantially**. Do not try to observe faint objects with bad seeing.

In the days of astronomical photography, 24^{th} magnitude stars were the faintest detected by the world's largest telescopes (4–5 m diameter). With CCD arrays, experiments can be done with a 24-inch telescope that once required a 200-inch telescope.