Everything You Always Wanted to Know About Narrowband Filters, But Were Afraid to Ask

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Astrodon Imaging

Advanced Imaging Conference

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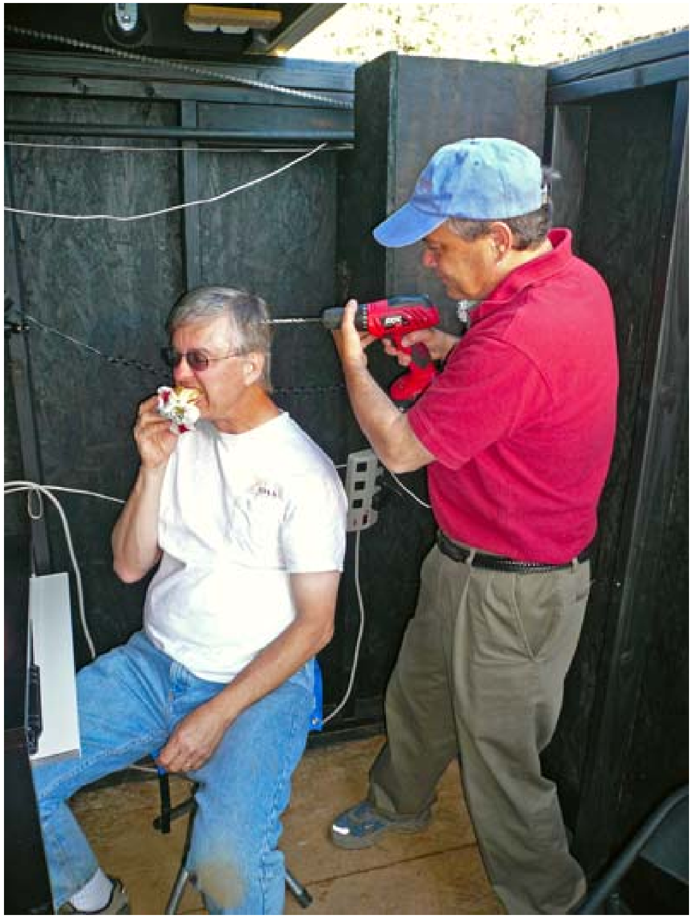
Steve Mandel (what it looks like)

Re-decorating Steve's and Sandy Barnes' SRO Observatory (we use it a lot!)



If that doesn't work, drastic action may be needed. Keith Quatrocchi, M.D. helping Mike Mayda.

Narrowband Filter (NB)Topics

- Benefits
- Terminology
- Definition
- Bandwidth
  - Contrast, light pollution, moon, angular velocity, NII/H-α
- Manufacturing variability
  - FWHM myth
- Spectral (angular) blue shift
  - Faster optics
  - One filter works for all?
- Practical implications

Benefits of NB Imaging

Enhance contrast

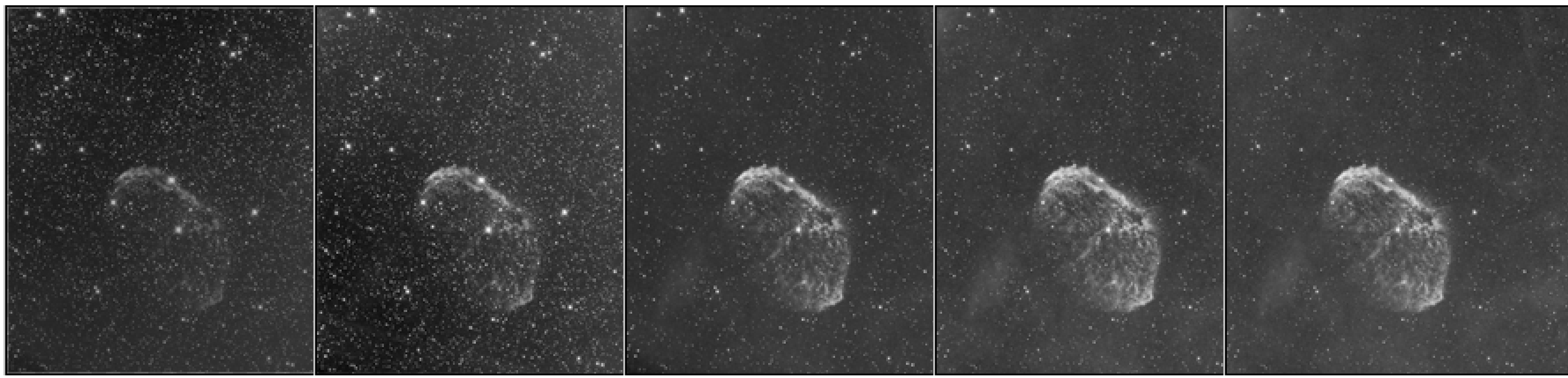
Emphasize different structures H-a, OIII, SII..

Use in light polluted areas

Extend Imaging Time when the moon is up

Contrast Improvement

Crescent Nebula, Wolf-Rayet
Bubble in Cygnus, NGC 6888



Wide Red (Orange) | Narrow Red | H-α 9 nm | H-α 6 nm | H-α 4 nm

3x5min exposures, RCOS 12.5” Ritchey-Crétien, SBIG
STL11000XM CCD, Bisque Paramount ME

Enhanced Structure at Hi-Res

Crescent Nebula in Cygnus, NGC 6888

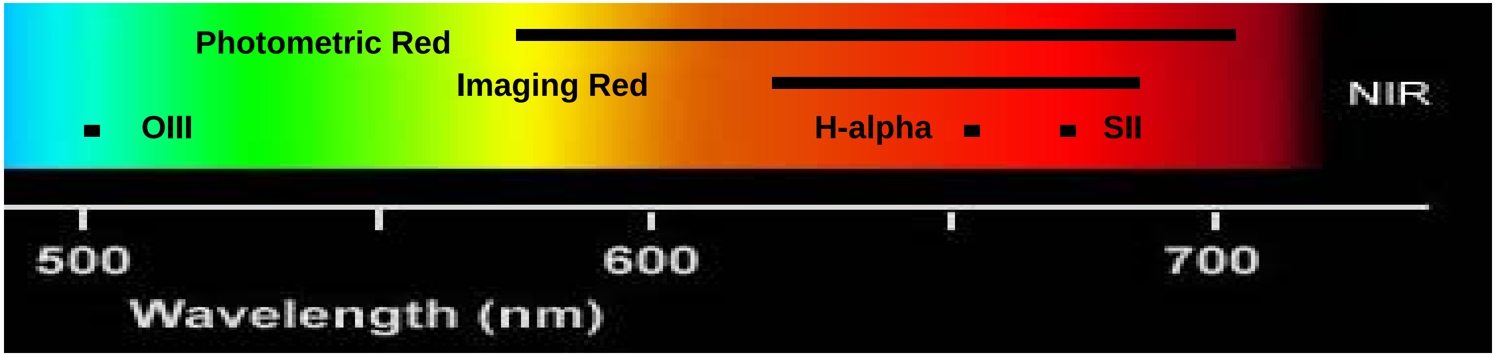
Conventional RRGB
(courtesy Rob Gendler)

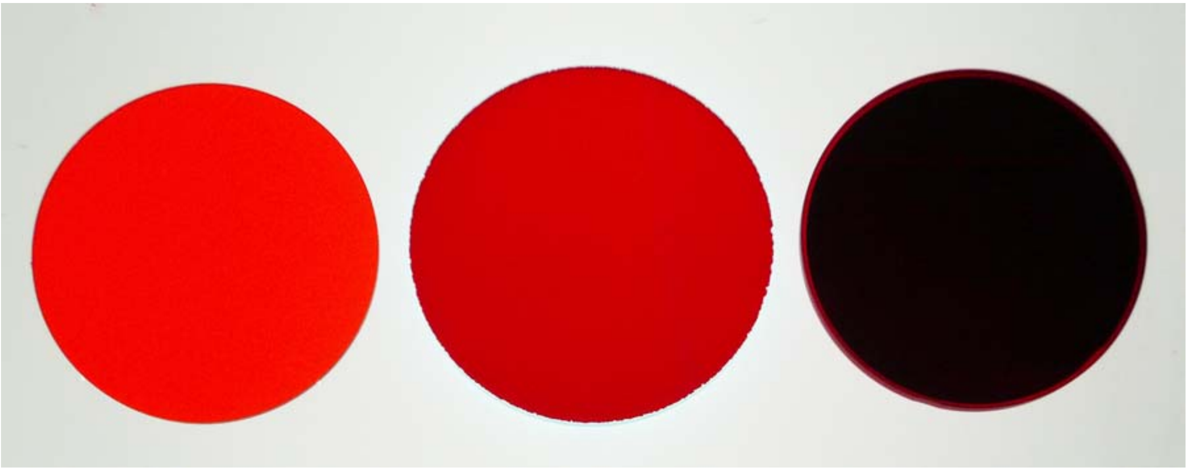
Red = H-α
Blue=Green=OIII
(Don Goldman)

Narrowband Terminology

- Wavelength
- Transmission Plot
- OD, or Blocking Plot
- S/N or IB, Integrated Blocking

Filters and Wavelength





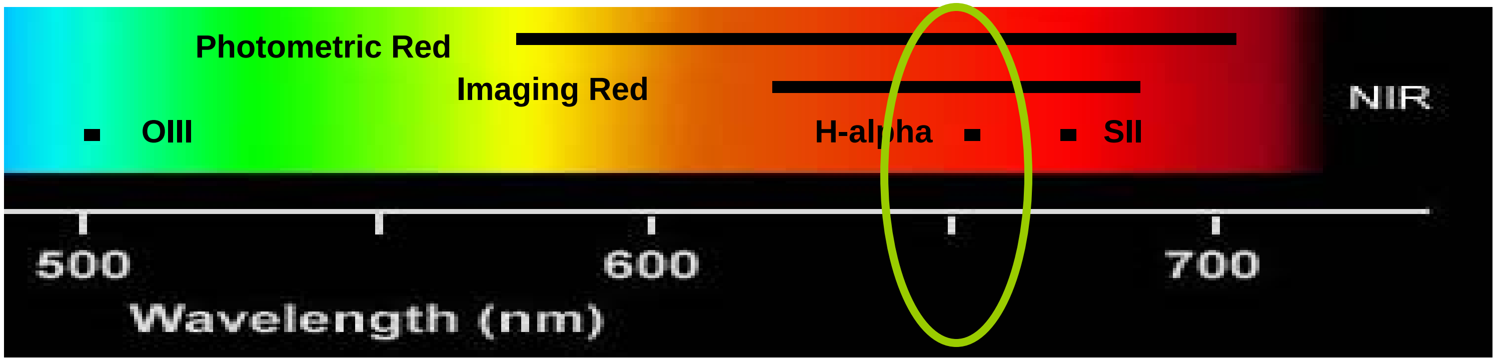
Photometric Red (UVB**R**I)

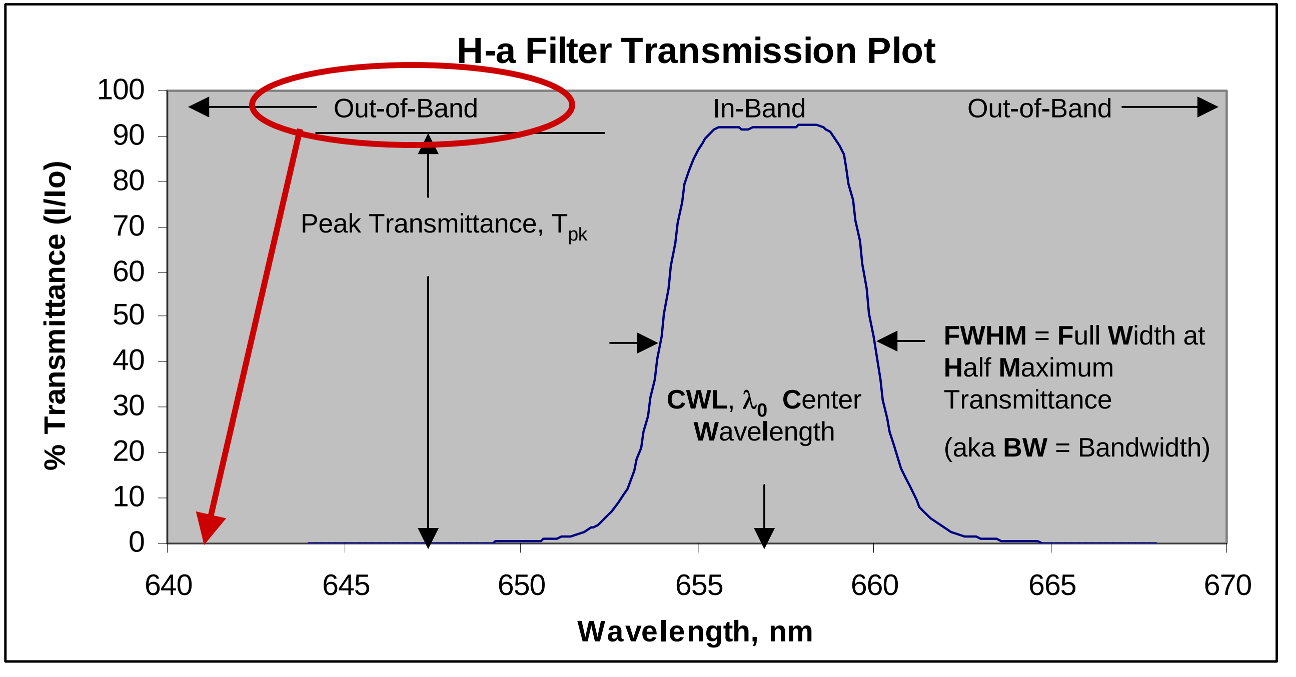
Imaging Red (**R**GB)

H-alpha

H-alpha

Narrowband Terminology





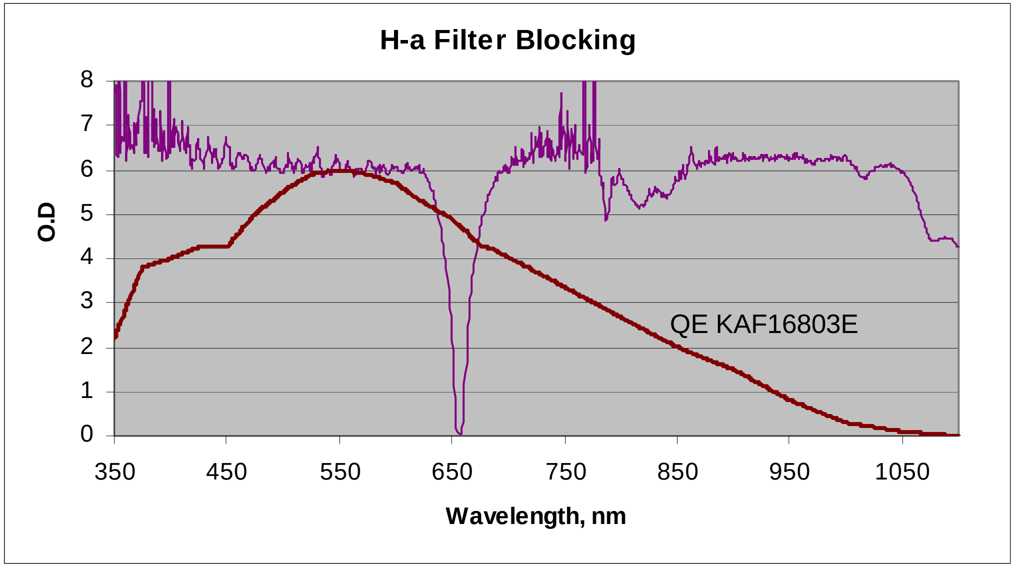
Out-of-Band Blocking

- O.D. = Optical Density = Absorbance
- OD = -log(Transmittance) = -log (%T/100)
- Larger OD means less out-of band light leakage

OD	Transmittance	%T
0.3	0.50	50
1.0	0.10	10
2.0	0.01	1
3.0	0.001	0.1
4.0	0.0001	0.01
5.0	0.00001	0.001

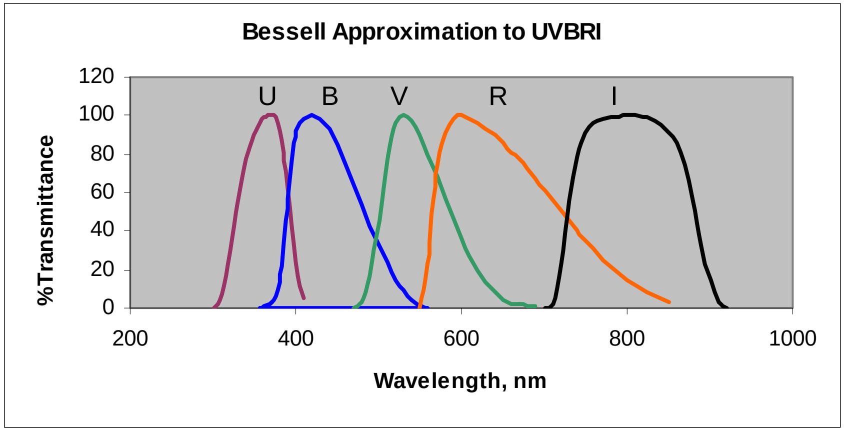
- An OD 4 filter blocks 99.99% of the light outside the bandpass
- Must use OD scan, not %T scan

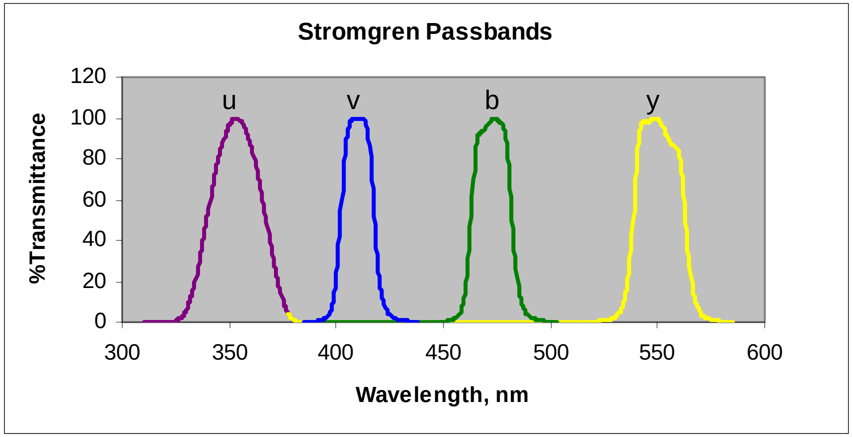
Blocking Scan



- Blocking covers the sensitivity range of the CCD
- Light leakage outside of the bandpass will be detected
- Comparing significant light coming through the narrow bandpass to little light coming in over a huge wavelength range outside the bandpass
- This filter could be specified as > OD4 (good)
- Quantified by S/N or IB (Integrated Blocking)

What is a Narrowband Filter?

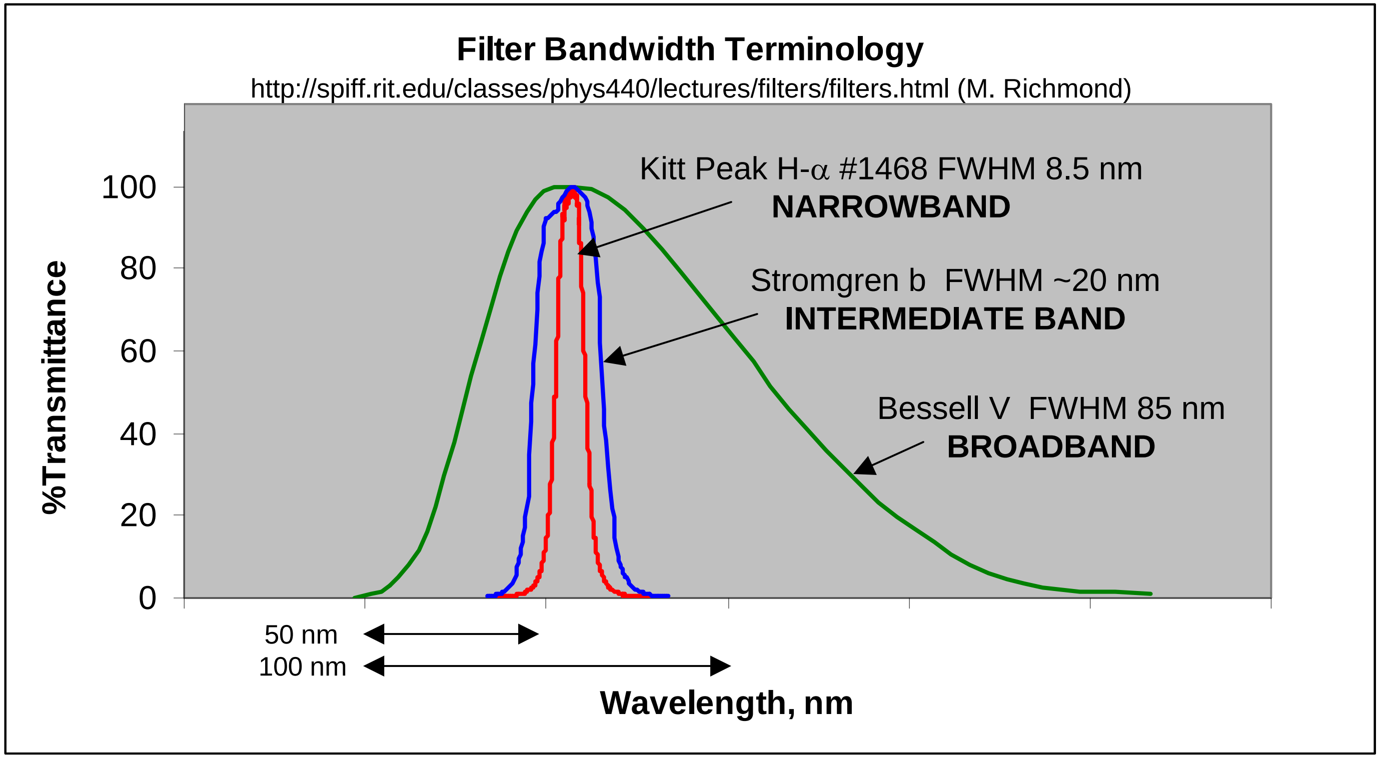




- Use photometric filters as a guide
- Johnson-Cousins (Bessell) UVBRI as broadband
- Stromgren* uvby as intermediate filters

* Originally designed for fast surface gravity and metallicity studies of stars

What is a Narrowband Filter

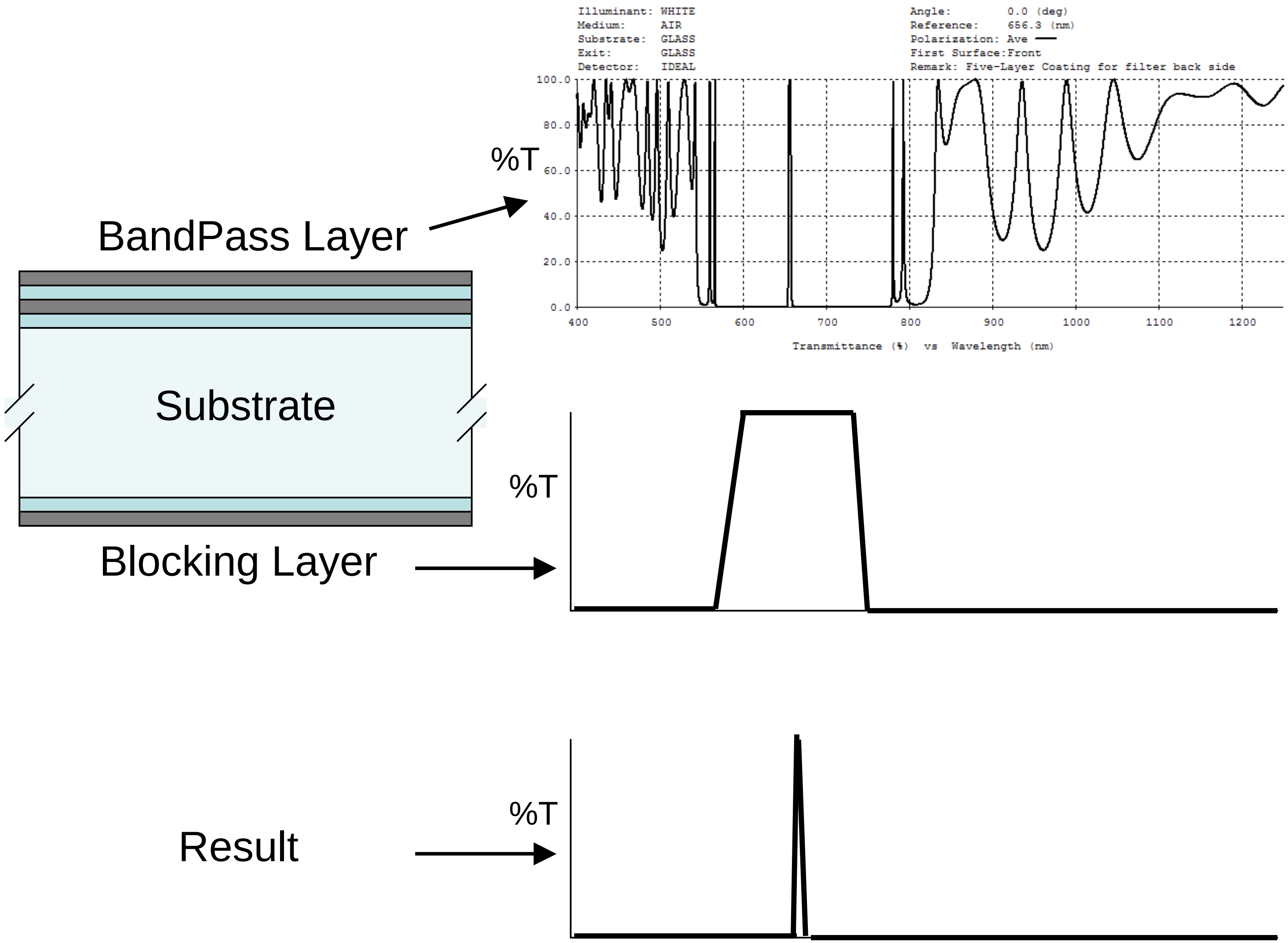


- Melles Griot Glossary
  - http://www.mellesgriot.com/glossary/wordlist/glossarydetails.asp?wID=100
  - Broadband FWHM >60 nm
  - Intermediate FWHM 20-60 nm
  - Narrowband FWHM <20 nm
- Michael Bessell
  - http://www.mso.anu.edu.au/~bessell/araapaper.pdf (Annu. Rev. Astron. Astrophys, 2005, 43)
  - Broadband FWHM < ~100 nm
  - Intermediate FWHM ~7 – 40 nm
  - Narrowband FWHM < ~7 nm

Proposed Narrowband Definition

- Broadband > 60 nm (FWHM)
- Intermediate Band 11 – 60 nm
- Narrowband ≤ 10 nm
- Ultra-narrowband < 4 nm (split H-a, NII)

How NB Filters Are Made



Close Up of Narrowband Filter

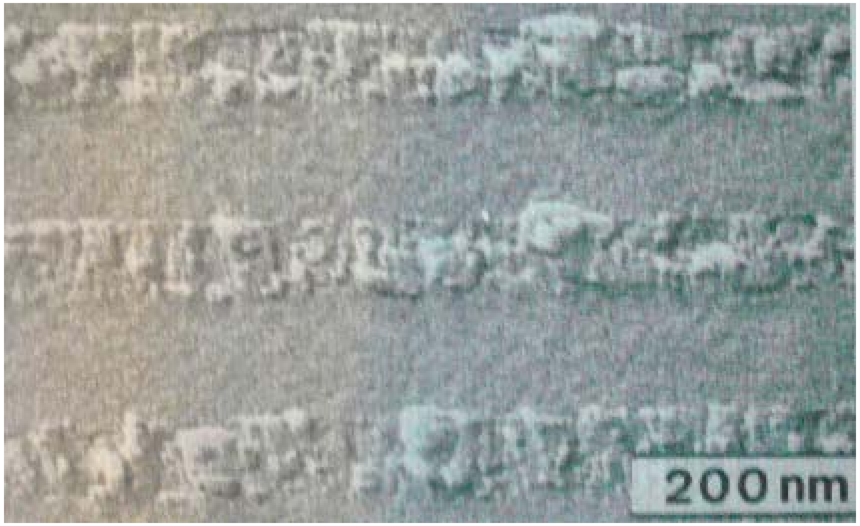
H

L

H

L

H



Ta_2O_5 tantalum pentoxide

SiO_2 silicon dioxide

Ta_2O_5

SiO_2

Ta_2O_5

Micrograph ref. ThermoCorion

0.2 microns
0.0002 mm
Human hair 50 mic.

H = High refractive index layer (e.g. 2.3)

L = Low refractive index layer (e.g. 1.45)

N_e = effective index of layer = sqrt (H * L) = 1.8 (affects blue shift)

Are Astronomy NB Filters Special?

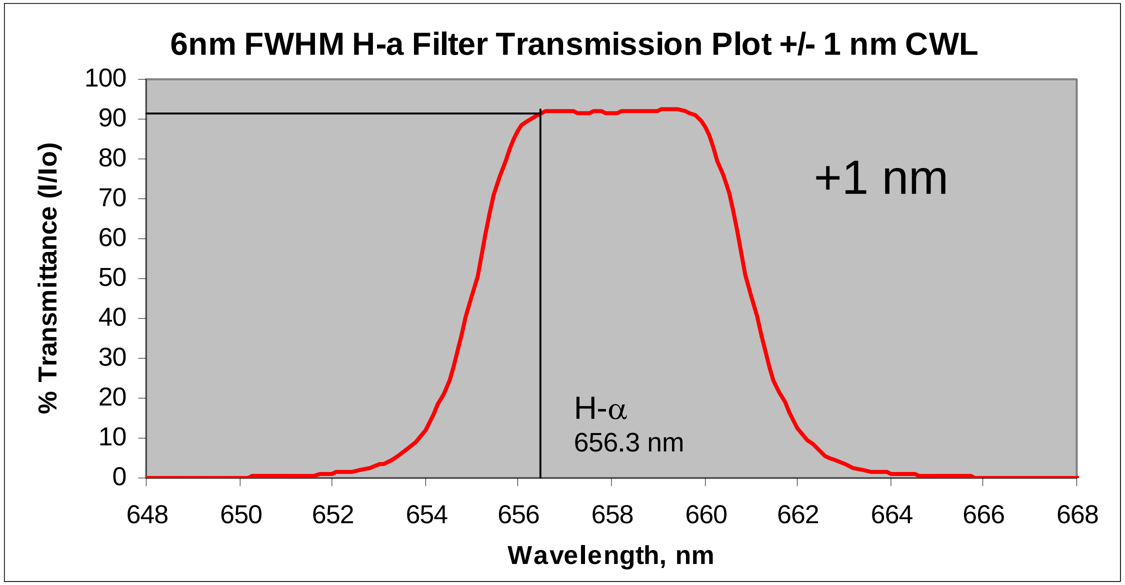
Off-the-Shelf

Company	Part	CWL	FWHM	OD	T_{pk} (%)	25mm	50mm
Thermo Corion	S10-656-	656 ±2	11 ±2	4	50	$106	$256
Edmund Optics	M43-138	656 ±2	10 ±2	3	≥50	$79.50	$153.70
Melles Griot	03FIR06	656.3 +2/-0	10 ±2	4	45	$111	-

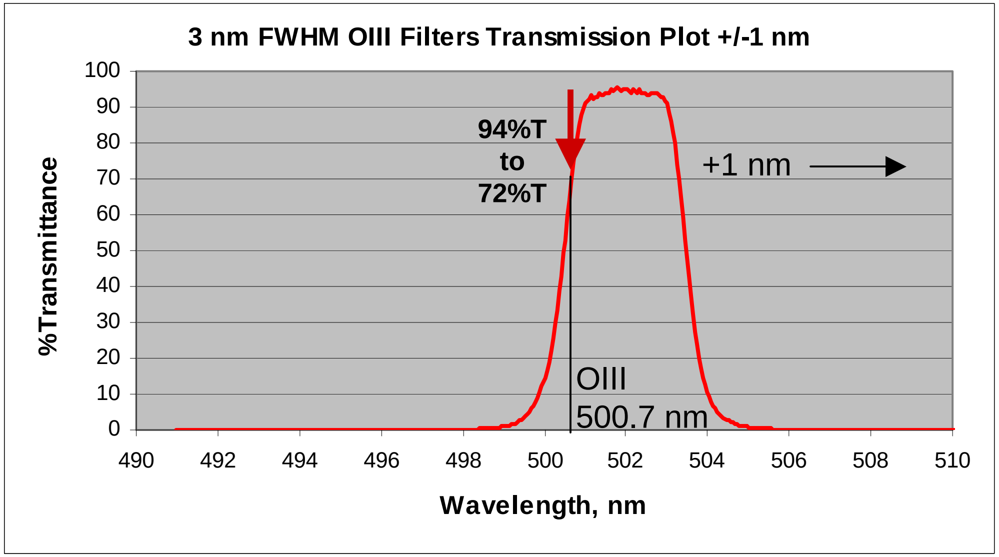
Astronomy NB CCD Filters

- Smaller FWHM - typically 4.5 – 7 nm
- Higher T_{pk} - 70-95%
- OD - often not specified (important?)
- Need better than ±2 nm CWL for 6 nm FWHM
- Let's see what effect ±1 nm CWL has

Manufacturing - ±1 nm CWL 6 nm H-α

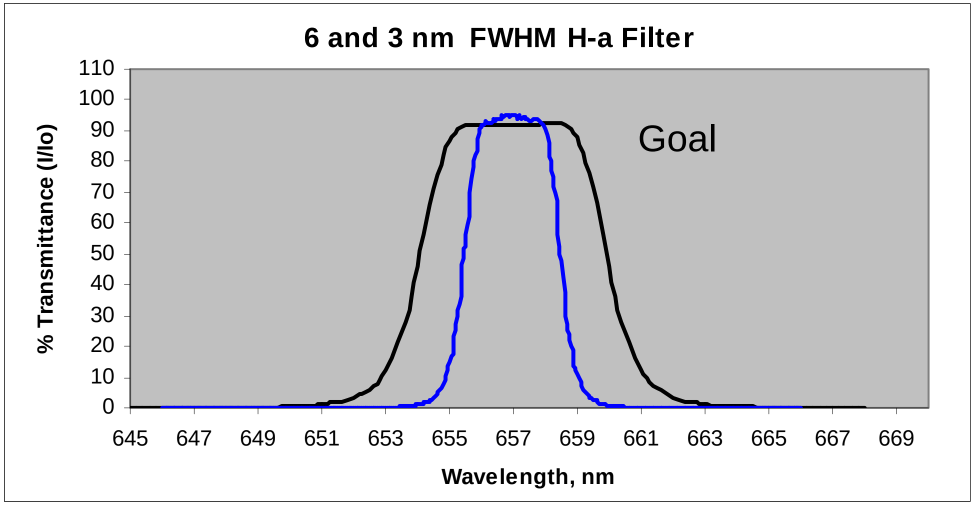


Manufacturing ±1 nm CWL 3 nm OIII

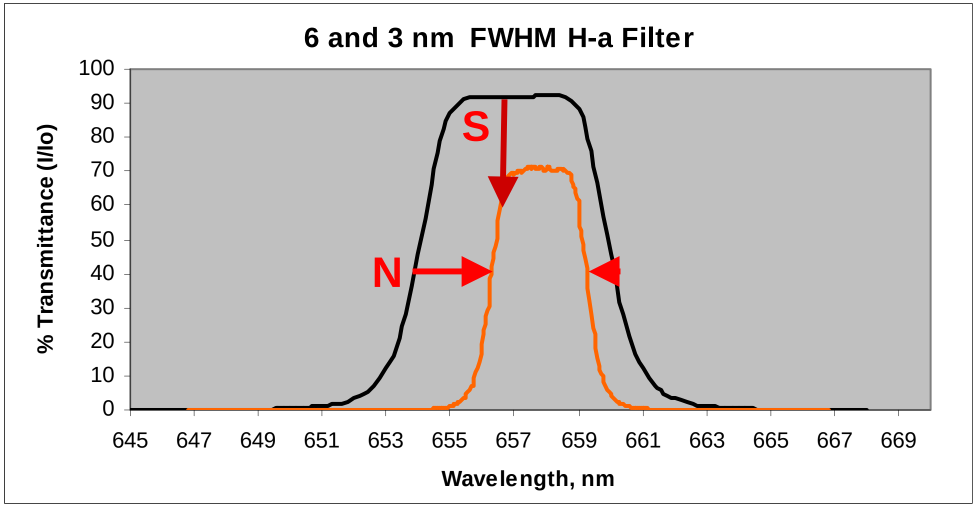


- No change for -1 nm shift (~94%T)
- 94% to 72% for +1 nm shift at OIII
- If T_{pk} at λ_0 is 80%, +1 nm shift $\rightarrow$ <62%T at OIII

T_{pk} and FWHM Myth



- Idealized case – same T_{pk}, different FWHM
- Can compare effect of just FWHM on **S/N**
- Very difficult to CONSISTENTLY keep T_{pk} large with narrower filters



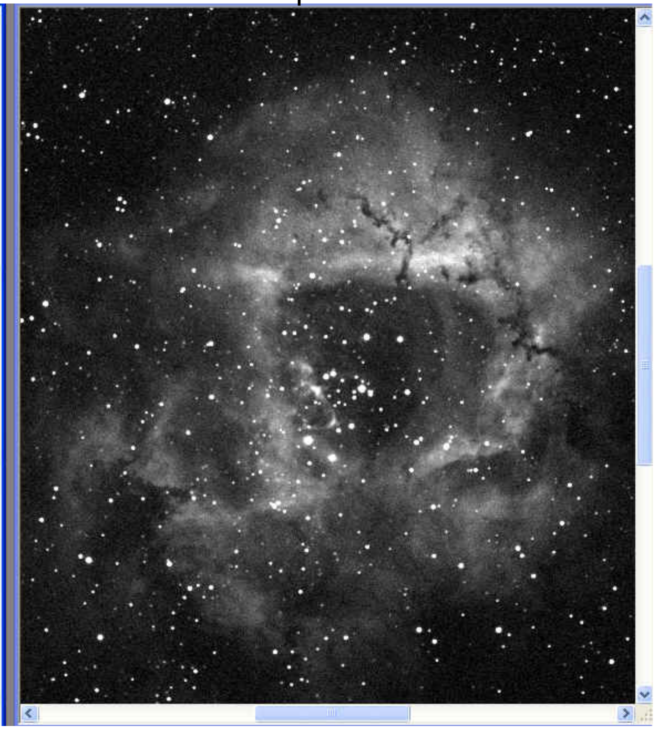
- Lower graph is typical
- Causes confusion (two parameters are changing)
- Smaller FWHM lowers **N** in **S/N** (moon, light poll)
- Smaller T lowers **S** in **S/N**
- ~Cancels the **S/N** "perceived" advantage of narrower filter

OIII FWHM Image Comparison

6 nm, T_{pk} = 90%

Sig = 325 ADU
Bkg = 257 ADU
Bkg STD = 16.84
S = 81.6
N = 19.1
S/N = 4.27

3 nm, T_{pk} = 93%



Sig = 187 ADU
Bkg = 118 ADU
Bkg STD = 13.04
S = 82.8
N = 15.9
S/N = 5.21

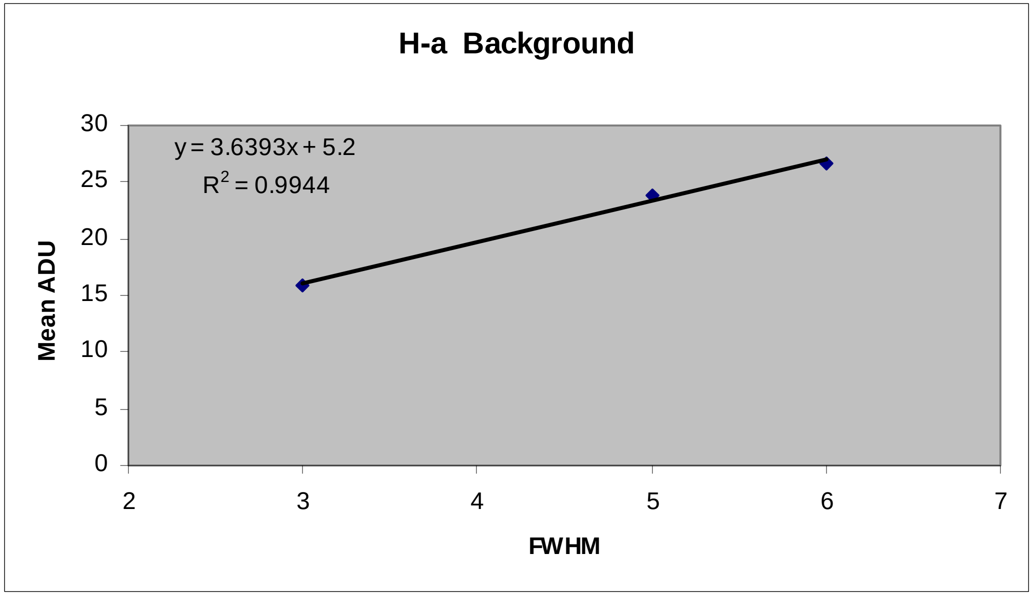
- Apogee U16M (KAF16803) at -25C (gain = 1.2)
- Takahashi FSQ106N at f/5
- 3 x 10 min mean combined with darks and flats
- City backyard (18.3 mag/sqarcsec, no moon)
- S = (Sig-Bkg)·g
- N = SQRT(S · g + BKG STD^2)
- Compare regions with no stars

S/N improvement of 22% with similar T_{pk} but half the FWHM

OIII Test Implications

- Halving the FWHM halved the bkg ADU
- Signals are comparable due to similar T_{pk}
- OIII is more sensitive to moonlight and light pollution
- May mix narrower OIII filter with wider H-α and SII filters
- Need T_{pk} to be similar to achieve advantage

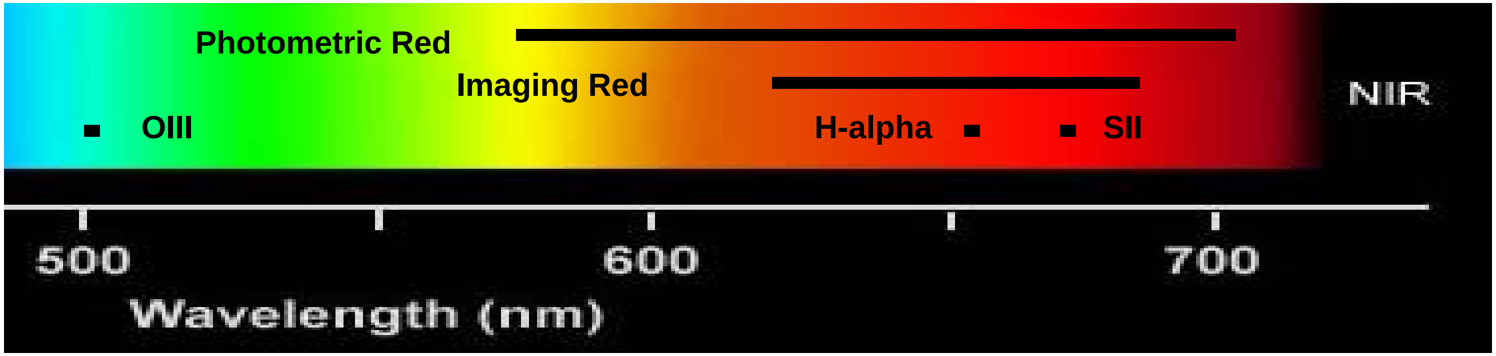
H-α - FWHM vs. Background

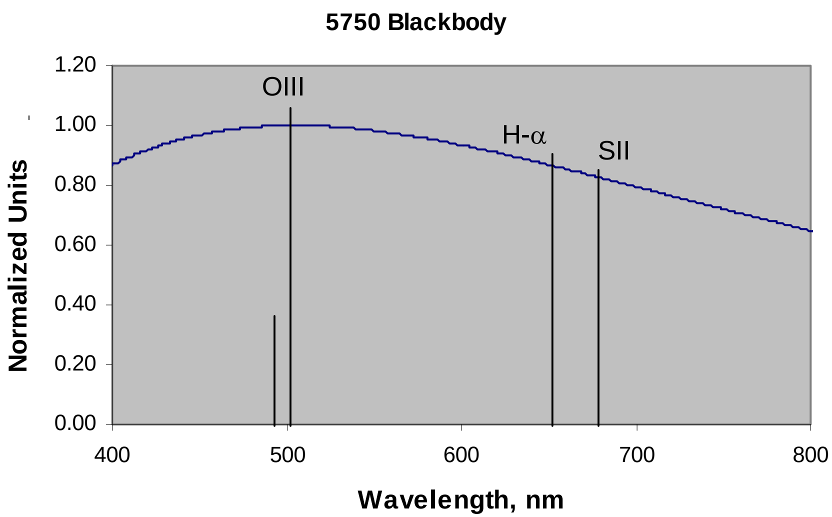


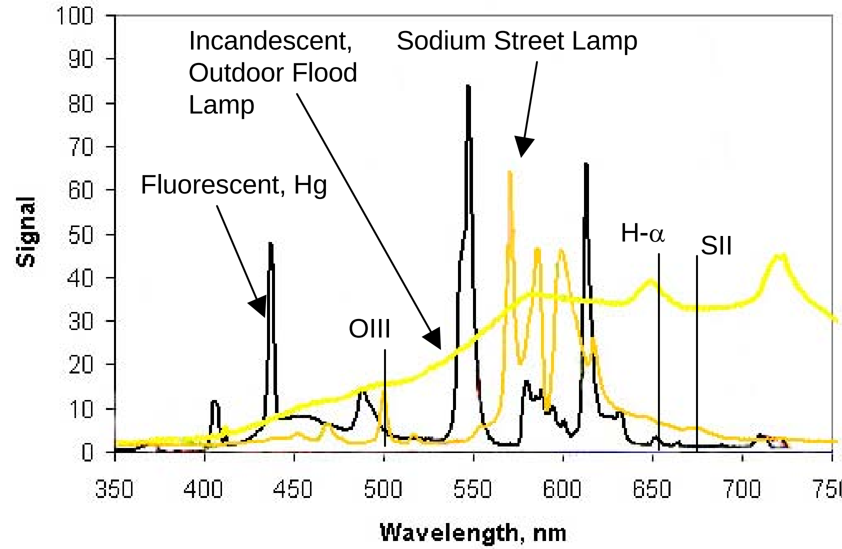
- 12.5” RCOS RC
- Apogee U16M at -20 °C
- 3 x 10 min unbinned exp.
- Darks, flats, bias calibrated
- Mean combined
- Taken in same region w/o stars in CCDStack
- T_{pk} ~ 92-95%T

- Regular relationship
- Lower FWHM leads to lower background
- Need to keep high T_{pk} for good S/N

Moonlight & Light Pollution

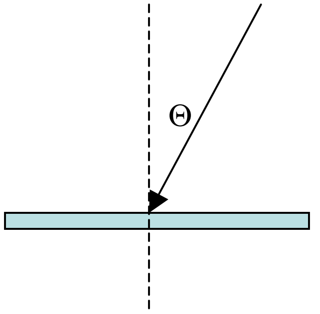




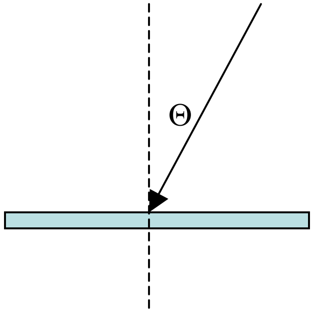


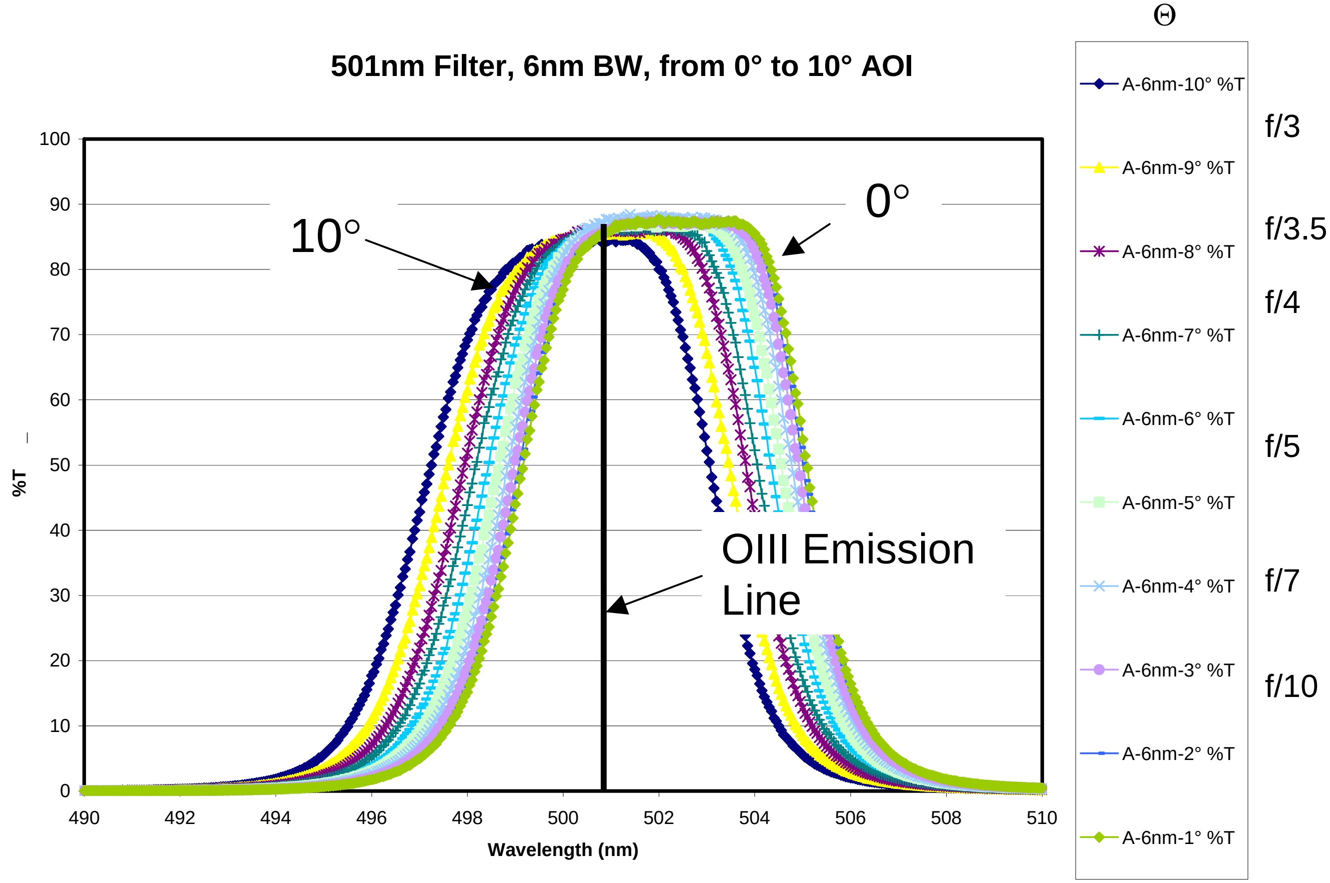
Blue Shift With Faster Optics

- Simple tilts in collimated light will cause λ_0 to shift toward shorter (blue) wavelengths
- $\lambda_\Theta = \lambda_0 \cdot \sqrt{(n_e^2 - \mathrm{Sin}^2\,\Theta)}\ /\ n_e$
- n_e effective index of the coating (~1.8)
- λ_Θ is the shifted wavelength
- Faster optics may shift the passband off of the emission line



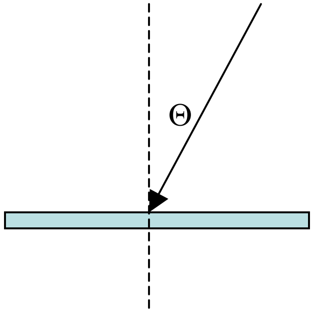
Angular Measurement 6 nm OIII

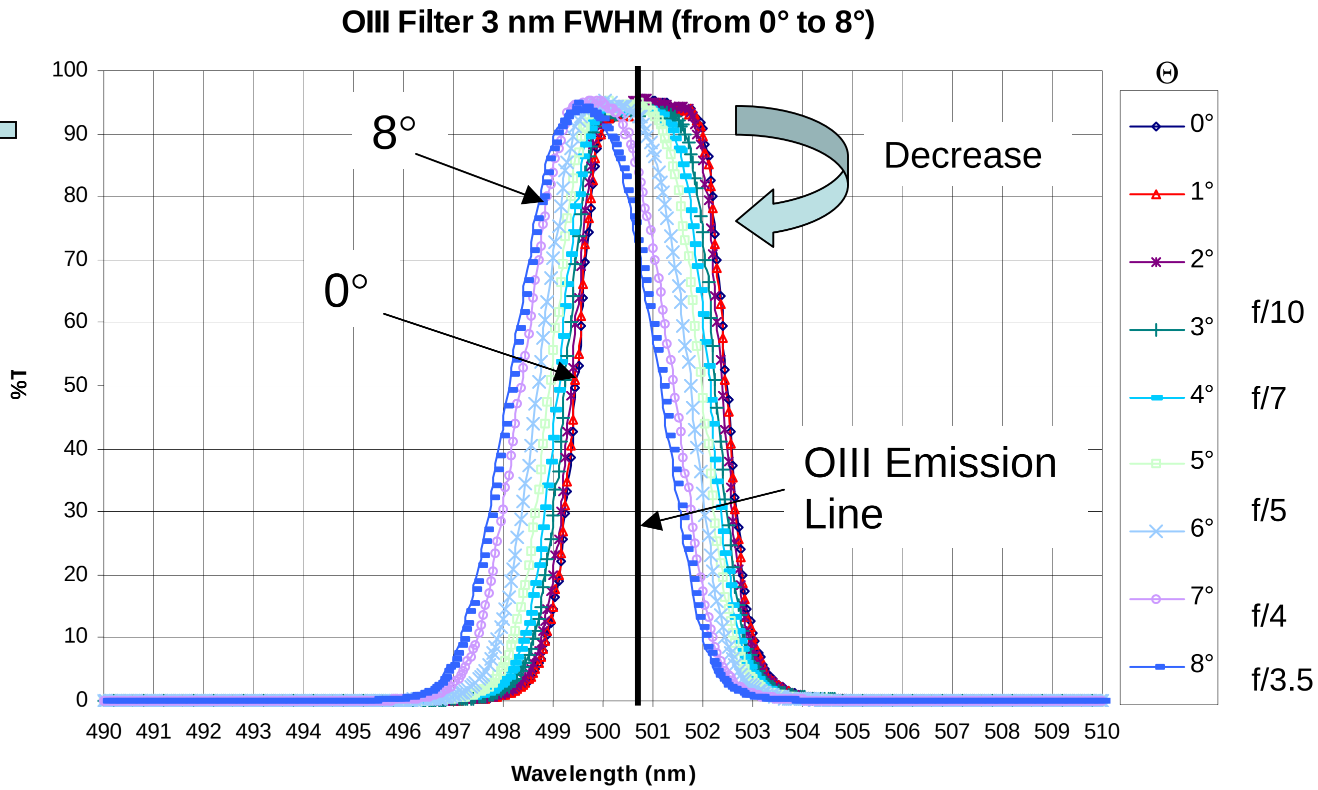




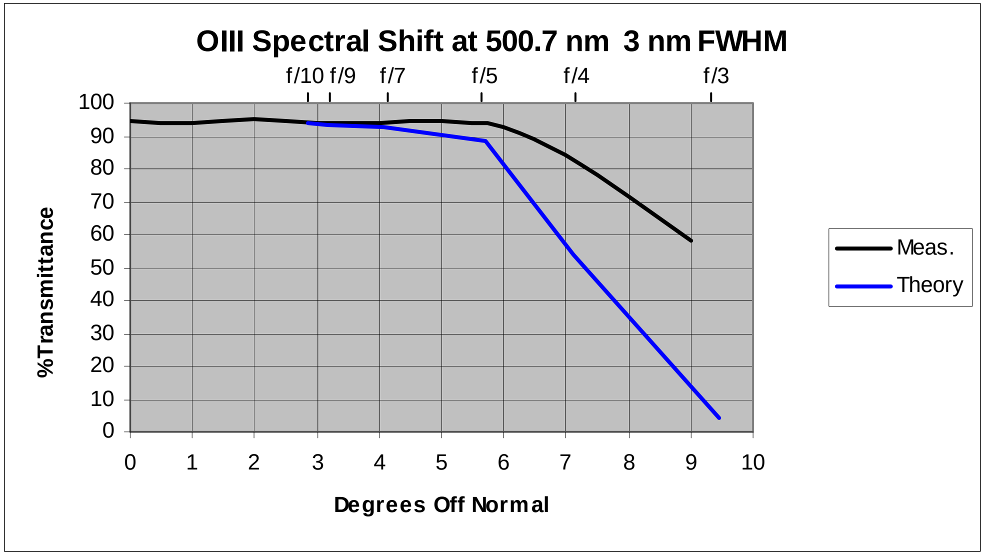
- Not much effect at 6 nm FWHM
- Because emission line at low wavelength side
- If at high side, will see lower T at OIII

Angular Measurement 3 nm OIII



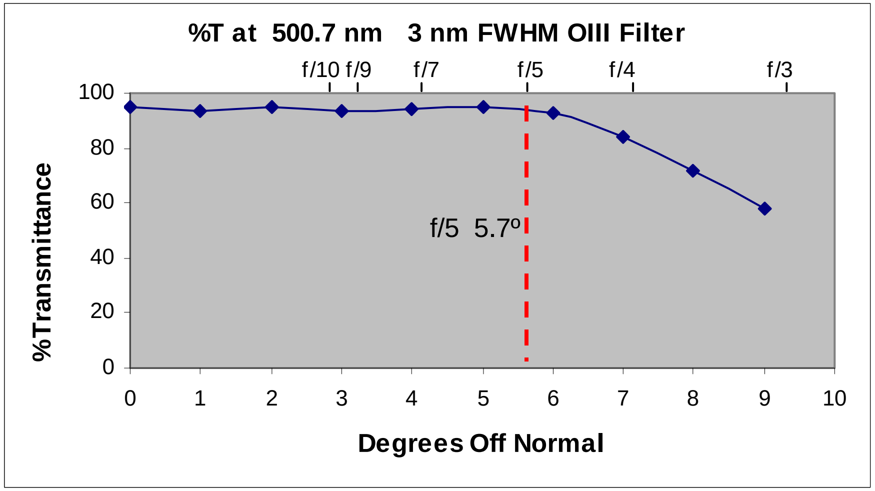


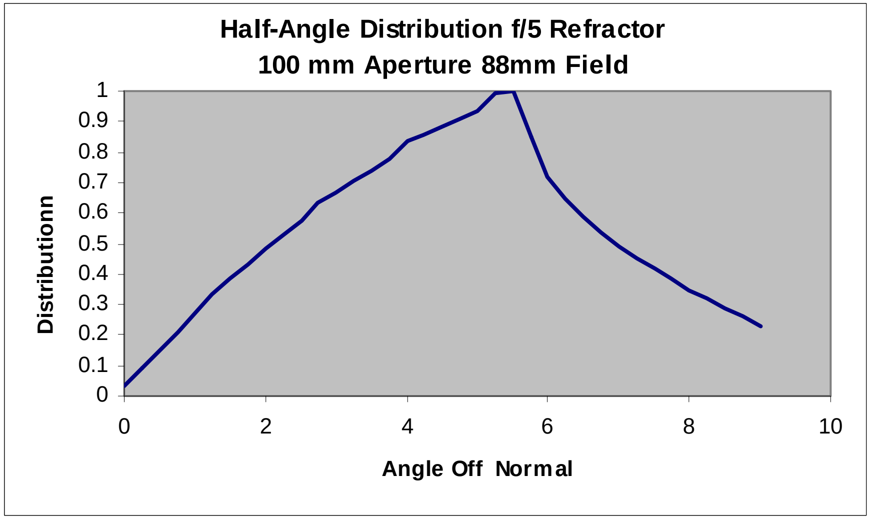
Compare Theory & Experiment



- Measurements show less shift than theory
- 3 nm filter is reasonable to f/3.5
- Not significant effect for >4 nm FWHM
- Not the whole story
  - Telescope optics

3 nm FWHM OIII on f/5 530 mm Refractor

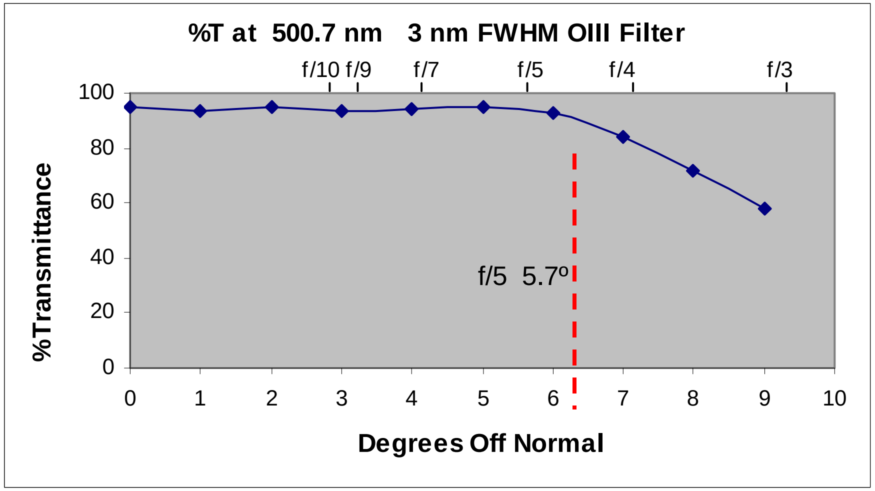


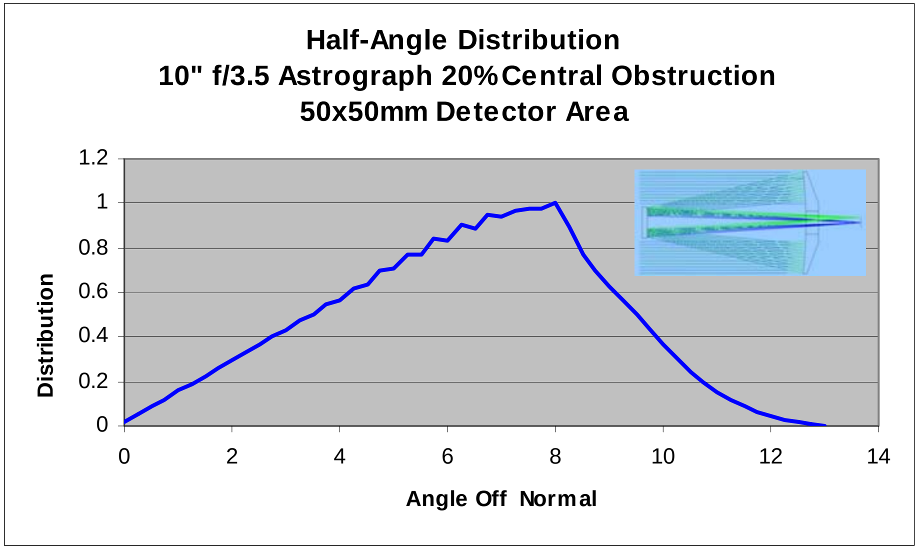


Ray trace results courtesy of Mike Jones, Optical Designer, Lockheed Martin

- Peak distribution at f/5 ~ 5.7°
- Many other angles striking the CCD
- Multiply the frequency of the angle (lower graph) * %T at 500.7 nm in the upper graph
- Effective %T for 3 nm FWHM OIII is 92%
- Not much loss from 94%
- Slower telescopes, including RCs, SCTs will not be affected.
- Wider NB filters will not be affected

3 nm FWHM OIII on 10” f/3.5 mm Astrograph



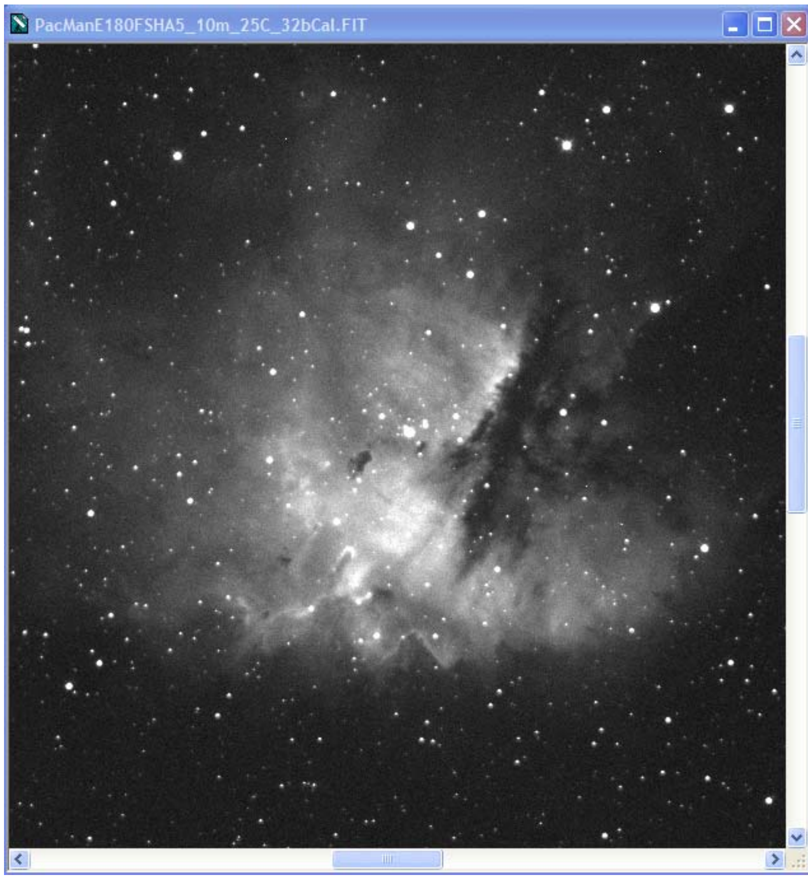


Ray trace results courtesy of Mike Jones, Optical Designer, Lockheed Martin

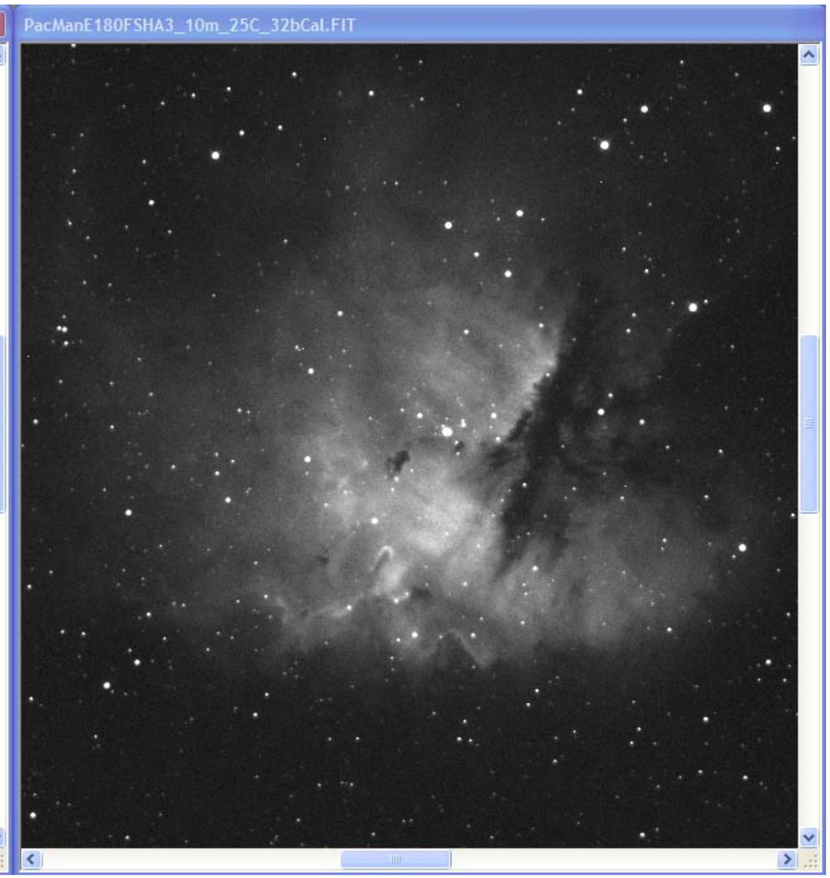
- 20% obstruction (area)
- 50 mm square detector area
- Peak distribution at f/3.5 ~ 8°
- Many other angles striking the CCD
- Multiply the frequency of the angle (lower graph) * %T at 500.7 nm in the upper graph
- Effective %T for 3 nm FWHM OIII is 80%
- Still useable at f/3.5?
- Slower telescopes, including RCs, SCTs will not be affected.
- Wider NB filters will not be affected

H-a Comparison on E-180 at f/3

5nm FWHM >92%T



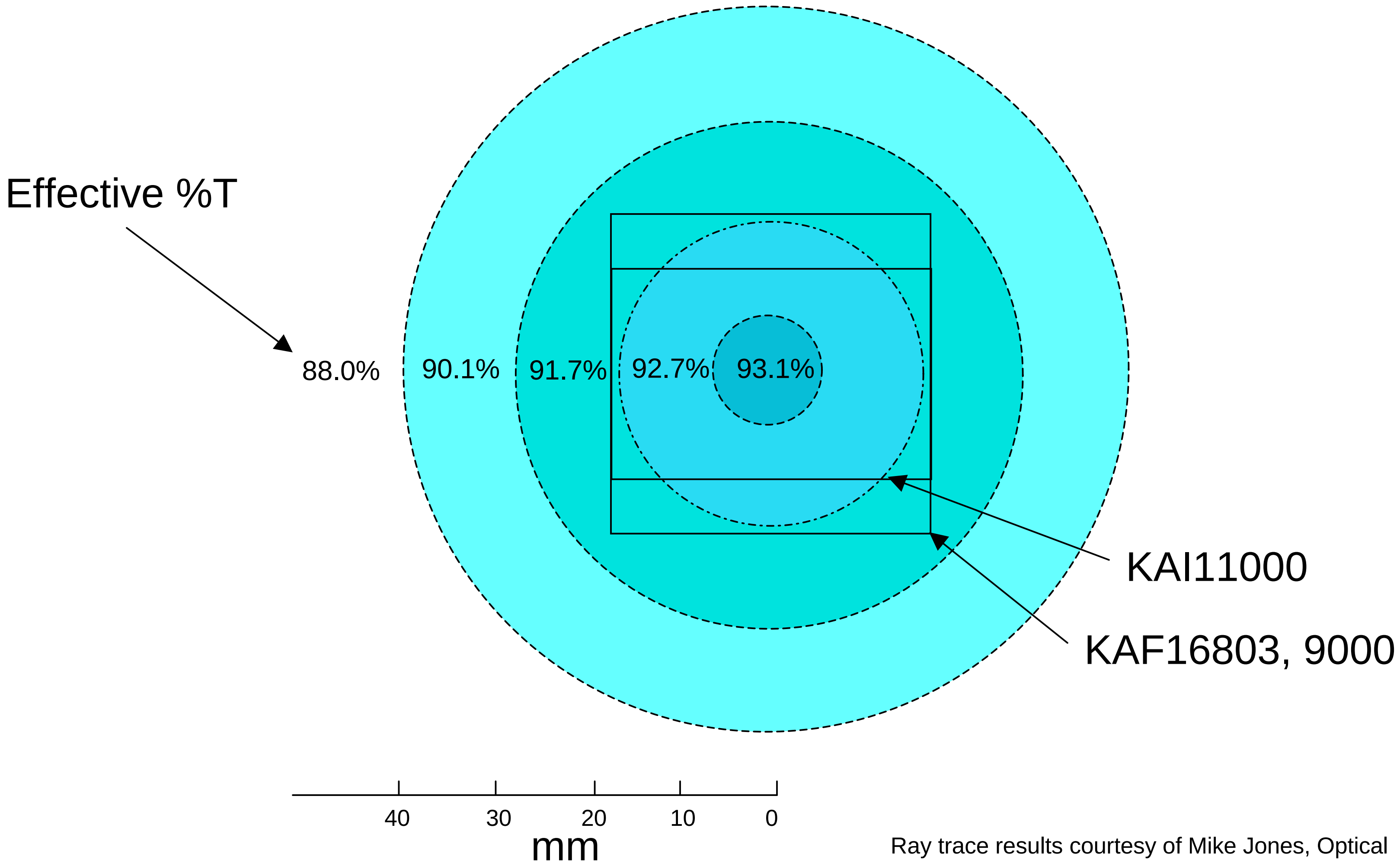
3nm FWHM > 92%T



SBIG STL11000XM, -25C, 1 10 min unbinned exposure, calibrated (dark, flat, bias), equalize screen stretch in MaximDL, same S/N

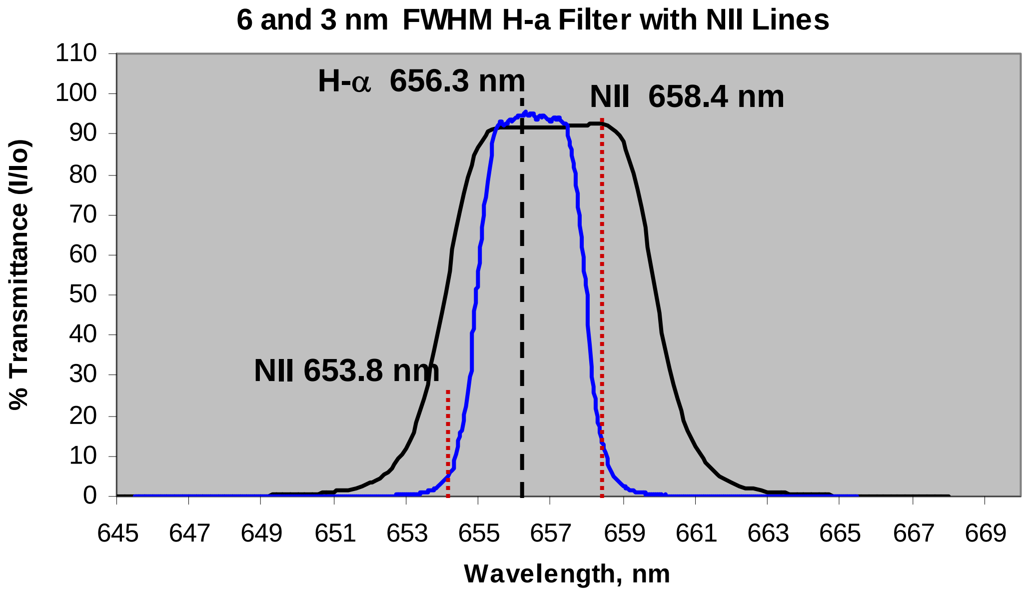
3 nm FWHM OIII Spatial Sensitivity

f/5 100mm System, 88 mm Field Angle Histograms in Each “Strip”



Ray trace results courtesy of Mike Jones, Optical Designer, Lockheed Martin

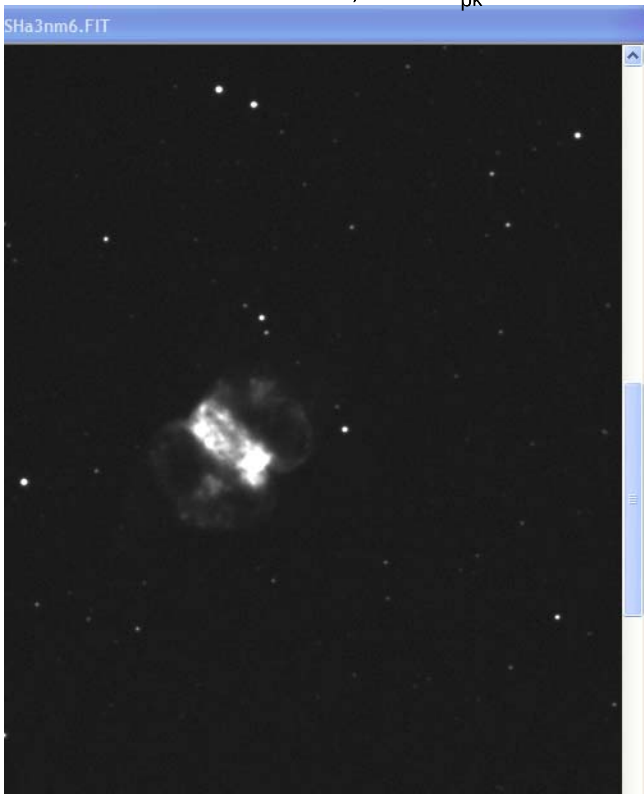
FWHM, H-α and Nitrogen



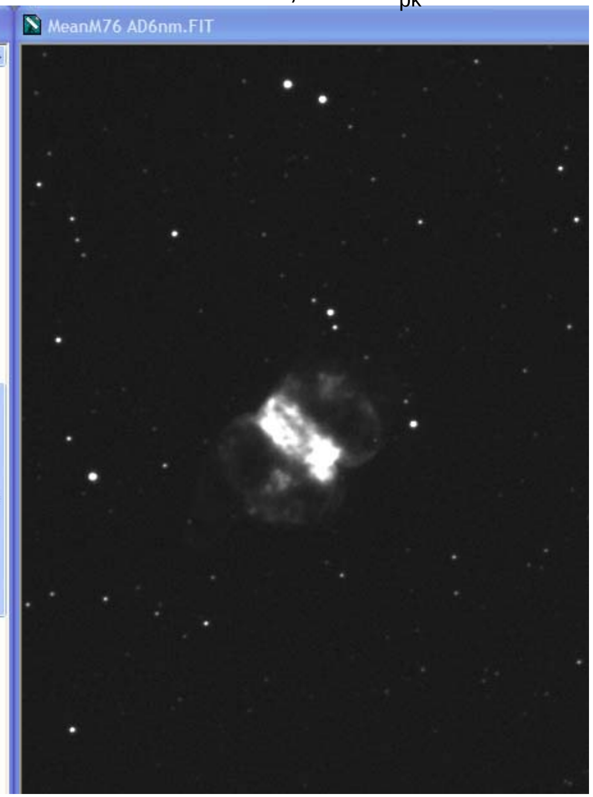
- NII doublet occurs close to H-α on either side
- NII can be 20% to >100% of H-α in PN and some galaxies
- Most H-α filters will include H-α AND NII
- Need ≤3 nm FWHM to exclude most NII in H-α
- Imagers want narrower filter to exclude light pollution & moonlight
- Imagers want highest signal, even if it comes from NII + H-α
- 3 nm H-α may not have S/N of 4.5 – 7 nm H-α on some objects (e.g. planetary nebula, WR bubbles, etc.) due to minimizing NII signal

M76 H-a S/N Comparison

3 nm, 94% T_{pk}



6 nm, 92% T_{pk}



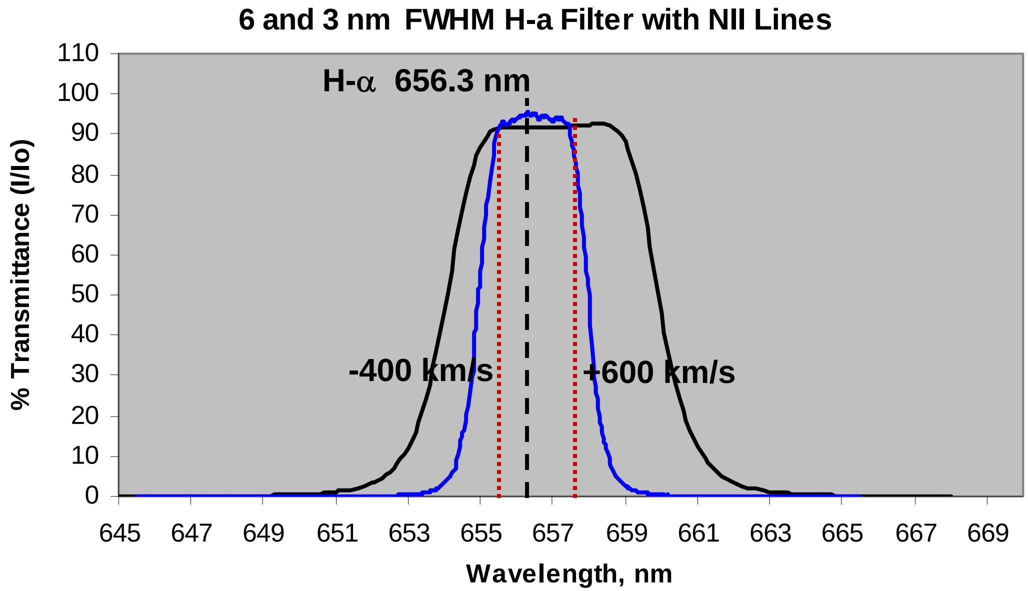
- Apogee U16M at -20C
- Gain 1.2
- RCOS 12.5" RC
- 5 x 10 min 1x1
- Dark, Flat, Bias calibrated in CCDStack
- S = (Sig-Bkg)*g
- N = SQRT (S * g + BKG STD^2)
- Compare regions with no stars

Sig = 208 ADU
Bkg = 16.1 ADU
Bkg STD = 1.68
S = 230
N = 15.3
S/N = 15.1

Sig = 257 ADU
Bkg = 30.4 ADU
Bkg STD = 1.61
S = 271
N = 16.6
S/N = 16.4

Unlike OIII, narrower H-α may not improve S/N perhaps due to loss of NII

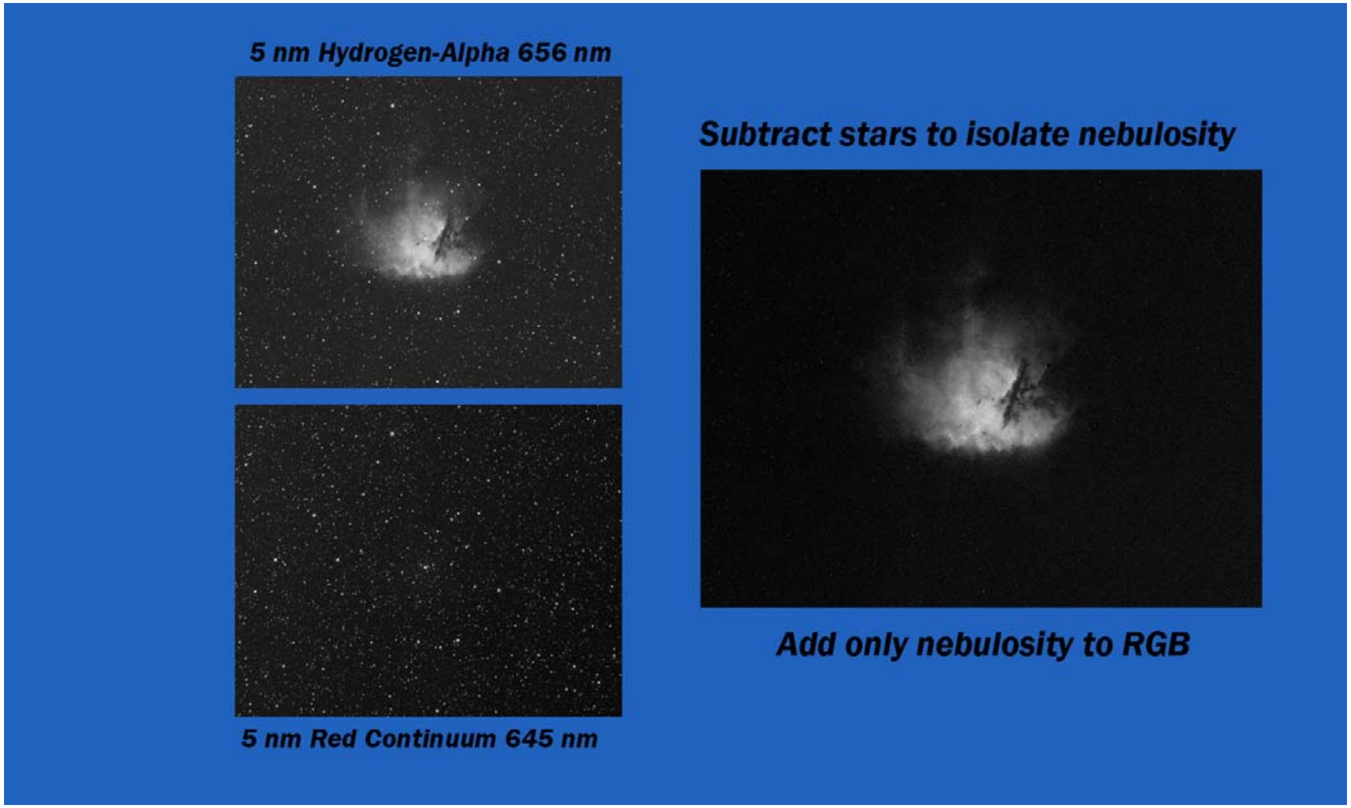
FWHM & Radial Velocities



- AAO/UKST H-α survey of the galactic plane
  - Q.A. Parker and J. Bland-Hawthorn, “Technical Aspects of the New AAO/UKST Hα Interference Filter”, Publ. Astron. Soc. Aust. 1998, 15, 33-7
- -400km/s to +600 km/s
- -0.9 nm to +1.3 nm
- 655.4 nm to 657.6 nm
- No significant effect for most H-α filters

Red Continuum Filter

- Subtract stars from H-a, SII data



Conclusions

- Narrowband Filters
  - FWHM ≤ 10 nm
  - Tuned to specific emission lines
  - Increase contrast by eliminating continuum
  - Show different structures (OIII, SII, NII, etc.)
  - Extend imaging time with moonlight
  - Allow us to image in light pollution
  - Astronomical NB filters are special

Conclusions (2)

Narrower Filters

- Want lowest FWHM with highest T_{pk}
- More difficult to make CONSISTENTLY
- More expensive
- Cannot achieve S/N advantage unless high T_{pk} is maintained.
- Wavelength blue shift is not as significant as previously thought
- Off-the-shelf appropriate for ≥ f/3.5
- Specially shifted filter for <f/3.5?
- May not achieve large advantage for H-α due to loss of NII in PN and galaxies


Thank You!!
Clear Skies

How Do the Pros Do It – AAO/UKST

- "Technical Aspects of the New AAO/UKST Hα Interference Filter", Pub. Astron. Soc. Aust, 1998, V15, pp 33-37
- Consortium for Hα survey of the Galactic plane
- Cover radial velocities of galaxies of -400 to +600 km/s (shifts of -0.9 nm and +1.2 nm from 656.3 nm)
- Placed in the f/2.48 convergent beam
- Coated 305 mm Hα diameter (~10") on a 356 x 356 mm plate (12")
- 7 nm FWHM
- CWL 659 nm ±2.5 nm to account for blue shift at f/2.48
- Blocking 4 OD from 200 to 699 nm
- T_{pk} >85%
- ¼ wave transmitted wavefront
- 0.004 nm/C blue shift with temperature.
- Narrow enough for use under a bright moon